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Representing icebergs in the *i*LOVECLIM model (version 1.0) – a sensitivity study

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Abstract

Recent modelling studies have indicated that icebergs alter the ocean's state, the thickness of sea ice and the prevailing atmospheric conditions, in short play an active role in the climate system. The icebergs' impact is due to their slowly released melt water which freshens and cools the ocean. The spatial distribution of the icebergs and thus their melt water depends on the forces (atmospheric and oceanic) acting on them as well as on the icebergs' size. The studies conducted so far have in common that the icebergs were moved by reconstructed or modelled forcing fields and that the initial size distribution of the icebergs was prescribed according to present day observations. To address these shortcomings, we used the climate model *i*LOVECLIM that includes actively coupled ice-sheet and iceberg modules, to conduct 15 sensitivity experiments to analyse (1) the impact of the forcing fields (atmospheric vs. oceanic) on the icebergs' distribution and melt flux, and (2) the effect of the used initial iceberg size on the resulting Northern Hemisphere climate and ice sheet under different climate conditions (pre-industrial, strong/weak radiative forcing). Our results show that, under equilibrated pre-industrial conditions, the oceanic currents cause the bergs to stay close to the Greenland and North American coast, whereas the atmospheric forcing quickly distributes them further away from their calving site. These different characteristics strongly affect the lifetime of icebergs, since the wind-driven icebergs melt up to two years faster as they are quickly distributed into the relatively warm North Atlantic waters. Moreover, we find that local variations in the spatial distribution due to different iceberg sizes do not result in different climate states and Greenland ice sheet volume, independent of the prevailing climate conditions (pre-industrial, warming or cooling climate). Therefore, we conclude that local differences in the distribution of their melt flux do not alter the prevailing Northern Hemisphere climate and ice sheet under equilibrated conditions und constant supply of icebergs. Furthermore, our results suggest that the applied radiative forcing scenarios have a stronger impact on climate than the used initial size distribution of the icebergs.

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1 Introduction

Icebergs are an important part of the climate system as they interact with the ocean, atmosphere and cryosphere (e.g. Hemming, 2004; Smith et al., 2011; Tournadre et al., 2012). Most importantly, icebergs play an important part in the global fresh water cycle since currently two thirds of the mass loss of the Antarctic and Greenland ice sheets is due to calving (approx. 0.01 Sv, $1\,\mathrm{Sv} = 1 \times 10^6\,\mathrm{m}^3\,\mathrm{s}^{-1}$, Hooke et al., 2005). As the icebergs are melting, they affect the upper ocean not only by freshening, but also by cooling due to their take up of latent heat. Several studies have revealed that the freshening and cooling have opposing effects on ocean stratification, as the cooling enhances the surface density, thereby promoting deep mixing, whereas the freshening decreases the water density, thereby stabilizing the water column (Jongma et al., 2009, 2013; Green et al., 2011).

Moreover, the implementation of dynamical icebergs in climate models has revealed that icebergs enhance the formation of sea ice (Jongma et al., 2009, 2013; Wiersma and Jongma, 2010; Bügelmayer et al., 2014), which forms a barrier between the ocean and the atmosphere. Therefore, on the one hand sea ice shields the ocean from being stirred by atmospheric winds, and on the other hand from losing heat to the relatively cold atmosphere, thus, reducing mixing of the upper water column. Further, this reduced oceanic heat loss leads, in combination with an increase in surface albedo, to a changed atmospheric circulation (Bügelmayer et al., 2014). Thus, icebergs even indirectly alter the ice sheet's mass balance through their effect on the atmospheric temperature and precipitation (Bügelmayer et al., 2014).

The effects of icebergs on climate depend on the calving flux provided by the ice sheets, which is altered by the prevailing climate conditions. For instance, in the relatively cold climate of the last glacial, episodically discharges of icebergs into the North Atlantic Ocean, so-called Heinrich events, have been recorded in distinct layers of ice rafted debris (Andrews, 1998; Hemming, 2004). These periods of enhanced ice discharge were probably caused by ice shelf collapses (e.g. Broecker et al., 1993;

GMDD
7, 4353–4381, 2014

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McManus et al., 2004; Gherardi et al., 2005) and resulted in a (partial) collapse of the thermohaline circulation (Kageyama et al., 2010). The collapse was caused by the long duration (Marcott et al., 2011) and massive amount of freshwater released (0.04 up to 0.4 Sv, Roberts et al., 2014) and affected the global climate.

So far, different approaches have been taken to incorporate icebergs from the Antarctic and Greenland ice sheets into numerical models for different time periods. Bigg et al. (1996, 1997) presented an iceberg module, which was fed with the present-day atmospheric and oceanic forcing provided off-line by atmospheric and oceanic models to investigate the drift patterns of icebergs in the Northern Hemisphere. Their approach was further developed for the Southern Ocean by Gladstone et al. (2001), who used modelled oceanic forcing and modern reconstructed wind fields, as well as observed calving amounts to seed the iceberg module. Subsequently, the same iceberg module was implemented in an earth system model of intermediate complexity (EMIC) by Jongma et al. (2009) to investigate the impact of icebergs on the Southern Ocean under pre-industrial conditions. In the latter study, the icebergs were moved according to the modelled atmospheric and oceanic forcing fields and were interacting with the climate model. Recently, Martin and Adcroft (2010) investigated the impact of icebergs on the Northern Hemisphere by adding this iceberg module into a coupled general circulation model. A further step was taken by Bügelmayer et al. (2014), who used an EMIC that was dynamically coupled to both an ice sheet model and an iceberg model. In their model setup, the climate–ice-sheet–iceberg system was fully interactive, with the icebergs' calving positions and amounts being determined by the ice sheet model, and with the ice sheet responding to the icebergs' effect on climate.

Coupled climate–iceberg models have been used for several specific purposes, such as the investigation of drift patterns of icebergs under present-day (Venkatesh and El-Tahan, 1988; Bigg et al., 1996) and glacial climate conditions (Death et al., 2005). In addition, these models have been utilized to study the effect of icebergs on the climate during present (e.g. Gladstone et al., 2001; Martin and Adcroft, 2010), pre-industrial (Jongma et al., 2009; Bügelmayer et al., 2014) and past times (Wiersma and Jongma,

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2010; Green et al., 2011; Jongma et al., 2013) using both prescribed and interactively modelled forcing fields, and have shown that icebergs and their melt water have an impact on climate.

The spatial distribution of the icebergs' freshwater flux depends on the forces acting on the icebergs (atmospheric and oceanic). Therefore, uncertainties in the reconstructions as well as model-dependent errors in the used forcing fields have a direct effect on the iceberg tracks and consequently on the distribution of the freshwater. Another uncertainty of iceberg modelling lies in the used initial size distribution of the icebergs, which is prescribed according to present day observations (Dowdeswell et al., 1992). Yet, the used size distribution may not be a valid representation of calving events in past or future climate conditions.

We therefore propose in this study to extend the approach of Bügelmayer et al. (2014), evaluating in detail the impact of different forcing fields and iceberg size distributions. We use the same earth system model of intermediate complexity (*i*LOVECLIM) coupled to an ice sheet/ice shelf model (GRISLI) and an iceberg module to answer the following research questions.

1. How do atmospheric and oceanic forcing fields affect the icebergs (their lifetime and movement) in the Northern Hemisphere under pre-industrial conditions?

2. How sensitive is the pre-industrial Northern Hemisphere climate and Greenland ice sheet to spatial variations in the iceberg melt flux?

3. Do the Northern Hemisphere climate and the Greenland ice sheet respond differently to icebergs of different initial size distributions?

4. Is the Northern Hemisphere climate and the Greenland ice sheet response to icebergs of different initial size distributions dependent on the prevailing climate conditions (pre-industrial (PI), warmer than PI and colder than PI)?

We will address these questions by presenting results from 15 different sensitivity experiments (Table 1) that differ in the applied forcing (atmospheric, oceanic,

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pre-industrial, warmer, colder climate) and the initial size distribution (CTRL (standard sizes), BIG, SMALL, Table 2) of the icebergs.

We will first introduce the model and the experimental set-up, then present the results and the discussion, followed by a conclusion section.

2 Methods

We use the earth system model of intermediate complexity *i*LOVECLIM (version 1.0) which is a code fork of the LOVECLIM climate model version 1.2 (Goosse et al., 2010). *i*LOVECLIM differs in the ice sheet module included and the further developed iceberg module (Roche et al., 2013; Bügelmayer et al., 2014) but shares some physical climate components (atmosphere, ocean and vegetation) with LOVECLIM.

2.1 Atmosphere–ocean–vegetation model

The climate model *i*LOVECLIM consists of the atmospheric model ECBilt (Opsteegh et al., 1998), a quasi-geostrophic, spectral model with a horizontal resolution of T21 (5.6° in latitude/longitude) and three vertical pressure levels (800, 500, 200 hPa). The atmospheric state (including e.g., temperature, humidity) is calculated every four hours. Precipitation depends on the available humidity in the lowermost atmospheric level and the total solid precipitation is given to the ice-sheet model at the end of one model year, as are the monthly surface temperatures.

*i*LOVECLIM includes the sea–ice and ocean model CLIO, which is a 3-D ocean general circulation model (Deleersnijder and Campin, 1995; Deleersnijder et al., 1997; Campin and Goosse, 1999) consisting of a dynamic–thermodynamic sea–ice model (Fichefet and Morales Maqueda, 1997, 1999). Due to its free surface, the freshwater fluxes related to iceberg melting can be directly applied to the ocean's surface. The horizontal resolution is 3° × 3° in longitude and latitude and the ocean is vertically divided

GMDD
7, 4353–4381, 2014

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into 20 unevenly spaced layers. CLIO consists of a realistic bathymetry. The oceanic variables (e.g., sea surface temperature and salinity) are computed once a day.

The vegetation (type and cover) is calculated by the vegetation model VECODE (Brovkin et al., 1997), which runs on the same grid as ECBilt. VECODE accounts for fractional use of one grid cell because of the small spatial changes in vegetation. It simulates the dynamics of two plant functional types (trees and gras) as well as bare soil, in response to the temperature and precipitation coming from ECBilt.

2.2 GRISLI–ice sheet model

The ice-sheet model included in *i*LOVECLIM is the Grenoble model for Ice Shelves and Land Ice (GRISLI), which is a three-dimensional thermomechanical model that was first developed for the Antarctic (Ritz et al., 1997, 2001) and was further developed for the Northern Hemisphere (Peyaud et al., 2007). GRISLI consists of a Lambert azimuthal grid with a 40 km × 40 km horizontal resolution. In the present study, it computes the evolution of the thickness and extension of the Greenland ice sheet (GrIS) only, as we do not consider the Southern Hemisphere grid. GRISLI distinguishes three types of ice flow: inland ice, ice streams and ice shelves. Calving takes place whenever the ice thickness at the border of the ice sheet is less than 150 m and the points upstream do not provide enough inflow of ice to maintain this thickness. After one model year, the total yearly amount of calving is given to the iceberg module to generate bergs. The runoff of GRISLI is calculated at the end of the year by computing the difference between the topography at the beginning of the model year and the end of the year, and taking into account the mass loss due to calving. The runoff is then given to ECBilt where it is incorporated into the land routing system. GRISLI is run for one model year and then provides the runoff and calving, as well as the updated albedo- and topography fields to the atmosphere–ocean–vegetation component. A more detailed explanation of the coupling between ECBilt, CLIO and the ice sheet model GRISLI is provided in Roche et al. (2013) and Bügelmayer et al. (2014).

GMDD
7, 4353–4381, 2014

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2.3 Iceberg module

As discussed in detail in Bügelmayer et al. (2014), the dynamic–thermodynamic iceberg module (Jongma et al., 2009; Wiersma and Jongma, 2010) included in *i*LOVECLIM is based on the iceberg-drift model of Smith and co-workers (Smith and Banke, 1983; Smith, 1993; Loset, 1993) and on the developments done by Bigg et al. (1996, 1997) and Gladstone et al. (2001). According to the calving mass and locations calculated by GRISLI over one model year, icebergs of up to ten size classes are generated per day following a seasonal cycle (Martin and Adcroft, 2010). The control size distribution of the icebergs is according to Bigg et al. (1996) and based on observations of Dowdeswell et al. (1992) and represents the Greenland present day distribution (Table 2). Icebergs are moved by the Coriolis force, the air drag, sea–ice drag, the horizontal pressure gradient force and the wave radiation force. The forcing fields are provided by ECBilt (winds) and CLIO (ocean currents) and are linearly interpolated from the surrounding grid corners to the icebergs' position. The icebergs melt over time due to basal melt, lateral melt and wave erosion and may roll over as their length to height ratio changes. The heat needed to melt the bergs is taken from the ocean layers corresponding to the icebergs' depth and the freshwater fluxes are put into the ocean surface layer of the current grid cell. The refreezing of melted water and the break-up of icebergs is not included in the iceberg module.

2.4 Experimental set-up

We have performed 15 sensitivity experiments that differ in the initial size distribution (CTRL/SMALL/BIG, Table 2), in the applied CO_2 forcing (pre-industrial = 280 ppm, $4 \times CO_2$ = 1120 ppm, $1/4 \times CO_2$ = 70 ppm) or in the forces that move the icebergs (atmosphere and ocean). A summary of the experiments performed is given in Table 1. All runs were started from an equilibrated climate and ice sheet under pre-industrial conditions (Fig. 5a) that has already been used in the study of Bügelmayer et al. (2014). The fact that the initial ice sheet thickness is about 1/3 bigger than the observed one does

GMDD
7, 4353–4381, 2014

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not impact our results since we are interested in the effect of the forcing fields and the initial size distribution on the development of the ice sheet and not in the resulting ice sheet extension compared to observations. The model runs were conducted for 200 model years (pre-industrial) and 1000 model years (4xCO_2, 1/4 × CO_2), respectively. The last 100 years are presented in the results.

2.4.1 Impact of forcing fields

To differentiate between the impact of the ocean and the atmosphere, the equation of motion (Eq. 1) of an iceberg is used:

$$M\frac{DV_I}{DT} = -M_F k_x V_I + F_\mathrm{A} + F_\mathrm{R} + F_\mathrm{W} + F_\mathrm{P} + F_\mathrm{S} \quad (1)$$

with M being the Mass of the iceberg, $\mathrm{d}V_I/\mathrm{d}t$ is the time derivative of the icebergs' velocity, the first term ($-M_F k_x V_I$) on the right side corresponds to the Coriolis force, the second and third are the air drag (F_A) and wave radiation force (F_R) and therefore depend on the atmospheric winds; the last three terms represent the oceanic forcing namely water drag (F_W), horizontal pressure gradient (F_P) and sea–ice drag (F_S).

In the so-called "ATM" set-up (Table 1), all the forcing terms corresponding to ocean currents are set to zero, thereby ensuring that the icebergs are only moved by the Coriolis and the atmospheric forcing. In the "OCE" set-up on the contrary, the air drag and the wave radiation force are defined to be zero, thus only the Coriolis force and the ocean currents are acting on the bergs.

2.4.2 Initial size distribution

By comparing the CTRL, SMALL and BIG experiments, we are able to investigate the impact of the initial size distribution. In the CTRL experiments, depending on the available mass, icebergs of all 10 size classes can be generated (Bügelmayer et al., 2014). In the SMALL (BIG) experiments, the available mass is used to generate an equal amount of the three smallest (biggest) iceberg sizes (Table 2). The differences in the

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resulting atmospheric and ocean conditions as well as the ice-sheet allow us to identify the different impact of the BIG and the SMALL icebergs on the climate and the ice sheet. We conducted three sets of experiments using these three size distributions, the first set was done under pre-industrial equilibrium conditions for 200 years. In the second one, a "warm" experiment, we applied a CO_2 concentration four times as strong as the pre-industrial value (1120 vs. 280 ppm CO_2) and in the third, a "cold" experiment, only a quarter of the pre-industrial CO_2 concentration is used (70 vs. 280 ppm CO_2). The latter two sets of experiments were done to analyse the effect of the size (CTRL/SMALL/BIG) distribution under non-equilibrated conditions.

3 Results

3.1 Pre-industrial conditions

3.1.1 Impact of the forcing fields on the icebergs and the resulting climate

Applying only atmospheric forcing transports CTRL-ATM icebergs far into the North Atlantic and Arctic Ocean (Fig. 1a) as the wind pushes them quickly away from the Greenland ice sheet (GrIS) margin. Such a wide spread distribution is only found in CTRL-ATM as there icebergs of all size classes are generated, therefore also middle-sized bergs (Table 2). But in BIG-ATM or SMALL-ATM (Fig. 1b and c) the bergs are not spread as far due to two different mechanisms. The SMALL-ATM bergs quickly melt as soon as they enter the relatively warm North Atlantic (Fig. 3) whereas the atmospheric forcing is not strong enough in the case of the BIG-ATM icebergs to push them into the Arctic Ocean (Fig. 1b). This is also seen in the lesser amount of iceberg melt flux released in BIG-ATM in the Arctic Ocean in comparison to SMALL-ATM or CTRL-ATM (80 vs. 110–120 $m^3 s^{-1}$, Fig. 2b). In the Greenland–Iceland–Norwegian Seas (GIN Seas) and the North Atlantic however, all the purely atmospheric driven experiments release about the same amount of melt water, but again the SMALL and CTRL icebergs spread

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over a much wider area (Fig. 2c and d). Comparing the pattern of the iceberg distribution of SMALL-ATM and BIG-ATM in the North Atlantic (Fig. 1b and c) also shows the effect of the Coriolis force as the bigger bergs experience an eastward movement. Even though, the SMALL and CTRL icebergs in the ATM experiments cover a bigger area in the GIN Seas and the North Atlantic than the BIG ones, the resulting mean sea surface temperature (SST) does not differ strongly between them (Fig. 4a), nor does the mean air temperature (TAIR, Fig. 4b) because the amount of iceberg melt flux is comparable (Fig. 2). Even though there is less freshwater released in BIG-ATM in the Arctic Ocean, the climate response is not altered since the prevailing cold sea surface temperatures are not strongly affected by the cooling and freshening effect of the icebergs (not shown). Considering the Mid- to High latitudes (40–90° Lat and 80° W–15° E), the area that is covered by icebergs is the highest in CTRL-ATM but the amount of freshwater released is comparable to the other two ATM experiments (Fig. 2a).

The effect of the oceanic forcing is in strong contrast to the atmospheric one as it causes the icebergs to stay close to the GrIS margin (Fig. 1d). The icebergs movement reflects the prevailing ocean currents, such as the East Greenland and the Labrador Current and the Beaufort Gyre. This is especially seen in the CTRL-OCE and the BIG-OCE experiments (Fig. 1d and e) since the icebergs survive longer (Fig. 3) and are thus transported further than in SMALL-OCE. Except from the Arctic Ocean, where less melt water is released in BIG-OCE, the area covered and the freshwater released by oceanic driven icebergs is almost independent of their initial size distribution (Fig. 2). Therefore, the mean climate does not differ significantly between the OCE experiments either (Fig. 4a and b).

The combined effect of atmospheric and oceanic forcing is displayed in the CTRL-, BIG-, and SMALL-COM experiments (Fig. 1g–i). Especially in the Arctic Ocean generating icebergs of the three biggest size classes, BIG-COM, results in a wider spread distribution than in the BIG-ATM or BIG-OCE (Fig. 2a). Adding the atmospheric to the oceanic forcing allows the icebergs that are transported by the Beaufort Gyre to be moved even further into the Arctic Ocean (Fig. 1h). Although the area covered by

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BIG-COM icebergs is larger than in the BIG-ATM/OCE, less icebergs are transported into the Arctic Ocean and thus less melt water is released in BIG-COM (Fig. 2b). In the North Atlantic the pattern of the BIG-COM iceberg distribution clearly displays the effect of the Coriolis force that depends on the mass and the velocity of the moving object. Due to the combination of atmospheric and oceanic forcing, the bergs are moved faster and thus are stronger influenced than the BIG-ATM or BIG-OCE. In contrast to the Arctic Ocean and the North Atlantic, where the wind and ocean currents enhance each other, in the GIN Seas they counteract each other and keep the BIG-COM closer to shore than the BIG-ATM or BIG-OCE (Figs. 1h and 2c).

In the case of the SMALL-COM and CTRL-COM the resulting iceberg distribution and iceberg melt flux linearly displays the combination of the applied forcings (Figs. 1g, i and 2). Even though the spatial pattern of the icebergs differ in BIG-, SMALL-, and CTRL-COM, the mean SST and also TAIR are very similar (Fig. 4a and b).

3.1.2 Lifetime of icebergs

The impact of the forcing fields is clearly seen in the icebergs' lifetime, that is the time (in months) it takes to completely melt the bergs. 90 % of all the atmospheric forced icebergs (SMALL-, BIG-, and CTRL-ATM) melt up to two years faster compared to the oceanic forced bergs SMALL-, BIG-, and CTRL-OCE and compared to the icebergs of the SMALL-, BIG-, and CTRL-COM set-up (Fig. 3). This can be explained by the fact that the atmospheric forcing pushes the majority of icebergs into the North Atlantic where they are quickly spread into warmer waters and melt (Fig. 2d). The shorter lifetime of the atmospheric driven icebergs does not cause alterations in the climate and GrIS because the calving flux provided by GRISLI is almost constant over the years and comparable in all the pre-industrial experiments. Therefore, the same amount of freshwater is supplied to the ocean.

Under pre-industrial equilibrium conditions the atmospheric and oceanic forcing do transport the icebergs differently but the resulting spatial patterns of the iceberg melt

GMDD
7, 4353–4381, 2014

flux cause only local differences in the Greenland ice sheet volume (Table 3), the oceanic and atmospheric conditions.

3.2 Impact of initial iceberg size under a changing climate

To have more confidence in using the present day iceberg distribution also for simulations of past and future climates, we conducted two more sets (CTRL, BIG, SMALL), the so-called HIGH = 4 × CO_2 (1120 ppm) and LOW = 1/4 × CO_2 (70 ppm) experiments, with a duration of 1000 years. The HIGH experiments resulted in an up to 4 °C warmer global mean temperature and caused the Greenland ice sheet to lose 10 % of its volume, whereas the LOW experiments caused the mean global temperatures to decrease about 3 °C and an increase of the Greenland ice sheet volume of up to 5 %, compared to the pre-industrial ice sheet volume (Table 3).

3.2.1 HIGHCO experiments

The effects of the boundary conditions on the Greenland ice sheet are shown in Fig. 5 where the resulting CTRL-HIGH ice sheet extensions and thickness are shown (Fig. 5b) compared to the equilibrated CTRL-COM ice sheet (Fig. 5a).

At the end of the simulations of constant 1120 ppm CO_2 forcing, there are only small differences between the SMALL-, BIG-, and CTRL-HIGH runs. As the ice sheet is shrinking and retreating from the coast (Fig. 5b), the amount of calving flux from the GrIS is decaying (0.003 SV vs. 0.02 SV in the CTRL-COM), especially in South Greenland, and so is the icebergs melt flux. The released iceberg melt flux in the GIN Seas is in the range of 50 (SMALL-, CTRL-HIGH) to 80 $m^3 s^{-1}$ (BIG-HIGH, Fig. 2c), compared to 150 $m^3 s^{-1}$ in the CTRL-COM. Moreover, there are hardly any icebergs entering the North Atlantic, independent of the used size distribution (Fig. 2d). In contrast to the North Atlantic, the amount of iceberg melt flux in the Arctic Ocean is almost not altered (Fig. 2b) despite the enhanced CO_2 concentration as the ice sheet is still reaching the coast (Fig. 5b), thus providing a steady calving flux.

GMDD
7, 4353–4381, 2014

Although the size of the icebergs generated varies from the beginning, the resulting climate conditions, such as sea surface or air temperatures do not vary at the end of the 1000 year period between the SMALL-, BIG-, and CTRL-HIGH experiments (Fig. 4a and b), nor does the GrIS volume (Table 3). Also during periods of strong background changes, different iceberg distributions do not result in different climate states. This indicates that the applied forcing has a stronger impact than local differences due to the chosen iceberg size.

3.2.2 LOWCO experiments

Modelling the impact of different initial size distributions of the icebergs on the evolution of the climate and the Greenland ice sheet during an up to 3 °C colder climate (70 ppm CO_2 constant over 1000 model years) shows that it does not affect the resulting climate (Fig. 4) or ice sheet volume (Table 3). Due to the increased ice sheet thickness, more calving takes place and so the iceberg melt flux increases almost everywhere around Greenland (Fig. 2). The released iceberg melt flux displays a bigger spread than seen in the previous experiments, especially in the North Atlantic (Fig. 2b). Since the cold prevailing conditions prevent the BIG-LOW icebergs from melting quickly, almost all of them are transported into the North Atlantic where they finally melt. The pattern found in the Arctic Ocean (Fig. 2b) has been prominent in all the performed experiments as the BIG icebergs do not spread as much as the CTRL or SMALL ones. Independent of the chosen size distribution, the resulting temperatures are about 5 °C lower than during pre-industrial conditions in the North Atlantic and the GIN Seas (Fig. 4) displaying the strong CO_2 forcing.

These results show that the used initial size distributions do not alter the response of the climate and the GrIS to the applied forcing. Thus indicating that the extreme boundary conditions have a stronger impact on the results than the used iceberg sizes.

GMDD
7, 4353–4381, 2014

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4 Discussion

By testing the impact of the atmospheric vs. the oceanic forcing on icebergs' lifetime and movement, we find that the atmospheric forcing causes the bergs to travel further away from their calving sites and into the North Atlantic, whereas the ocean currents lead to iceberg tracks closer to shore. It is difficult to compare our results to previous studies, since the studies that investigated the impact of the background forcing (Smith, 1993; Keghouche et al., 2002) focused on observations of single icebergs and the ability of models reproducing their specific tracks. Bigg et al. (1997) noted that the modelling of specific iceberg tracks is very unlikely to be successful and it is important to notice that we do not expect our model to resolve single tracks due to its coarse resolution, but to reflect the wide spread effect of icebergs on climate.

In our model, the impact of icebergs on climate does not strongly depend on the two types of forcing (atmospheric and oceanic), yet their lifetime is shortened up to two years when they are transported by atmospheric forces only. Bigg et al. (1997) showed that about 80 % of the small bergs (size class 1 to 3) melt within the first year, which lies between our SMALL-ATM and SMALL-COM/SMALL-OCE results where about 90 % and 60 % are melted, respectively. Also Venkatesh and El-Tahan (1988) conducted a study to investigate the impact of modelling complete deterioration on predicting specific iceberg tracks. In their study they showed that most of the icebergs corresponding to class 1 to 3 disappear within 3 to 22 months, reassuring our results. The maximum lifetime of the BIG bergs is found to be eight years, which is up to two years longer than modelled by Bigg et al. (1997). This discrepancy can be due to the pre-industrial climate conditions used in our study that are slightly colder than the present day conditions applied by Bigg et al. (1997).

To better understand the response of the modelled climate to the initial size distribution, we performed different sensitivity experiments using pre-industrial as well as strongly increased and decreased radiative forcing, respectively. We find that independent of the forcing and climate background, BIG icebergs release less freshwater and

GMDD
7, 4353–4381, 2014

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spread over a smaller area in the Arctic Ocean than SMALL and CTRL icebergs. In the other areas considered (GIN Seas, North Atlantic and Northern Hemisphere) we do not find a uniform pattern. In the North Atlantic the impact of the Coriolis force is especially pronounced in the BIG-ATM and BIG-COM experiment, confirming the findings of Roberts et al. (2014). In their study they noted that BIG icebergs travel further south than small icebergs due to the stronger impact of the Coriolis force. Even though the SMALL icebergs cause locally different ocean and atmospheric conditions than the BIG bergs, the overall effect on climate and especially on the Greenland ice sheet is negligible.

There might be different reasons why the climate conditions and the GrIS are not strongly affected by the initial size distribution. One reason could be that the ice sheet and the climate model are too insensitive to the experienced changes as they have a relatively coarse resolution. Therefore, it would be interesting to repeat this study with a finer model grid. Another reason might be that in the experiments where really strong forcing was applied (HIGH = 1120 ppm CO_2, LOW = 70 ppm CO_2), the feedbacks related to calving have a smaller signal than the forcing and are therefore overruled.

5 Conclusions

Within a fully coupled climate–ice sheet–iceberg model set up, we have performed sensitivity experiments to investigate the effect of the forcing fields such as winds and ocean currents, as well as the prescribed initial size distribution on the icebergs and the climate.

We find that, under pre-industrial conditions, the wind forcing pushes the icebergs further away from their calving sites and further into the North Atlantic, whereas the ocean currents transport the bergs close to Greenland and southward along the Canadian coast. The combined effect of the forces (control set-up) allows for a wide-spread iceberg distribution in the Arctic Ocean and into the North Atlantic. The icebergs' spread depends on both the forcing fields and the icebergs size with the CTRL bergs

GMDD
7, 4353–4381, 2014

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being transported the furthest, followed by the SMALL bergs (size class 1 to 3). The amount of released iceberg melt flux is comparable in all the experiments, though locally different. In our model set-up, the biggest impact of the applied forcing (atmospheric or oceanic) is on the icebergs' lifetime which is up to two years shorter if the icebergs are only transported by winds.

In the presented model framework, the implementation of icebergs of different size classes under equilibrated pre-industrial conditions reveals that there are local differences in the released freshwater flux. But these differences do not cause significant changes in the resulting Greenland ice sheet volume and climate conditions.

When repeating the experiments with different size distributions with strong radiative cooling or warming (1120 ppm CO_2 or 70 ppm CO_2, 1000 model years), the response of the climate and the ice sheet volume are almost identical in all the performed experiments.

Even though the iceberg and freshwater distribution differ between the conducted experiments (all size classes, only SMALL and only BIG bergs, respectively), their impact on the northern hemispheric climate does not differ strongly. We can therefore conclude that for the resulting climate and ice sheet small spatial differences between the runs do not have a strong impact as long as there is a wide spread impact of icebergs (cooling and freshening) around Greenland. Furthermore, our results show that the response of the climate to the applied radiative forcing is much stronger than its response to the used initial size distribution of the icebergs.

The presented results make us confident in applying the prescribed present day iceberg sizes under different climates without introducing a strong bias.

Code availability

The *i*LOVECLIM source code is based on the LOVECLIM model version 1.2 whose code is accessible at http://www.elic.ucl.ac.be/modx/elic/index.php?id=289. The developments on the iLOVECLIM source code are hosted at https://forge.ipsl.jussieu.fr/ludus but are not publicly available due copyright restrictions. Access can be granted on

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demand by request to D. M. Roche (didier.roche@lsce.ipsl.fr). The specific experimental set-up used for this study is available at https://forge.ipsl.jussieu.fr/ludus.

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GMDD
7, 4353–4381, 2014
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M. Bügelmayer et al.

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GMDD

7, 4353–4381, 2014

Table 1. Performed experiments.

	Only atmospheric forcing	Only oceanic forcing	Pre-industrial (ATM & OCE Forcing) = 280 ppm	$4 \times CO_2$ (ATM & OCE Forcing) = 1120 ppm	$1/4 \times CO_2$ (ATM & OCE Forcing) = 70 ppm	Name
Experiment name	ATM	OCE	COM	HIGH	LOW	
Big Bergs	x	x	x	x	x	BIG-exp.name
Small Bergs	x	x	x	x	x	SMALL-exp.name
All Sizes	x	x	x	x	x	CTRL-exp.name

GMDD
7, 4353–4381, 2014

Table 2. Used initial iceberg classes.

Class	Height (m)	Width (m)	Volume (m^3)	Percentage of total available volume	Experiment
1	67	67	5.16×10^5	0.15/0.33	CTRL/SMALL
2	133	133	4.07×10^6	0.15/0.33	CTRL/SMALL
3	200	200	1.38×10^7	0.2/0.33	CTRL/SMALL
4	267	267	3.28×10^7	0.15	CTRL
5	300	333	5.74×10^7	0.08	CTRL
6	300	400	8.28×10^7	0.07	CTRL
7	300	500	1.29×10^4	0.05	CTRL
8	300	600	1.86×10^8	0.05/0.33	CTRL/BIG
9	300	800	3.31×10^8	0.05/0.33	CTRL/BIG
10	300	1000	5.18×10^8	0.05/0.33	CTRL/BIG

GMDD
7, 4353–4381, 2014

Table 3. Ice-sheet Volume (m^3): mean and standard deviation of last 100 years, % diff = difference between the ice sheet volume of the CTRL experiment and the BIG/SMALL experiments in percent.

Experiment	Mean	STDEV	% diff
CTRL-COM	3.916×10^{15}	4.794×10^{11}	0.00
BIG-COM	3.917×10^{15}	5.925×10^{11}	−0.03
SMALL-COM	3.916×10^{15}	6.805×10^{11}	−0.01
CTRL-ATM	3.917×10^{15}	8.165×10^{11}	0.00
BIG-ATM	3.916×10^{15}	4.654×10^{11}	0.03
SMALL-ATM	3.917×10^{15}	5.222×10^{11}	0.01
CTRL-OCE	3.917×10^{15}	5.016×10^{11}	0.00
BIG-OCE	3.915×10^{15}	4.984×10^{11}	0.03
SMALL-OC	3.916×10^{15}	4.924×10^{11}	0.01
CTRL-HIGH	3.576×10^{15}	1.849×10^{12}	0.00
BIG-HIGH	3.583×10^{15}	2.093×10^{12}	−0.20
SMALL-HIGH	3.585×10^{15}	1.927×10^{12}	−0.26
CTRL-LOW	4.109×10^{15}	1.005×10^{12}	0.00
BIG-LOW	4.110×10^{15}	8.335×10^{11}	−0.02
SMALL-LOW	4.103×10^{15}	1.531×10^{12}	0.15

GMDD
7, 4353–4381, 2014

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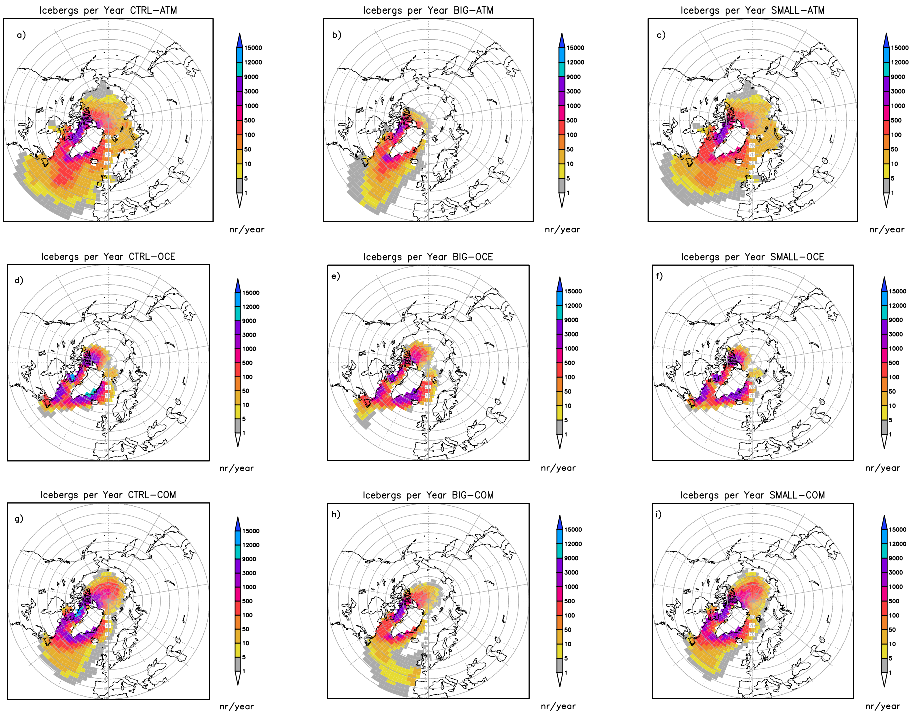

Figure 1. Number of icebergs passing by a grid cell per year (icebergs that are grounded are only counted once); first row: atmospheric forcing only (CTRL-, BIG-, SMALL-ATM); second row: oceanic forcing only (CTRL-, BIG-, SMALL-OCE), third row: the default set-up (icebergs are moved by both, atmospheric and oceanic forcing; CTRL-, BIG-, SMALL-COM).

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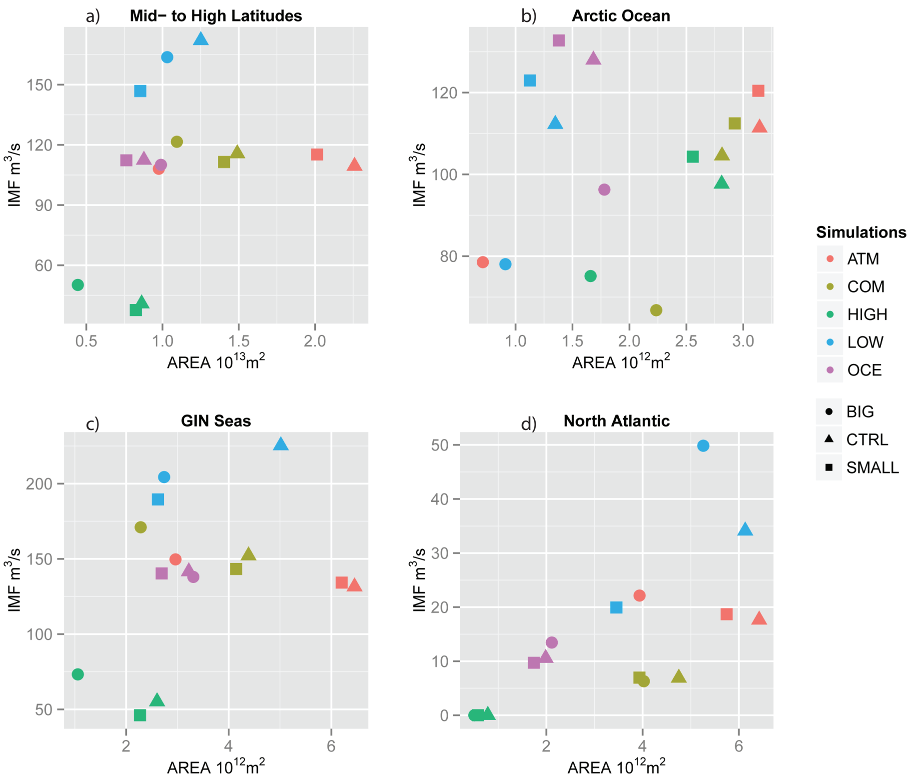

Figure 2. Area (m^2) vs. iceberg melt flux (m^3 s^{-1}); the area is computed by taking into account all the gridcells that are passed by more than 10 icebergs (be aware that the area is 10^{13} m^2 in **a**, 10^{12} m^2 otherwise); **(a)** mid- to high latitudes: mean computed over 40–90° N and 80° W–15° E, values of IMF: 30–180 m^3 s^{-1}; **(b)** Arctic Ocean: 80–90° N and 180° W–180° E, values of IMF: 60–140 m^3 s^{-1}; **(c)** Greenland–Iceland–Norwegian (GIN) Seas: 50–85° N and 45° W–15° E, values of IMF: 40–240 m^3 s^{-1}; **(d)** North Atlantic: 45–60° N and 60–20° W, values of IMF: 0–50 m^3 s^{-1}.

GMDD
7, 4353–4381, 2014
Representing icebergs in iLOVECLIM
M. Bügelmayer et al.

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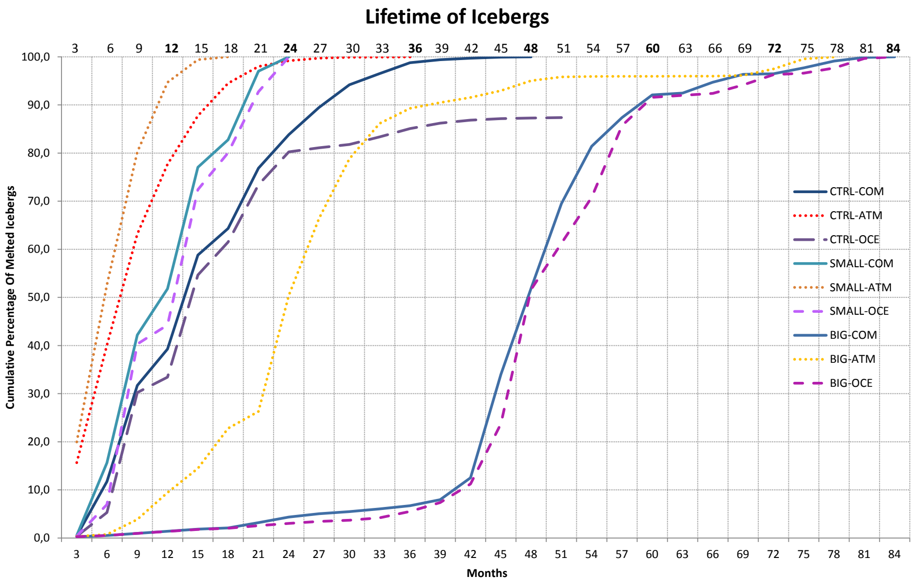

Figure 3. Cumulative percentage of icebergs melted within a certain time; *x* axis corresponds to months, *y* axis to cumulative percentage.

GMDD
7, 4353–4381, 2014

M. Bügelmayer et al.

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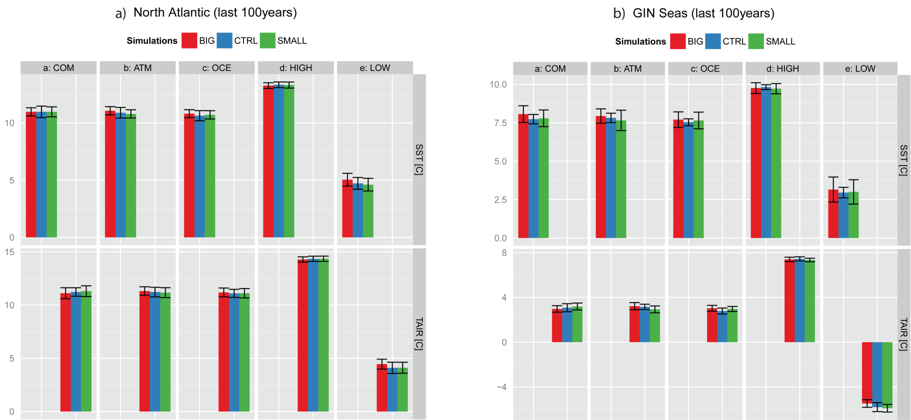

Figure 4. Mean and standard deviation of last 100 years of the performed experiments: sea surface temperature (SST, °C) and air temperature (TAIR, °C); red = BIG bergs, blue = CTRL, green = SMALL bergs; **(a)** North Atlantic: mean computed over: 45–60° N and 60–20° W; **(b)** Greenland–Iceland–Norwegian (GIN) Seas: 50–85° N and 45° W–15° E.

GMDD
7, 4353–4381, 2014
Representing icebergs in iLOVECLIM
M. Bügelmayer et al.

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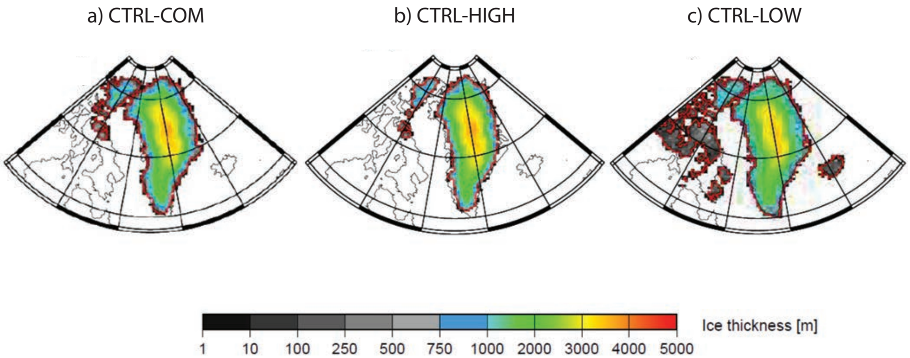

Figure 5. Ice sheet thickness at the end of the experiments (m); **(a)** CTRL-COM; **(b)** CTRL-HIGH; **(c)** CTRL-LOW.

GMDD
7, 4353–4381, 2014

Representing icebergs in iLOVECLIM

M. Bügelmayer et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀I ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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