Geosci. Model Dev., 8, 2139–2151, 2015
www.geosci-model-dev.net/8/2139/2015/
doi:10.5194/gmd-8-2139-2015

Geoscientific Model Development
Open Access

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

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Received: 25 June 2014 – Published in Geosci. Model Dev. Discuss.: 10 July 2014
Revised: 11 June 2015 – Accepted: 2 July 2015 – Published: 17 July 2015

Abstract. Recent modelling studies have indicated that icebergs play an active role in the climate system as they interact with the ocean and the atmosphere. The icebergs' impact is due to their slowly released meltwater, which freshens and cools the ocean and consequently alters the ocean stratification and the sea-ice conditions. The spatial distribution of the icebergs and their meltwater depends on the atmospheric and oceanic forces acting on them as well as on the initial 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 study the sensitivity of the modelled iceberg distribution to initial and boundary conditions, we performed 15 sensitivity experiments using the *i*LOVECLIM climate model that includes actively coupled ice sheet and iceberg modules, to analyse (1) the impact of the atmospheric and oceanic forces on the iceberg transport, mass and melt flux distribution, and (2) the effect of the initial iceberg size on the resulting Northern Hemisphere climate including the Greenland ice sheet, due to feedback mechanisms such as altered atmospheric temperatures, under different climate conditions (pre-industrial, high/low radiative forcing). Our results show that, under equilibrated pre-industrial conditions, the oceanic currents cause the icebergs to stay close to the Greenland and North American coast, whereas the atmospheric forcing quickly distributes them further away from their calving site. Icebergs remaining close to Greenland last up to 2 years longer as they reside in generally cooler 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 and continuous supply of icebergs. Furthermore, our results suggest that the applied radiative forcing scenarios have a stronger impact on climate than the initial size distribution of the icebergs.

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, 2011; Tournadre et al., 2012). Most importantly, icebergs play an important part in the global freshwater cycle since currently up to half of the mass loss of the Antarctic (Rignot et al., 2013) and Greenland ice sheets is due to calving (approx. 0.01 Sv, $1\,\mathrm{Sv} = 10^6\,\mathrm{m^3\,s^{-1}}$, Hooke, 2005). As icebergs are melting, they affect the upper ocean by freshening and cooling due to their uptake of latent heat. Several studies have revealed that freshening and cooling have opposing effects on ocean stratification, as cooling enhances the surface density, promoting deep mixing, whereas freshening decreases the water density, 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., 2015), which forms a bar-

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rier between the ocean and the atmosphere. 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. Furthermore, this reduced oceanic heat loss leads, in combination with an increase in surface albedo, to a changed atmospheric state (Bügelmayer et al., 2015). Thus, icebergs indirectly alter the ice sheet's mass balance through their effect on air temperature and precipitation (Bügelmayer et al., 2015).

The number of icebergs calved and their effects 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 massive episodic 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 have been proposed to be caused by ice shelf collapses (e.g. MacAyeal, 1993; Hulbe et al., 2004; Álvarez-Solas et al., 2011) and happened during periods of a (partial) collapse of the thermohaline circulation (Broecker et al., 1993; McManus et al., 2004; Gherardi et al., 2005; Kageyama et al., 2010). It has been suggested that the collapse was caused by the long duration (Marcott et al., 2011) and the increased amount of freshwater released (0.04 up to 0.4 Sv, Roberts et al., 2014) and coincided with globally altered climate conditions (Hemming, 2004).

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 forced with present-day atmospheric and oceanic input fields from uncoupled model simulations. The forcing was provided offline 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 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 seeded based on a prescribed constant calving flux from observational estimates, but moved according to the modelled winds and currents and interacted with the model atmosphere and ocean. Martin and Adcroft (2010) then implemented the iceberg model into a coupled global climate model (CGCM) using the model's variable runoff as a calving flux though still lacking an ice sheet component. Most recently, Bügelmayer et al. (2015) took the next step by using an EMIC with both dynamically coupled ice sheet and iceberg model components. In their model set-up, 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., 2015) and past times (Levine and Bigg, 2008; Wiersma and Jongma, 2010; Green et al., 2011; Jongma et al., 2013; Roberts et al., 2014) using both prescribed and interactively modelled forcing fields, and have shown that icebergs and their meltwater have an impact on climate. The spatial distribution of the icebergs' freshwater flux is according to the atmospheric and oceanic forces acting on the icebergs as they determine the icebergs' movement.

Computing iceberg melting and tracks is linked to various types of uncertainties. First, the iceberg's drift and melting, as computed in the iceberg module, are based on empirical parameters and simplifications (e.g. Jongma et al., 2009) that would need further observations to be improved. Second, uncertainties in the reconstructed and modelled wind fields and ocean currents, used to force the icebergs, directly affect the distribution of the freshwater. Third, the initial size distribution of the icebergs is prescribed and based on present-day observations (Dowdeswell et al., 1992). Yet, this chosen 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. (2015), evaluating in detail the impact of the modelled 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 are the pre-industrial Northern Hemisphere climate and the 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. Are the Northern Hemisphere climate and the Greenland ice sheet response to icebergs of different initial size distribution dependent on the prevailing climate conditions (pre-industrial (PI), warmer than PI and colder than PI)?

Table 1. Performed experiments.

	PRE-INDUSTRIAL (ATM & OCE FORCING) = 280 ppm	ONLY ATMOSPHERIC FORCING	ONLY OCEANIC FORCING	$4xCO_2$ (ATM & OCE FORCING) = 1120 ppm	$1/4xCO_2$ (ATM & OCE FORCING) = 70 ppm
ALL SIZES	CTRL-COM	CTRL-ATM	CTRL-OCE	CTRL-HIGH	CTRL-LOW
BIG ICEBERGS	BIG-COM	BIG-ATM	BIG-OCE	BIG-HIGH	BIG-LOW
SMALL ICEBERGS	SMALL-COM	SMALL-ATM	SMALL-OCE	SMALL-HIGH	SMALL-LOW

We will address these questions by presenting results from 15 different sensitivity experiments (Table 1) that differ in the applied forcing (atmospheric, oceanic, 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 setup, 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 (Roche et al., 2014) and the further developed iceberg module (Bügelmayer et al., 2015), but shares some physical climate components (atmosphere, ocean and vegetation) with LOVECLIM.

2.1 Atmosphere–ocean–vegetation model

The *i*LOVECLIM climate model consists of the ECBilt atmospheric model (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 4 h. 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 three-dimensional ocean general circulation model (Deleersnijder and Campin, 1995; Deleersnijder et al., 1997; Campin and Goosse, 1999) including 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 $3° \times 3°$ in longitude and latitude and the ocean is vertically divided into 20 unevenly spaced layers. CLIO uses 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 VECODE vegetation model (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 grass) as well as bare soil in response to the temperature and precipitation coming from ECBilt.

The Antarctic ice sheet is prescribed according to present-day conditions following the ETOPO1 topography (http://www.ngdc.noaa.gov/mgg/global/global.html). Icebergs are parameterized in the form of homogenous uptake of latent heat around Antarctica, thereby cooling the ocean without altering the salinity. Ice shelf melting is computed according to the prevailing ocean temperatures. The Greenland ice sheet is actively simulated using the GRISLI ice sheet model.

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 40×40 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 exclude 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 where icebergs are generated daily, as described in detail in Sect. 2.3. The runoff of GRISLI is calculated at the end of the year by computing the difference between the ice sheet thickness at the beginning of the model year and the end of the year, and taking into account the mass

Table 2. Used initial iceberg classes.

CLASS	HEIGHT (m)	WIDTH (m)	VOLUME (m^3) 1×10^5	FRACTION of total available volume	EXPERIMENT
1	67	67	5.16	0.15/0.33	CTRL/SMALL
2	133	133	4.07	0.15/0.33	CTRL/SMALL
3	200	200	138	0.2/0.33	CTRL/SMALL
4	267	267	328	0.15	CTRL
5	300	333	574	0.08	CTRL
6	300	400	828	0.07	CTRL
7	300	500	1297	0.05	CTRL
8	300	600	1860	0.05/0.33	CTRL/BIG
9	300	800	3310	0.05/0.33	CTRL/BIG
10	300	1000	5180	0.05/0.33	CTRL/BIG

loss due to calving. The runoff is then given to ECBilt where it is re-computed to fit its time step (4 h) and 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 GRISLI ice sheet model is provided in Roche et al. (2014) and Bügelmayer et al. (2015).

2.3 Iceberg module

As discussed in detail in Bügelmayer et al. (2015), 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. The provided ice mass is re-computed to fit the daily time step of the iceberg module, taking into account the seasonal calving cycle, with the maximum calving occurring from April to June and the minimum occurring in late summer (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) that represent the Greenland present-day distribution (Table 2). It does not take into account huge tabular icebergs such as those calved from Antarctica, but is a valid representation for icebergs calving from the Greenland ice sheet. The thickness and width of the calving front as defined in GRISLI affect the amount of ice mass available to generate icebergs, but not the icebergs' dimensions. Icebergs are moved by the Coriolis force, the air-, water-, and 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' positions. 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 icebergs 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, $4xCO_2 = 1120$ ppm, $1/4xCO_2 = 70$ 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 Greenland ice sheet under pre-industrial conditions that have already been used in the study of Bügelmayer et al. (2015). The initial ice sheet thickness is about 1/3 bigger than the observed one. We consider this bias negligible for the present study because we focus on differences between our sensitivity runs using the same initial state for all experiments. The differences between the individual simulations are therefore independent of the initial conditions and only functions of the different forcing applied. The model runs were conducted for 200 model years (pre-industrial) and 1000 model years ($4xCO_2$, $1/4xCO_2$), respectively. The last 100 years are presented in the results.

2.4.1 Iceberg dynamical forcing

To differentiate between the impact of the ocean and the atmosphere, we separate the individual forcing terms of the

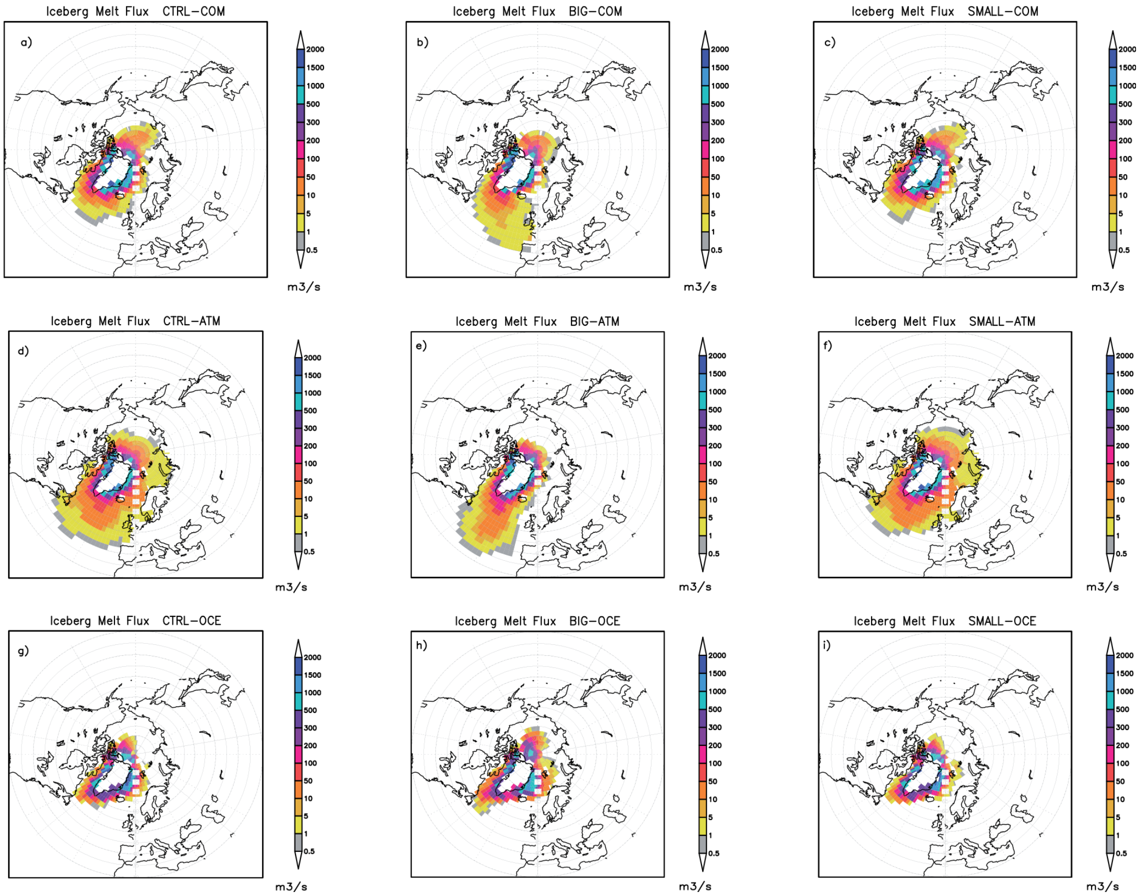

Figure 1. Iceberg melt flux ($m^3\,s^{-1}$); first row: the default set-up (icebergs are moved by both, atmospheric and oceanic forcing; CTRTL-, BIG-, SMALL-COM); second row: atmospheric forcing only (CTRL-, BIG-, SMALL-ATM); third row: oceanic forcing only (CTRL-, BIG-, SMALL-OCE).

equation of horizontal motion (Eq. 1) of an iceberg:

$$M\frac{\mathrm{d}V_i}{\mathrm{d}t} = -M_f k \cdot V_i + F_\mathrm{a} + F_\mathrm{r} + F_\mathrm{w} + F_\mathrm{p} + F_\mathrm{s}, \qquad (1)$$

with M being the mass of the iceberg, V its velocity, the first term ($-M_f k \cdot V_i$) on the right side corresponding to the Coriolis force, and the second and third being the air drag (F_a) and wave radiation force (F_r) and therefore depending 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 "COM" experiments, the icebergs are moved according to Eq. (1), thus by the combined atmospheric and oceanic forcing. In the so-called "ATM" set-up, 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 icebergs.

The differentiation between atmospheric and oceanic forces was only made in the equation of motion of an iceberg. The mass balance (Jongma et al., 2009), which depends on bottom and lateral melt (oceanic forcing) and the wave erosion (atmospheric forcing), is the same in all experiments. All the experiments are described in Table 1.

2.4.2 Iceberg initial size distribution

By altering the initial size distribution of the icebergs we are able to investigate the potential sensitivity of the atmosphere, ocean and ice sheet to iceberg sizes. In the CTRL experiments, depending on the available mass, icebergs of all 10 size classes can be generated (Bügelmayer et al., 2015). In the SMALL (BIG) experiments, the available mass is used to generate an equal amount of the three smallest (biggest) iceberg sizes (Table 2).

2.4.3 Radiative forcing

Using the three size distributions described in Sect. 2.4.2, we performed three sets of experiments. The first set was done under pre-industrial equilibrium conditions for 200 years. In the second one, a "high" experiment, we applied a CO_2

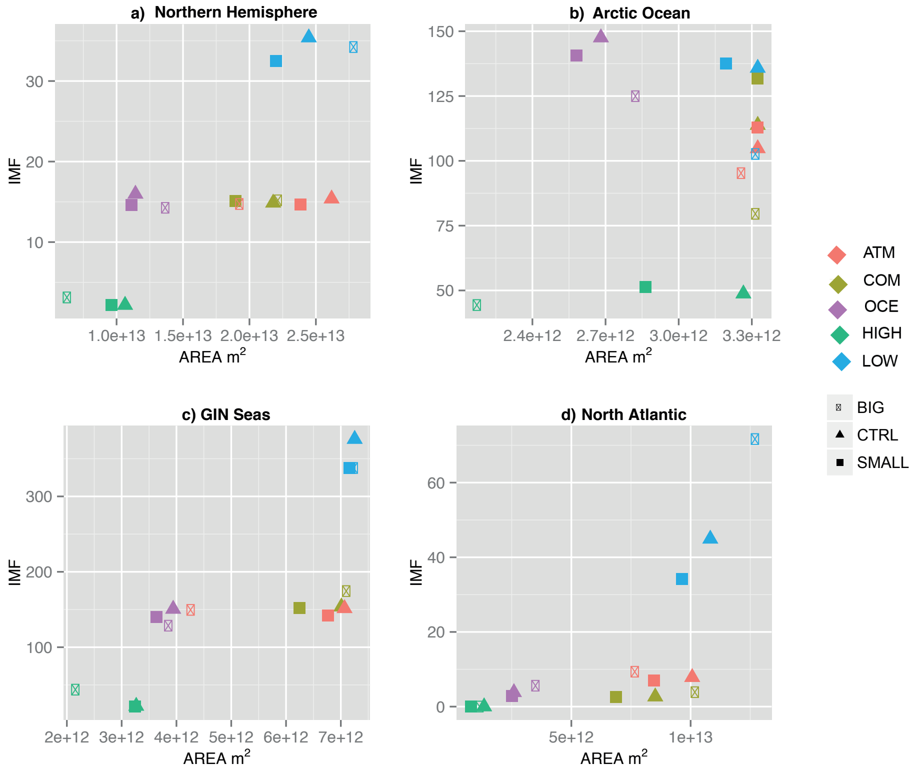

Figure 2. Area (m^2) vs. area weighted iceberg melt flux ($m^3\,s^{-1}$); the area is computed by taking into account all the grid cells that have at least 10 icebergs passing through per year (be aware that the area is $10^{13}\,m^2$ in **a**, $10^{12}\,m^2$ otherwise); **(a)** Northern Hemisphere: mean computed over 0–90° N and 180° W–180° E, values of IMF: 0–40 $m^3\,s^{-1}$ (area weighted IMF); **(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 $m^3\,s^{-1}$.

concentration 4 times as strong as the pre-industrial value (1120 vs. 280 ppm CO_2) and in the third, a "low" experiment, only a quarter of the pre-industrial CO_2 concentration is used (70 vs. 280 ppm CO_2). The "high" and "low" experiments were conducted to analyse the effect of the size (CTRL/SMALL/BIG) distribution during periods of a strongly changing ice sheet under non-equilibrated conditions.

3 Results

3.1 Impact of dynamical forcing and initial iceberg size on the transport and lifetime of icebergs under pre-industrial conditions

3.1.1 The CTRL experiments

The distribution of the CTRL-COM's iceberg melt flux displays the general transport of icebergs of all size classes due to atmospheric and oceanic forces (Fig. 1a). We find that most iceberg melt flux is distributed along the eastern and western coasts of Greenland, displaying that the icebergs' movement follows the oceanic currents. Furthermore, they are moved southward along the North American coast and spread into the North Atlantic. In the Arctic, most icebergs are found close to Ellesmere Island, as indicated by the freshwater flux, due to the calving sites in this region (not shown) and are then widely distributed by the Beaufort Gyre and the prevailing winds.

By applying only atmospheric forcing, we find that CTRL-ATM icebergs distribute their meltwater further into the North Atlantic and Arctic Ocean (Fig. 1d) than seen in CTRL-COM. After calving, they are quickly pushed away from the Greenland ice sheet margin. In CTRL-ATM fewer icebergs than in CTRL-COM melt along the coast of Greenland, highlighting the lack of ocean currents. Overall, the amount of iceberg melt flux released in CTRL-ATM (Northern Hemisphere: 30 $m^3\,s^{-1}$; please note that this is an area weighted mean) is of the same magnitude, but distributed over a broader area than in CTRL-COM (Fig. 2a). Yet, the lifetime of CTRL-ATM icebergs, that is the time (in months) it takes to completely melt the icebergs, is up to 1 year shorter than in CTRL-COM (Fig. 3) because they are transported faster away from the ice sheet and into warmer waters of the North Atlantic.

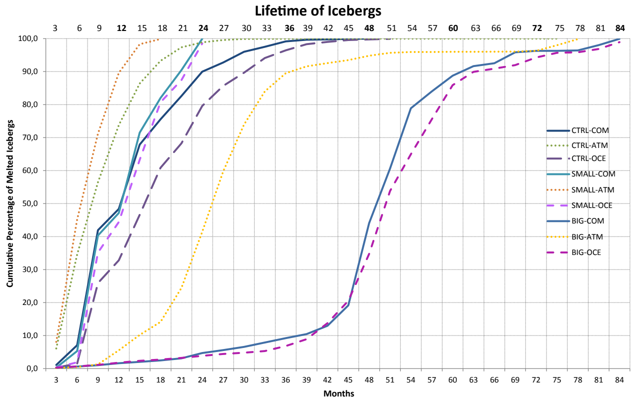

Figure 3. Cumulative iceberg melt distribution normalized to 100 % as a function of time (months); x axis corresponds to months, y axis to cumulative percentage.

The effect of the oceanic forcing is in strong contrast to the atmospheric one as it causes the CTRL-OCE icebergs to stay closer to the GrIS margin (Fig. 1g). The icebergs melt flux reflects the prevailing ocean currents, mainly the Beaufort Gyre, and the East Greenland and the Labrador currents. Far fewer icebergs are moved from the ice sheet into the Greenland–Iceland–Norwegian (GIN) seas and the North Atlantic in CTRL-OCE compared to CTRL-COM (Fig. 1a, g) due to the lack of wind forcing, which is also reflected in the area that they cover (Fig. 2c, d). Also in the Arctic Ocean, the CTRL-OCE icebergs do not spread as much, but a slightly larger iceberg melt flux (IMF) is released because the icebergs are not transported southwards by the wind, but stay and melt there. Overall, the amount of freshwater flux is comparable to the CTRL-COM experiment, though over a much smaller area (CTRL-COM: $2.4 \times 10^{13}\,\mathrm{m}^2$, CTRL-OCE: $1.2 \times 10^{13}\,\mathrm{m}^2$, Fig. 2a) and over a longer time period. The CTRL-OCE icebergs melt up to 4 months slower than CTRL-COM icebergs because they stay close to the GrIS margin and thus in colder water (Fig. 3).

3.1.2 The BIG experiments

The spatial distribution of the BIG-COM icebergs displays first, the effect of the Coriolis force since there is an eastward movement in the North Atlantic (Fig. 1b). The Coriolis force depends on the size and velocity of the icebergs and thus is acting more strongly on big icebergs than on small ones. Second, the area covered by BIG-COM icebergs is larger in the North Atlantic than in CTRL-COM (Fig. 2d). Over the Northern Hemisphere the area covered by more than 10 BIG-COM icebergs is only slightly bigger than the one of CTRL-COM (Fig. 2a), even though their lifetime is up to 3 years longer (Fig. 3). But in total there are fewer BIG icebergs generated than in the CTRL experiment because more mass is needed per berg (Table 2).

Applying only wind forcing to the BIG icebergs (BIG-ATM) transports fewer icebergs into the North Atlantic and especially the GIN seas (Fig. 1e), where they cover about half the area of BIG-COM ($4 \times 10^{12}\,\mathrm{m}^2$ compared to $7 \times 10^{12}\,\mathrm{m}^2$), but release the same amount of freshwater ($150\,\mathrm{m}^3\,\mathrm{s}^{-1}$, Fig. 2c). The strong southward component of the wind keeps the icebergs from drifting further into the GIN seas. Similar to the CTRL experiment, the BIG-ATM icebergs melt up to 2 years faster than the ones of BIG-COM or BIG-OCE (Fig. 3).

The impact of oceanic forcing on the iceberg melt flux is simulated in BIG-OCE. Since the big icebergs melt slowly, they are transported further south than CTRL-OCE icebergs (Fig. 1h). In the GIN seas the BIG-OCE icebergs are spread from the coast and cover almost the same area as the BIG-ATM (Fig. 2c). In the Arctic Ocean the BIG-OCE icebergs release a higher averaged melt flux than BIG-COM and BIG-ATM ($125\,\mathrm{m}^3\,\mathrm{s}^{-1}$ compared to 75 and $95\,\mathrm{m}^3\,\mathrm{s}^{-1}$, respectively; Fig. 2b), but over a smaller area. This is because of the missing wind forcing which prevents the icebergs from being distributed out of the Arctic Ocean. Instead the icebergs are stuck close to their calving sites. The higher IMF in BIG-OCE does not strongly impact the Arctic climate because of the prevailing cold conditions. Thus, more IMF, which is released to the ocean surface layer at 0 °C and consequently cools and freshens it, does not cause noticeable changes. The area covered by BIG icebergs over the Northern Hemisphere is clearly bigger than SMALL-, or CTRL-OCE (Fig. 2a) because of their lifetime, which is about 2 years longer compared to CTRL-OCE (Fig. 3).

3.1.3 The SMALL experiments

Generating only SMALL-COM icebergs results in a similar iceberg melt flux distribution as in CTRL-COM (Fig. 1c), but less widespread. The amount of freshwater that is released by SMALL-COM icebergs is almost the same over the Northern Hemisphere as CTRL-COM, but over a smaller area (Fig. 2a) because all the SMALL-COM icebergs are melted within 2 years, compared to 3 years in CTRL-COM (Fig. 3).

In the icebergs' distribution of the SMALL-ATM model runs (Fig. 1f), it is clearly visible that the light, small icebergs are easily pushed away from their calving sites by the atmospheric forcing, but as in the COM experiments, over a smaller area because they melt faster. In the North Atlantic, the general pattern is directed westward, in contrast to BIG-ATM icebergs that are strongly influenced by the Coriolis force.

The widespread meltwater distribution of SMALL-ATM is in strong contrast to the one of SMALL-OCE (Fig. 1i). The oceanic forcing restricts the icebergs' transport to the shore and due to their smaller size SMALL-OCE icebergs melt before being distributed as far as CTRL-OCE and especially BIG-OCE (Fig. 2a).

In short, the impact of the forcing fields is clearly seen in the icebergs' meltwater distribution and especially lifetime since 90 % of all the atmospheric forced icebergs (SMALL-, BIG-, and CTRL-ATM) melt up to 2 years faster compared to the oceanic forced icebergs and compared to the icebergs of the SMALL-, BIG-, and CTRL-COM set-up.

3.2 Impact of dynamical forcing and initial iceberg size on pre-industrial climate

The resulting sea surface and air temperatures (SST, TAIR) are comparable between the CTRL-COM, -ATM, and -OCE experiments (Fig. 4a, b), despite the different spatial distribution of the iceberg melt flux. The biggest spread in IMF is found in the Arctic Ocean (BIG-COM: 75 $m^3 s^{-1}$, CTRL-OCE: 150 $m^3 s^{-1}$, Fig. 2c), but these differences do not result in an altered climate state due to the prevailing cold conditions that are less sensitive to the freshening and cooling effect of icebergs (not shown). Also in the GIN seas and North Atlantic, the difference in SST and TAIR between the experiments does not significantly differ from internal variability (Fig. 4). In all the pre-industrial experiments, we find that the differences in air and ocean temperature between the CTRL and the BIG, SMALL experiments do not significantly exceed the internal variability of the CTRL experiment. This is also the case for sensitive areas such as the GIN Seas or the North Atlantic, due to the located convection sites there. Therefore, the impact of the dynamical forcing and initial iceberg size is smaller than natural climate variability, which is also reflected in the deep ocean circulation (not shown). This indicates that since the amount of freshwater released is comparable in the model runs, the exact location of the release does not have a strong impact on the prevailing climate conditions or the ocean circulation. Furthermore, the shorter lifetime of the atmospheric driven icebergs does not cause differences in the resulting climate and the 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 flux cause only local differences in the Greenland ice sheet volume (Table 3) that are within the internal variability of the ice sheet.

3.3 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 of experiments with enhanced or reduced radiative forcing to obtain warmer and colder climate states. This change in radiative forcing was applied through adjustment of the atmospheric CO_2 concentration in two experiments, the so-called HIGH = $4xCO_2$ (1120 ppm) and LOW = $1/4xCO_2$ (70 ppm), with a duration of 1000 years. For each of these settings, we performed experiments with CTRL, BIG and SMALL icebergs. 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 4 °C and an increase of the Greenland ice sheet volume of up to 4 %, compared to the pre-industrial ice sheet volume (Table 3).

Table 3. Ice sheet volume (m^3): mean and standard deviation of the last 100 years; the * corresponds to the CTRL SD that was computed over the last 200 years to have a more representative range of internal variability as a reference; difference between the ice sheet volume of the CTRL experiment and the BIG/SMALL experiments in absolute numbers, if the value is above 2 · SD of the CTRL experiments (*), then the difference is significantly different from internal variability (none of the experiments); % diff = difference between the ice sheet volume of the CTRL experiment and the BIG/SMALL experiments in percent.

ICE SHEET THICKNESS	Mean (1×10^{15})	SD (1×10^{12})	Difference (1×10^{12})	Difference in %
CTRL-COM	3.90	4.04*	–	–
BIG-COM	3.91	2.61	−3.50	−0.09
SMALL-COM	3.91	1.96	−2.97	−0.08
CTRL-ATM	3.91	2.79*	–	–
BIG-ATM	3.91	2.14	−2.58	−0.07
SMALL-ATM	3.91	1.99	−0.430	0.01
CTRL-OCE	3.91	3.18*	–	–
BIG-OCE	3.91	1.29	−1.20	−0.03
SMALL-OCE	3.91	2.20	−5.63	−0.14
CTRL-HIGH	3.50	5.03	–	–
BIG-HIGH	3.49	4.40	11.0	0.32
SMALL-HIGH	3.49	5.69	4.82	0.14
CTRL-LOW	4.04	1.90	–	–
BIG-LOW	4.06	2.74	−16.6	−0.41
SMALL-LOW	4.04	3.20	−1.85	−0.05

3.3.1 Experiments with high radiative forcing

The impact of the enhanced radiative forcing on the Greenland ice sheet is displayed in Fig. 5, where the resulting CTRL-HIGH ice sheet extensions and thickness are shown (Fig. 5b).

As the ice sheet is shrinking and retreating from the coast (Fig. 5b), the calving flux from the GrIS is decaying (0.003 Sv vs. 0.02 Sv in the CTRL-COM), which is reflected in the IMF and the area that they cover (Fig. 2). The strong retreat of the ice sheet in southern Greenland has a direct impact on the iceberg melt flux. The released iceberg melt flux in the GIN seas is in the range of 20 (SMALL-, CTRL-HIGH) to 50 $m^3 s^{-1}$ (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 the Arctic Ocean

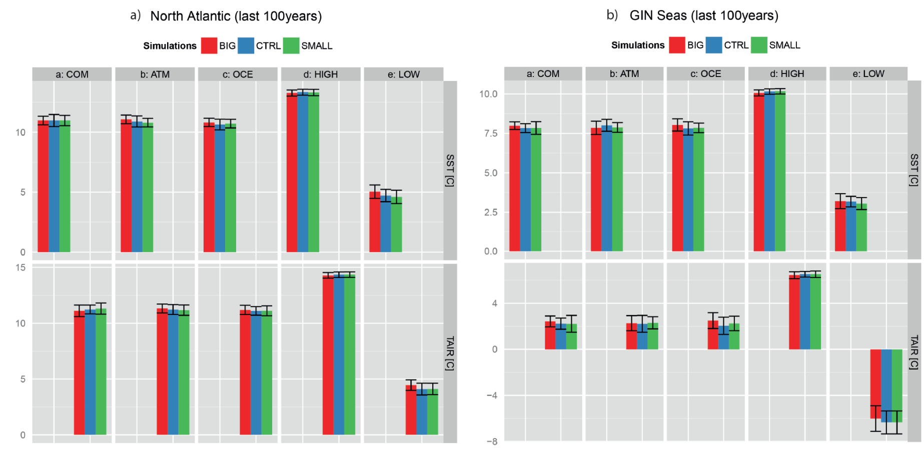

Figure 4. Mean + standard deviation of the last 100 years of the performed experiments: sea surface temperature (SST, °C) and air temperature (TAIR, °C); red = BIG icebergs, blue = CTRL, green = SMALL icebergs; **(a)** North Atlantic: mean computed over: 45–60° N and 60–20° W; **(b)** Greenland–Iceland–Norwegian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

the HIGH experiments result in a bigger spread between the CTRL, BIG and SMALL runs than any other performed set-up (Fig. 2b). The BIG-HIGH icebergs cover the smallest area because of the decreased calving flux far fewer BIG ones are generated. Furthermore, there are still SMALL icebergs, but due to their size and the warmer conditions they melt faster than seen in the SMALL experiments performed under pre-industrial conditions. The CTRL-HIGH experiment covers a slightly smaller area than the CTRL-COM,-OCE or -ATM, but much bigger than BIG-, and SMALL-HIGH (Fig. 2b). This is because the different iceberg sizes allow for the production of a higher number of icebergs than in BIG and the existence of icebergs bigger than size 3 (as in SMALL) allows for a longer lifetime.

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, b), nor does the GrIS (Table 3). 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.

3.3.2 Experiments with low radiative forcing

In contrast to the experiments with high radiative forcing, the low radiative forcing causes up to 4 °C lower global mean temperatures and consequently the ice sheet's volume is thickening and extending further down to the coastline (Fig. 5c), especially along the western margin and in southern Greenland. Similar to the other experiments performed, the impact of different initial size distributions of the icebergs is negligible on the resulting climate and ice sheet volume (Table 3).

Due to the increased ice sheet thickness, more calving flux is released (0.05 Sv in CTRL-LOW compared to 0.02 Sv in CTRL-COM) and so the iceberg melt flux increases to $\sim 40\,m^3\,s^{-1}$ over the Northern Hemisphere, compared to $15\,m^3\,s^{-1}$ in the pre-industrial experiments. The increase is seen almost everywhere around Greenland (Fig. 2), except in the Arctic Ocean. In the Arctic Ocean the released IMF is in the same range as in the experiments performed under pre-industrial conditions because the ice sheet's thickness and consequently the calving sites in North Greenland are not strongly altered by the colder climate (Fig. 5c). In the North Atlantic the released iceberg melt flux displays a big spread between the experiments with the BIG-LOW icebergs being spread the furthest and releasing the most IMF ($80\,m^3\,s^{-1}$ in BIG-LOW vs. $45\,m^3\,s^{-1}$ in CTRL-LOW; Fig. 2d). Since the cold conditions prevent the BIG-LOW icebergs from melting quickly, almost all of them are transported into the North Atlantic where they finally melt. This is also partly the case for the CTRL-LOW icebergs, thereby resulting in a higher iceberg melt flux than the SMALL-LOW (Fig. 2d). 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.

During a strongly changing climate, the initial size distribution does not alter the climate response (temperatures, ocean circulation) more strongly than internal variability. The BIG-LOW set-up causes a slightly larger mean ice sheet volume at the end of the 1000 years (Table 3), which indicates that the extreme case of BIG icebergs impacts the resulting ice sheet thickness, even though the climate conditions are similar to the CTRL- and SMALL-LOW runs.

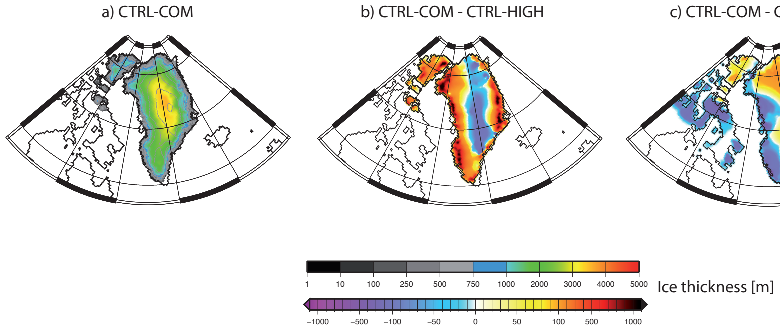

Figure 5. (a) CTRL-COM ice sheet thickness at the end of the experiments (m); **(b)** difference in ice sheet thickness at the end of the model runs CTRL-COM minus CTRL-HIGH; **(c)** difference in ice sheet thickness at the end of the model runs CTRL-COM minus CTRL-LOW.

4 Discussion

By testing the impact of the atmospheric versus the oceanic forcing on the lifetime and motion of icebergs, we find that the atmospheric forcing causes the icebergs 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 widespread 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 by up to 2 years when they are transported by atmospheric forces only. Bigg et al. (1997) showed that about 80 % of the small icebergs of up to 200 m diameter (size class 1 to 3, Table 2) melt within the first year, which is higher than in our SMALL-COM setup where about 60 % are melted. Also Venkatesh and El-Tahan (1988) conducted a study to investigate the impact of modelling complete deterioration of icebergs on the prediction of their tracks. In their study they showed that most of the icebergs corresponding to size classes 1 to 3 used in this study, disappear within 3 to 22 months, consistent with our results. The maximum lifetime of the BIG icebergs is found to be almost 7 years, which is slightly 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. First, using pre-industrial conditions we find that independent of the forcing, SMALL icebergs release less freshwater and spread over a smaller area than BIG and CTRL icebergs. In the North Atlantic the impact of the Coriolis force is especially pronounced in the BIG-ATM and BIG-COM runs, 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 icebergs, the overall effect on climate and on the Greenland ice sheet is within the natural climate variability.

Second, we repeated the experiments under a strongly increased and decreased radiative forcing for 1000 years. During this time, scale changes in the Southern Ocean can impact the Northern Hemisphere. Jongma et al. (2009) showed that including active icebergs increases the net production of Antarctic Bottom Water by 10 % under pre-industrial conditions. We do neglect this direct effect of icebergs here since icebergs and Antarctic ice sheet runoff are computed using parameterizations that depend on the prevailing climate conditions. Concerning the icebergs released from Greenland, we do not expect that the size of the icebergs will have an impact on the Southern Hemisphere through altered ocean circulation because the Atlantic Meridional Overturning Circulation is comparable within all the experiments (not shown). Thus, the uncertainty introduced by not actively coupling the Antarctic ice sheet is comparable in all the radiative forcing experiments.

There might be different reasons why the climate conditions and the GrIS are not strongly affected by the initial size distribution during strong radiative background conditions. 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 icebergs close to Greenland and southward along the North American coast. The combined effect of the forces (control set-up) displays a lesser spread iceberg distribution in the Arctic Ocean and into the North Atlantic than the purely atmospheric driven icebergs due to the restrictive effects of the oceanic forcing. The spread of icebergs depends on both the forcing fields and the iceberg size with the CTRL icebergs being transported the furthest, followed by the BIG icebergs. 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 2 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. However, 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 or 70 ppm CO_2, 1000 model years), the response of the climate and the ice sheet volume do not differ strongly within the experiments.

Even though the iceberg and freshwater distribution differ between the conducted experiments (all size classes, only SMALL, less than 200 m width, and only BIG icebergs, 600–1000 m width, respectively), their impact on the Northern Hemispheric climate does not differ significantly from internal variability. 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 widespread 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 chosen initial size distribution of the icebergs.

Code availability

The iLOVECLIM 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 to copyright restrictions. Access can be granted on 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.

The Supplement related to this article is available online at doi:10.5194/gmd-8-2139-2015-supplement.

Acknowledgements. M. Bügelmayer is supported by NWO through the VIDI/AC2ME project no. 864.09.013. D. M. Roche is supported by NWO through the VIDI/AC2ME project no. 864.09.013 and by CNRS-INSU. The authors wish to thank Catherine Ritz for the use of the GRISLI ice sheet model and all the anonymous reviewers for providing valuable comments. Institut Pierre Simon Laplace is gratefully acknowledged for hosting the *i*LOVECLIM model code under the LUDUS framework project (https://forge.ipsl.jussieu.fr/ludus). This is NWO/AC2ME contribution number 08.

Edited by: R. Marsh

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