Dear Bob Marsh and reviewers,

Thank you for your understanding and time so far!

Unfortunately, we had to re-do all the experiments due to a minor error in the orbital parameters that caused them to vary slightly over the years, instead of being fixed.

Analysing the new experiments, we found that the main results do not differ from the submitted manuscript. Namely, 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 sites, which strongly affects the lifetime of the icebergs. The wind-driven icebergs melt up to two years faster because they are quickly distributed into the warmer North Atlantic waters. Further, we find that local variations in the spatial distribution due to different iceberg sizes do not cause different climate states or Greenland ice sheet volume at the end of the model runs. This result is independent of the prevailing climate conditions (pre-industrial, warming or cooling climate). We thus conclude that local differences in the distribution of the icebergs' 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 used initial size distribution of the icebergs.

The only differences between the submitted and the new manuscript are found in the spread of the BIG-COM and BIG-ATM experiments that is now comparable to the distribution of the CTRL-COM / CTRL-ATM and SMALL-COM / SMALL-ATM runs. This change is due to a higher available calving flux in the new simulations, thus, there are more BIG bergs produced than in the previous runs.

We are sorry for any inconvenience and are looking forward to your comments.

Kind regards

Marianne & Co-Authors.

Geosci. Model Dev. Discuss., 7, C1249–C1250, 2014
www.geosci-model-dev-discuss.net/7/C1249/2014/

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Interactive comment on “Representing icebergs in the iLOVECLIM model (version 1.0) – a sensitivity study” by M. Bügelmayer et al.

Anonymous Referee #1

Received and published: 26 July 2014

This is an interesting paper, exploring the impact of iceberg size on climate in three different climate states, while documenting inclusion of an iceberg model in a well used EMC. Their main conclusion is that whether icebergs are small, large, or a mix of sizes (at least using the standard size classes of current iceberg models) their impact on climate is similar and small. This is true even if net flux varies between states – the large-scale radiative forcing is most important for producing change. This is a conclu- sion that would have been expected a priori, but it is good to have the unimportance of iceberg size verified. The authors explain their procedures, and set forth their experi- ments clearly.

I do have a few specific comments that the authors may wish to comment on:

1. The authors seem not to differentiate between ocean and atmospheric components of the melting parameterisation. One of the big effects – the wave-induced erosion – is purely wind-related, while the other large effects, such as basal melting and buoy- ant convection, are oceanic effects. This will impact on the southward extent of the tracks, possibly as significantly as size. Was this effect included, but not noted? If not, its exclusion needs to be made clear.

It is correct that the melt function has not been changed between the OCE or ATM experiments and that this causes the icebergs to melt faster than when only be melted by either ocean forcing or wind forcing, as correctly stated by the reviewer. But we were specifically interested in the movement of the icebergs, on their drift pattern and how this is dependent on the forcing fields. By changing also the melt function, we would have prolonged their lifetime and thus additionally altered their melt flux distribution.

We have added lines 222-224 to state clearly that only the equation of motion was changed:

The differentiation between atmospheric and oceanic forces was only made in the equation of motion of an iceberg. The melting of icebergs, which depends on bottom- and lateral melt (oceanic forcing) and the wave erosion (atmospheric forcing) was not altered.

2. It is not clear what the experiments do in the Southern Hemisphere. Is it only Greenland that is supplying icebergs, and is the ice sheet model also causing changes in calving fluxes in each hemisphere?

In the current model set-up, the Greenland ice sheet is actively coupled and its freshwater fluxes (calving and runoff) are computed explicitly. The Southern Hemisphere ice sheet however, is fixed. It is thus correct, that changes in the Antarctic's topography due to the applied high/low radiative forcing are not considered. Yet, altered ice shelf melting is taken into account because ice shelf melting is parameterized depending on the ocean's temperature. Also iceberg calving is parameterized as homogenous uptake of latent heat around Antarctica. The amount of heat taken up from the ocean depends on the excess snow that is defined by the accumulation rate. Thus, changes in climate also alter the iceberg parameterization. Having both, the Greenland and the Antarctic ice sheet interactively coupled is a goal that, unfortunately, lies beyond this study.

We have included a short paragraph concerning the Southern Hemisphere into the manuscript (lines 149-153):

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 and ice shelf melting is computed according to the prevailing ocean conditions. The Greenland ice sheet is coupled actively and computed using the GRISLI ice-sheet model.

3. By only considering Greenland the restriction of the iceberg sizes to 1 km in length is reasonable, even under glacial conditions. However, the Antarctic has a proportion of icebergs at > 10 km size. These provide a significant freshwater flux to the Southern Ocean, but previous models have capped SH icebergs at the same 1 km size as used here. It would have been interesting to see if a predominantly giant iceberg flux from Antarctica led to the same lack of impact, although as the paper focuses on the North- ern Hemisphere this paper only requires comment on this issue, rather than additional work.

Please see comment about Southern Hemisphere above.

Technical points p. 4354, l. 26 ". . . conditions and constant . . ."

We have changed "und" to "and".

p. 4356, l. 10-15: the authors should acknowledge, in the otherwise good description of the development of iceberg models, the extension of the Bigg et al. model to include coupling to an inter- mediate complexity model by Levine and Bigg (2008). It was the first published coupled iceberg model considering climate conditions in both the present and a low carbon diox- ide climate. Levine, R. C., and G. R. Bigg, 2008, The sensitivity of the glacial ocean to Heinrich events from different sources, as modeled by a coupled atmosphere-iceberg- ocean model, Paleoceanogr., 23: PA4213, doi:10.1029/2008PA001613.

Thank you for this citation, we have included it.

Interactive comment on Geosci. Model Dev. Discuss., 7, 4353, 2014.

Interactive comment on “Representing icebergs in the *i*LOVECLIM model (version 1.0) – a sensitivity study” *by* M. Bügelmayer et al.

Anonymous Referee #2

Received and published: 26 August 2014

In “Representing icebergs in the iLOVECLIM model (version 1.0) – a sensitivity study” Bügelmayer, Roche and Renssen discuss results from simulations with a recently ex- tended earth system model of intermediate complexity (EMIC) that now also includes interactive ice sheets as well as icebergs. The new model is also presented in Roche at al. (2013) and Bügelmayer et al. (2014) of which the former paper has been accepted while the latter is still under review/discussion.

The present manuscript focuses on the sensitivity of the EMIC to the iceberg component. However, considering the two publications above and that the iceberg component has been applied to various sorts of model environments before (see references in Section 2.3) the work presented here lacks novelty.

Besides this issue I am also not comfortable with the experimental set up. The authors study the influence of atmospheric and oceanic forcing on the ice- berg momentum balance by comparing the large-scale spatial distribution of icebergs between simulations in which the one or the other forcing is artificially neglected. How- ever, the spatial resolution of the model grid used (atmosphere: 5.6 deg and vertical 3 layers; ocean: 3 deg and 20 layers) is hardly sufficient to resolve local characteris- tics of winds and currents around Greenland and to draw conclusions that would be applicable beyond this particular model. The model set up further lacks Antarctic ice sheet and icebergs that, however, may well influence the Atlantic Meridional Overturn- ing Circulation and hence imprint on the climate in the northern North Atlantic, which is studied here, in multi-centennial to millennial integrations. Finally, the null-hypothesis that the iceberg size distribution might have a greater influence on the climate over Greenland than strong (70 vs 1120 ppm CO2) changes in radiative forcing is provoca- tive at best. Considering the model has been presented already in earlier publications and the weakness in scientific merit of the sensitivity simulations presented here, I cannot recommend publication of the manuscript.

Nevertheless, I do think that iLOVECLIM is a valid model and one can make valuable contributions to the current scientific discussion with it. Including interactive ice sheets as well as icebergs in AOGCM is an important step forward. I thus would like to en- courage the authors to rethink their experimental set up and research questions posed. Hoping that the authors submit a revised version later I add some detailed comments below.

We would like to thank reviewer #2 for carefully evaluating our manuscript and for providing valuable suggestions for improvement.

Before answering the comments point by point, we would like to address the two main concerns of the reviewer regarding the lack of novelty and the experimental set-up of the presented study.

Concerning the novelty of this study, we would like to emphasize that the paper of Roche et al. (2014) describes the coupling of the ice-sheet model to the atmosphere – ocean – vegetation model, without the iceberg module included. In their study, the coupling methods, e.g. downscaling procedures, are described as well as the effect of the coupling on the different model components such as the ice sheet, the oceanic or atmospheric model component. The coupling of the iceberg module to the ice-sheet – atmosphere – ocean – vegetation model is presented in the paper of Bügelmayer et al. (2014) where the skill of the coupled model to represent observations is tested as well as the validity of parameterizing icebergs by using freshwater fluxes. In Bügelmayer et al. (2014) we thus presented the model developments and performance. In the latter study, we found an indirect effect of the icebergs on the Greenland ice sheet’s development. The next step is *to perform sensitivity studies to further test this behavior, which was done in the present study. The iceberg module has been used in previous studies, as correctly stated by the reviewer. Yet, the iLOVECLIM set-up is the only one, that we are aware of, where it is included in an ice-sheet – atmosphere – ocean – vegetation model. The novelty of this study is therefore that for the first time such a coupled model is used to evaluate the impact of icebergs and their sizes on the Greenland ice sheet itself, and also the effect of different forcings (wind and ocean currents) on the iceberg distribution and melt.*

Therefore, we have designed two different types of experiments. First, our aim was to better understand the different effects of the atmosphere and the ocean on the movement of the icebergs. Of course, this is a hypothetical approach as there will always be a combination of winds and ocean currents acting on the icebergs. Nevertheless, we think it is of interest to investigate how the general pattern of iceberg melt flux depends on the wind or ocean current forcing and how this pattern influences its own forcing fields. We explicitly state that we do not aim on reproducing single iceberg tracks because of the coarse resolution, but the model allows us to investigate the interactions between all the different model components over a longer timeframe, which is what we are interested in. Second, we want to use the model to perform experiments to understand climate changes happening in the past and maybe happening again in the future. As correctly stated by the reviewer, we do not model icebergs explicitly in the southern hemisphere yet. But by testing the impact of the initial iceberg size, and even if this is only done for the Greenland ice sheet, we can quantify the error we might introduce by using the respective iceberg size. All the model output has to be interpreted by keeping in mind the shortcomings of the used model, such as its coarse resolution. Yet, we do think that the results and conclusions drawn here are of general interest and validity because the model captures the main properties of icebergs. Further, the results that can be compared are consistent with previous studies as we discussed in the present manuscript and in Bügelmayer et al. (2014). But as also mentioned by the reviewer, the model has a coarse resolution and it would be of great interest to us if the experiments were repeated using a higher resolved model, such as the one currently presented by Marsh et al. (2014) in GMDD.

Further, we submitted the presented study to the GMD manuscript type **"Technical, Development and Evaluation papers"** *and in this type of manuscript it is explicitly stated that* **"in-depth evaluations of already published models"** *are welcomed.*

http://www.geoscientific-model-development.net/submission/manuscript_types.html

Detailed comments: page/line(s)

4354/3 these examples of icebergs effects are not self-explanatory. Please think of a generally more agreeable opening.

As suggested by the reviewer, we changed to opening to (Lines 12-13):

Recent modelling studies have indicated that icebergs play an active role in the climate system as they interact with the ocean and the atmosphere.

4354/6 rewrite to ". . . atmospheric and oceanic forces acting . . ."

We have changed Lines 15-16 as suggested by the reviewer.

The spatial distribution of the icebergs and their melt water depends on the atmospheric and oceanic forces acting on them as well as on the icebergs' size.

4354/10 replace "To address these shortcomings, . . ." with "To study the sensitivity of the modeled iceberg distribution to initial and boundary conditions, . . .". Your previous sentence does not necessarily list shortcomings.

Thank you for pointing this out, we have changed the sentence accordingly (Lines 19-21):

To study the sensitivity of the modeled iceberg distribution to initial and boundary conditions, we performed 15 sensitivity experiments using the climate model iLOVECLIM that includes actively coupled ice-sheet and iceberg modules, …

4354/12 rewrite to ". . . atmospheric and oceanic forcing fields . . ."

We have changed Line 21 as suggested by the reviewer.

… 1) the impact of the atmospheric and oceanic forces on the icebergs' distribution and melt flux, …

4354/22 At this point it is unclear how icebergs feedback on the ice sheet they calved from, i.e. why the authors assume that there is a feedback.

To take this valid comment into account, we have changed Lines 23-25 to

… 2) the effect of the used initial iceberg size on the resulting Northern hemisphere climate as well as on the ice sheet, due to feedback mechanisms such as altered atmospheric circulation, under different climate conditions (pre-industrial, high/low radiative forcing).

4355/6 update reference. Rignot et al. 2013 recently showed that in some places ice- ocean melt dominates calving. Rignot, E., S. Jacobs, J. Mouginot, B. Scheuchl, 2013, Ice Shelf Melting Around Antarctica, Science Express, DOI: 10.1126/science.1235798.

Thank you for pointing this out, we have modified the Lines 40-43 accordingly:

Most importantly, icebergs play an important part in the global fresh water 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 Sv = $1*10^6$ m^3/s, Hooke et al., 2005).

4355/8 replace "take up" with "uptake"

We have changed Line 44 as suggested by the reviewer.

/11 remove "thereby"

We have changed Line 46 as suggested by the reviewer.

4365/15ff please rephrase (be careful about the advancements made with each study). I suggest: "In the latter study, the icebergs were seeded based on a prescribed constant calving flux based on observational estimates but moved according to the modeled 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. (2014) took the next step by using an EMIC with both dynamically coupled ice sheet and iceberg model components."

This paragraph has been re-written following the kind suggestion of the reviewer (Lines 77-83):

In the latter study, the icebergs were seeded based on a prescribed constant calving flux based on observational estimates but moved according to the modeled 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. (2014) took the next step by using an EMIC with both dynamically coupled ice sheet and iceberg model components.

4357/4 ". . . on the atmospheric and oceanic forces acting on the icebergs."

We have changed Line 95 as suggested by the reviewer.

4357/5ff Although I generally agree with the assessment of uncertainties in this para- graph I believe that uncertainties inherent to the empirical relationships contained in the iceberg model of Bigg and Gladstone and others, which is used here, are much greater. However, we lack observations, in particular on iceberg decay, to reliably esti- mate these. Nevertheless, I think this should be noted here.

Thank you for pointing this out, we have modified this paragraph to also state the uncertainties related to the iceberg module (Lines 97-104):

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.

4358/5 The methods section lacks detail and relies heavily on Bügelmeyer et al. (2014) instead, which is a paper still under review. I suggest to either add considerable detail to the present paper to make it independent or wait until the former has been accepted.

The paper of Bügelmayer et al. (2014) will likely be accepted before this one, but if this is not the case, we will be happy to add the needed information in the methods section.

/12 I must say that I have considerable trouble with the idea of estimating the uncertainty of iceberg distribution due to the atmospheric forcing using a model with such very coarse resolution of 5.6 deg and only 3 layers.

/24 same holds for the coarse ocean grid.

As correctly stated by the reviewer, our model has a coarse resolution, in both, the atmosphere and ocean model components. This is exactly why we think it is important to perform these sensitivity studies because in the manuscript submitted to TC, we show that we capture the main characteristics of iceberg drift and more importantly, we find that including icebergs has an impact on climate and, through feedback mechanisms, on the ice sheet. So in the current study we want to investigate, if and to what extent the interactions of the icebergs with the ocean-atmosphere-ice-sheet are dependent on the exact location of the iceberg melt flux because we do not expect to model this as accurately as a higher resolution model.

4359/15 When running millennial control simulations one should take the Southern Hemisphere into account. Icebergs in the Southern Ocean affect the stratification and thus bottom water formation, which may impact on the AMOC. AMOC variability forced in the South can emerge in the North Atlantic within a century.

In the current model set-up, the Greenland ice sheet is actively coupled and its freshwater fluxes (calving and runoff) are computed explicitly. The Southern Hemisphere ice sheet however, is fixed. It is thus correct, that changes in the Antarctic's topography due to the applied high/low radiative forcing are not considered. Yet, altered ice shelf melting is taken into account because ice shelf melting is parameterized depending on the ocean's temperature. Iceberg calving is parameterized as homogenous uptake of latent heat around Antarctica whose amount depends on the total accumulation. Jongma et al (2009) investigated the impact of explicitly modelling icebergs in the Southern Hemisphere, without an ice-sheet model coupled, and found that including active icebergs increases the Antarctic Bottom Water (AABW) by up to 10%. It is correct that we *neglect this effect, but since we do not expect that the initial iceberg size has an impact on the Southern Ocean, this effect is comparable in all the radiative forcing experiments and thus does not influence the difference between the experiments. Having both the Greenland and the Antarctic ice sheet interactively coupled in iLOVECLIM is a goal that, unfortunately, lies beyond this study.*

We have included a short paragraph concerning the Southern Hemisphere in the methods (Lines 149-153):

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 and ice shelf melting is computed according to the prevailing ocean conditions. The Greenland ice sheet is coupled actively and computed using the GRISLI ice-sheet model.

and discussion (Lines 398-406) :

Second, we repeated the experiments under a strongly increased and decreased radiative forcing for 1000 years. During this time scale, changes the Southern Ocean can interact with 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. However, we do not expect that the size of the icebergs released from Greenland has an impact on the Southern Hemisphere, thus, the uncertainty introduced by not actively coupling the Antarctic ice sheet is comparable in all the radiative forcing experiments.

/17 This statement is inconsistent with Table 2, where you list iceberg thicknesses of up to 300m. Please check that this is not an inconsistency in the model code.

*The 150m threshold, as stated in Line 17, is applied in GRISLI to provoke calving. As soon as one grid cell is calved, the volume (thickness of ice * grid cell size) is stored as calving mass at the corresponding location. The sum over one GRISLI model year at each calving location is then used in the iceberg module to generate icebergs according to the size distribution based on observations in Greenland (Dowdeswell et al., 1992) where the calved icebergs measure up to 300m. In our method, the thickness of the calving front does not directly determine the icebergs size but the amount of icebergs.*

We have clarified this information in Lines 184-187:

Therefore, the thickness and width of the calving front as defined in GRISLI affects the amount of ice mass available to generate icebergs, but not the icebergs' dimensions.

/19 Why does the ice sheet model exchange fluxes with the iceberg model only once per year?

The coupling time step of one year is chosen on the one hand to fit the ice sheet's response time that is much slower than the one of the atmosphere (4hours) or of the ocean (1 day) and on the other hand to save computation time. But in the climate and the iceberg model, the freshwater fluxes are incorporated according to the respective time step, thus the iceberg model receives a daily amount of ice discharge to generate icebergs.

We have modified lines 167-168:

The runoff is then given to ECBilt where it is re-computed to fit its time-step (4 hours) and incorporated into the land routing system.

As well as lines 162-164:

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 Section 2.3.

And lines 179-182:

The provided ice mass is re-computed to fit the daily time-step of the iceberg module and 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).

4360/8 I think Martin and Adcroft presented two opposing seasonal cycles, one for ice- berg calving and one for iceberg melt. I believe observations rather support enhanced calving in summer (melt water lubricates and lets ice move faster; lack of stabilizing sea ice cover) and fall (refreezing of melt water in cravasses). Add a note about the shape of the seasonal cycle you applied.

As correctly stated by the reviewer, Martin and Adcroft (2010) displayed both the melting rate and calving rates. In the presented study, we followed the calving rate for Greenland, with the maximum occurring in April to June and the minimum in late summer (August, September). This seasonal cycle fits relatively well to observed iceberg numbers on the Grand Banks (Reid, E. J.: NRC Publications Archive (NPArC) Archives des publications du CNRC (NPArC) Iceberg Distribution on the Grand Banks : Past and Present).

We have added some information on the shape of the seasonal cycle, as stated above.

/17 Why don't you put the melt water at the respective depth in the ocean?

We add the melt water to the surface layer because we have to simplify the complex process of upwelling of the iceberg's basal meltwater.

/27 But doesn't an offset in ice sheet thickness potentially bias the feedback to variations in iceberg distribution that you do study? An error of 1/3 seems a lot to me. I think you need to argue why this does not affect your results.

It is correct that the overestimation of the ice sheet has implications for the iceberg distribution because the fact that the ice sheet is too extensive and in combination with the pre-industrial boundary conditions causes higher calving rates than observed. Further, the too extensive central Greenland ice sheet results in a negative temperature bias (Roche et al., 2014). Yet, this does not affect the conclusions we draw here because all the experiments are started from the same ice sheet and climate conditions and thus changes at the end of the model runs are only due to the different forcing or iceberg size distribution. To clarify this point, we have modified lines 202-205:

The fact that the initial ice sheet thickness is about $^1/_3$ bigger than the observed one does not impact our results because all the experiments are started from the same ice sheet and climate conditions and thus changes at the end of the model runs are only due to the different forcing fields or iceberg size distribution.

4361/19 please add at end of paragraph an introduction of experiment COM, e.g.: "In experiments called COM the combined atmosphere and ocean forcing is applied, i.e. all terms of (1) are used."

We have added this information as suggested by the reviewer (lines 216-217):

In the so-called "COM" experiments, the icebergs are moved according to Equation 1, thus by the combined atmospheric and oceanic forcing.

Question: In order to truly assess the impact of atmospheric vs. oceanic forcing wouldn't you need to split the melt functions as well? For instance bottom melt is ocean forcing but erosion due to waves is a function of wind speed, i.e. atmospheric forcing.

It is correct that the melt function has not been changed for the OCE and ATM experiments and that this causes the icebergs to melt faster than when only be melted by either ocean forcing or wind forcing. But we were specifically interested in the movement of the icebergs, on their drift pattern and how this is dependent on the forcing fields. By changing also the melt function, we would have prolonged their lifetime and thus additionally altered their melt flux distribution.

We have added lines 222-224 to state clearly that only the equation of motion was changed:

The differentiation between atmospheric and oceanic forces was only made in the equation of motion of an iceberg. The melting of icebergs, which depends on bottom- and lateral melt (oceanic forcing) and the wave erosion (atmospheric forcing), was not altered.

4362/11 I strongly recommend to re-arrange your results section in the sense that you first discuss the control simulation CTRL-COM and then discuss deviations from these results. With respect to Figure 1, start with panel 1g, then discuss 1a and 1d in section

We have changed the result section as suggested by the reviewer. The revised sections are 3.1, 3.2 and 3.3 in the manuscript (lines 239-394).

3.1.1. Introduce new section 3.1.2 that discusses BIG and SMALL runs, again first BIG-COM and SMALL-COM, then the other cases. Rearrange Figure 1 accordingly. (Section 3.1.2 Lifetime of icebergs would become new section 3.1.3.)

We have changed the result section as suggested by the reviewer, please have a look at the manuscript.

/19 remove "(Fig. 3)" in favor of addressing figures in the correct sequence. I think a reference to Fig. 3 is not necessary here. Lifetime of icebergs is discussed in a later section.

Since the whole results section has been modified, this is no longer an issue.

/20 I am confused. I would expect that BIG icebergs provide a greater area and higher freeboard for the wind stress to act on. Then, why is the "atmospheric forcing not strong enough"? Please explain.

We have repeated the experiments to correct for a minor internal error in the model set-up (the orbital parameters were not fixed to pre-industrial conditions) and have redone all the figures and revised the manuscript accordingly. The corrected results did not change in comparison to the previous manuscript, except that the corrected results of the BIG-ATM experiment display that the icebergs are spread as far as the SMALL-, and CTRL-ATM ones, except in the GIN Seas where they follow the strong southward wind without being distributed. This sentence has thus been removed from the manuscript and changed to (lines 278 - 281):

The BIG-COM icebergs are transported further than the BIG-ATM in all the regions considered and especially in the GIN Seas (Fig. 2c). There, the BIG-ATM bergs follow the strong southward component of the wind without being distributed further into the GIN Seas.

4365/12 suggest to revise section titles to "Experiments with high radiative forcing" . . .

4366/8 . . . and "Experiments with low radiative forcing"

We have changed the titles as suggested by the reviewer.

4367/13 While I think that it is worth exploring the impact of atmospheric vs. oceanic forcing in order to understand the spatial distribution of icebergs, a discussion with respect to climate impacts is purely hypothetically since icebergs are driven by both atmospheric as well as oceanic forces. I recommend to limit the climate sensitivity discussion to the BIG and SMALL scenarios.

To take this good advice into account, we have modified the discussion (lines 407-409):

Bigg et al. (1997) showed that about 80% of the small bergs (size class 1 to 3) melt within the first year, which is higher than in our SMALL-COM set-up where about 60% are melted.

4368/14 This is why I think the experiments could have been chosen more carefully. Maybe you also need to consider Antarctic sized tabular icebergs, i.e. bigger than BIG, for the cold climate.

As we also stated in the discussion, we are aware of the fact that the strong forcing probably overrules feedback coming from the iceberg size. But we have chosen this set-up consciously because we wanted to force a strong change in the ice sheets' topography so that we also have a strongly altered calving flux and thus iceberg number.

We have added Lines 236 - 238 at the end of the methods section:

The latter two sets of experiments were done to analyse the effect of the size (CTRL/SMALL/BIG) distribution during periods of a strongly changing ice-sheet under non – equilibrated conditions.

Concerning the iceberg size, as was also noted by reviewer #1, when only modelling Greenland, the chosen distribution is valid, even for glacial periods.

4374/Tab.1 I don't understand this table. My first impression was that since all cells onlycontain "x" all scenarios are the same. Now I suggest, if I interpret this table correctly, to remove line "Experiment name" and column "Name" and instead write the respective full experiment name in each cell, i.e. BIG-ATM, BIG-OCE, BIG-COM, BIG-HIGH, BIG- LOW for the "Big Bergs" row. In fact, "COM" should be in the first column and CTRL the first row. Please provide more information in the caption.

We improved table 1 as suggested by the reviewer.

	PRE-INDUSTRIAL (ATM & OCE FORCING) **= 280 ppm**	**ONLY ATMOSPHERIC FORCING**	**ONLY OCEANIC FORCING**	**4xCO_2** (ATM & OCE FORCING) **= 1120ppm**	**¼xCO_2** (ATM & OCE FORCING) **= 70ppm**
ALL SIZES	CTRL-COM	CTRL-ATM	CTRL-OCE	CTRL-HIGH	CTRL-LOW
BIG BERGS	BIG -COM	BIG-ATM	BIG -OCE	BIG-HIGH	BIG-LOW
SMALL BERGS	SMALL -COM	SMALL-ATM	SMALL-OCE	SMALL-HIGH	SMALL-LOW

Table 1: performed experiments

4376/Tab.3 add lines every third row (grouping CTRL, BIG, and SMALL); also replace "0.00" by "-" for all CTRL cases, since it is the respective reference.

We improved Table 3 as suggested by the reviewer.

Experiment	**Mean**	**STDEV**	**% diff**
CTRL-COM	3,90E+15	2,53E+12	-
BIG-COM	3,91E+15	2,61E+12	-0,09
SMALL-COM	3,91E+15	1,96E+12	-0,08
CTRL-ATM	3,91E+15	1,90E+12	-
BIG-ATM	3,91E+15	2,14E+12	0,02
SMALL-ATM	3,91E+15	1,99E+12	-0,06
CTRL-OCE	3,91E+15	2,11E+12	-
BIG-OCE	3,91E+15	1,29E+12	-0,03

SMALL-OC	3,91E+15	2,20E+12	-0,14
CTRL-HIGH	3,50E+15	5,03E+12	-
BIG-HIGH	3,49E+15	4,40E+12	0,32
SMALL-HIGH	3,49E+15	5,69E+12	0,14
CTRL-LOW	4,04E+15	1,90E+12	-
BIG-LOW	4,06E+15	2,74E+12	-0,41
SMALL-LOW	4,04E+15	3,20E+12	-0,05

Table 3: Ice-sheet Volume (m3): 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

4378/Fig.2 I find this graph confusing.

We agree with the reviewer that there is a lot of information in this figure since all the experiments and all the size classes are shown. But we do think that it is an important figure to compare the behavior of the different experiments (e.g. do the BIG bergs cluster, etc.). If you have a suggestion on how to improve this figure, we are happy to do so!

4379 & 4380 Switch figures 3 and 4 as this would suite the presentation of results better.

We have changed to result section, so now 3 and 4 suit the way they were.

Regarding Fig. 4 Are the differences between COM, ATM, and OCE significant with respect to the internal (inter-annual) variability? Same for CTRL, BIG, and SMALL.

*To analyze whether or not the differences of the last 100 years between CTRL-COM/ATM/OCE and CTRL-COM/BIG/SMALL are 95% significant, we computed for 1000 years of CTRL-COM its 100yr running mean and its standard deviation to determine the internal variability. In the GIN Seas we see the biggest internal variability (2*sd of 1000 year equilibrium experiment is: SST 0.23°C and TAIR 0.32°C). This already indicates that this region is especially variable and sensitive due to the ocean convection site. Variations in the deep ocean circulation directly affect the sea surface and air temperatures. We therefore also find the biggest differences between the different experiments in the GIN Seas because the spatial distribution of the IMF directly impacts the deep ocean circulation, but none of the experiments are significantly different from the internal variability (Table 1).*

	Sea Surface Temperature			**Air Temperature**		
	40-90°N	**GIN**	**NA**	**40-90°N**	**GIN**	**NA**
	2*sd of 100yr running mean (95%)			**2*sd of 100yr running mean (95%)**		
CTRL-COM (1000 yrs)	0,18	0,23	0,17	0,25	0,32	0,21
	mean 100 yr Difference			**mean 100 yr Difference**		
CTRL-COM – CTRL-ATM	-0,09	-0,18	-0,06	-0,06	-0,18	-0,10
CTRL-COM – CTRL-OCE	0,08	0,02	0,07	0,20	0,19	0,06
CTRL-COM – BIG-COM	-0,10	-0,15	-0,08	-0,13	-0,19	-0,12
CTRL-COM – SMALL-COM	0,03	-0,01	0,05	0,05	0,02	0,06

Table 1: The internal variability of the CTRL-COM experiment was calculated by first, computing the 100yr running mean of 1000 years equilibrated conditions and second, to determine the internal variability, its

standard deviation. The 2*standard deviation is used to analyze whether or not the mean difference of the last 100 years of the performed experiments is significant within the 95% interval; the areas correspond to Figure 2.

Representing Icebergs in the ~~-~~iLOVECLIM ~~-~~Model (version 1.0)– A Sensitivity Study

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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~~.~~ as they interact with the ocean and the atmosphere. The icebergs' impact is due to their slowly released melt water, which freshens and cools the ocean~~.~~ and consequently alters the ocean stratification and the sea ice conditions. The spatial distribution of the icebergs and ~~thus~~ their melt water depends on the ~~forces (~~atmospheric and oceanic~~)~~ forces 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~~study the sensitivity of the modelled iceberg distribution to initial and boundary conditions, we ~~used~~performed 15 sensitivity experiments using 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~~and oceanic~~)~~ forces on the icebergs' distribution and melt flux, and 2) the effect of the used initial iceberg size on the resulting Northern hemisphere climate ~~and~~as well as on the ice sheet, due to feedback mechanisms such as altered atmospheric temperatures, under different climate conditions (pre-industrial, ~~strong/weak~~high/low 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~~Hemisphere climate and ice sheet under equilibrated conditions ~~und constant~~and continuous 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.

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~~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 Sv = 1*10^6 m^{3}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~~uptake 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~~consequently, 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~~state (Bügelmayer et al., 2014). Thus, icebergs ~~even~~ indirectly alter the ice sheet's mass balance through their effect on the ~~atmospheric~~air temperature and precipitation (Bügelmayer et al., 2014).

The ~~effects~~amount 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~~, episodically~~ 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 ~~were probably~~have been proposed to be caused by ice shelf collapses (e.g. MacAyeal, 1993; Hulbe et al., 2004; Alvarez-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~~) and resulted in a (partial) collapse of the thermohaline circulation (~~; Kageyama et al., 2010). ~~The~~It has been suggested that the collapse was caused by the long duration (Marcott et al., 2011) and ~~massive~~the increased 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 input fields. The forcing was provided off-line by atmospheric and oceanic models to investigate the drift patterns of icebergs in the Northern ~~hemisphere~~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 seeded based on a prescribed constant calving flux based on observational estimates, but moved according to the ~~modelled atmospheric~~modeled winds and ~~oceanic forcing fields~~currents and ~~were interacting~~interacted with the ~~climate~~ model~~. Recently,~~ atmosphere and ocean. Martin and Adcroft (2010) ~~investigated~~then implemented the ~~impact of icebergs on the Northern hemisphere by adding this~~ iceberg ~~module~~model into a coupled ~~general circulation model. A further step was taken by~~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. (2014~~), who used~~) took the next step by using an EMIC ~~that was~~with both dynamically coupled ~~to both an~~ ice sheet ~~model~~ and ~~an~~ iceberg model components. 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 (Levine and Bigg, 2008; Wiersma and Jongma, 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 is according to the atmospheric and oceanic forces acting on the icebergs as they determine the icebergs' movement.

~~The spatial distribution~~Computing iceberg melting and tracks is linked to various types of uncertainties. First, the ~~icebergs' freshwater flux depends~~iceberg's drift and melting, as computed in the iceberg module, are based on ~~the forces acting 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 ~~(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~~, directly affect the distribution of the freshwater. ~~Another uncertainty of iceberg modelling lies in the used~~ Third, the initial size distribution of the icebergs~~, which~~ is prescribed ~~according to~~and based on present day observations (Dowdeswell et al., 1992). Yet, ~~the used~~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. (2014), evaluating in detail the impact of ~~different~~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.

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

~~b)~~2. How sensitive is the pre-industrial northern hemisphere climate and Greenland ice sheet to spatial variations in the iceberg melt flux?

~~c)~~3. Do the northern hemisphere climate and the Greenland ice sheet respond differently to icebergs of different initial size distributions?

~~d)~~4. Is 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~~)?~~?

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 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 (Roche et al., 2014) 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, 200hPa). 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 3D 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°x3° in longitude and latitude and the ocean is vertically divided 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.

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 and ice shelf melting is computed according to the prevailing ocean conditions. The Greenland ice sheet is coupled actively 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 40x40km 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 metres 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.~~where icebergs are generated daily, as described in detail in Section 2.3. The runoff of GRISLI is calculated at the end of the year by computing the difference between the ~~topography~~ice sheet thickness 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 re-computed to fit its time-step (4 hours) 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 ice sheet model GRISLI is provided in Roche et al. (~~2013~~2014) and Bügelmayer et al. (2014).

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~~. 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) ~~and represents~~that represent the Greenland present day distribution (Table 2). It does not take into account huge tabular icebergs as those calved from Antarctica, but is a valid representation for icebergs calving from the Greenland ice sheet. Therefore, the thickness and width of the calving front as defined in GRISLI affects the amount of ice mass available to generate icebergs, but not the icebergs' dimensions. Icebergs are moved by the Coriolis force, the air~~-drag,-~~ , 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' ~~position~~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 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 =280ppm, $4xCO_2$ =1120ppm, $¼xCO_2$ =70ppm) 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 ~~(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 not impact our results ~~since we are interested in~~because all the ~~effect~~experiments are started from the same ice sheet and climate conditions and thus changes at the end of the model runs are only due to the different forcing fields ~~and the initial~~or iceberg 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 (4xCO2, $¼xCO_2$), 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:

~~$M\,{}^{dV_I}/_{dt} = -M_F k x V_I + F_A + F_R + F_W + F_P + F_S$ (1)~~

$$M\frac{dVi}{dt} = -MfkxVi + Fa + Fr + Fw + Fp + Fs \qquad (1)$$

with M being the Mass of the iceberg, **V** its velocity, the first term (−~~MFkx~~$Mfkx$ **V**i) on the right side corresponds to the Coriolis force, the second and third are the air drag (~~FA)~~Fa and wave radiation force ~~(FR)~~(Fr) and therefore depend on the atmospheric winds; the last three terms represent the oceanic forcing namely water drag ~~(FW),~~(Fw), horizontal pressure gradient ~~(FP)~~(Fp) and sea-ice drag ~~(FS).~~(Fs).

In the so-called “COM” experiments, the icebergs are moved according to Equation 1, thus by the combined atmospheric and oceanic forcing. 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.

The differentiation between atmospheric and oceanic forces was only made in the equation of motion of an iceberg. The melting of icebergs, which depends on bottom- and lateral melt (oceanic forcing) and the wave erosion (atmospheric forcing), was not altered.

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~~Table 2). The differences in the resulting ~~atmospheric~~atmosphere 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 280ppm CO_2) and in the third, a “cold” experiment, only a quarter of the pre-industrial CO_2 concentration is used (70 vs 280ppm CO_2). The latter two sets of experiments were done 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 Pre- Industrial Conditions~~

~~3.1.1~~3.1 *Impact Of ~~The~~ Forcing Fields And Initial Iceberg Size On The Transport And Lifetime Of Icebergs ~~And The Resulting Climate~~ (Pre-Industrial)*

3.1.1 *The Control Experiments (CTRL-COM, CTRL-ATM, CTRL-OCE)*

The iceberg distribution of the CTRL-COM experiment displays the general transport of icebergs of all size classes due to atmospheric and oceanic forces (Fig. 1a). We find that most icebergs are transported along the eastern and western coast of Greenland, following the oceanic currents. Further, they are moved southward along the North American coast and spread into the North Atlantic. In the Arctic, most bergs are found close to Ellesmere Island, 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 are transported 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 (GrIS) margin. In CTRL-ATM less bergs than in CTRL-COM move along the coast of Greenland as can be seen in the number of bergs travelling along the coast (Fig. 1d, f), highlighting the lack of ocean currents. Overall, the amount of iceberg melt flux released in CTRL-ATM (mid- to high latitudes: 150 m^3/s) is of the same magnitude as in CTRL-COM and over the same area (Fig. 2a).~~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,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 m3/s, 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 over a much wider area (Fig.~~ Yet, the lifetime of CTRL-ATM icebergs, that is the time (in months) it takes to completely melt the bergs, is up to one year shorter than in CTRL-COM (Fig. 3) because they are transported faster away from the ice sheet and into warmer conditions.

~~2c,d). Comparing the pattern of the iceberg distribution of SMALL-ATM and BIG-ATM in the North Atlantic (Fig. 1b,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 CTRL-OCE icebergs to stay ~~close~~closer to the GrIS margin (Fig. ~~1d~~1g). The icebergs movement reflects the prevailing ocean currents, ~~such as~~mainly the Beaufort Gyre, 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,e) since the icebergs survive longer (Fig. 3) and are thus transported further than in SMALL-OC. Except from the Arctic Ocean, where~~. Much 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,b).~~

~~The combined effect of atmospheric and oceanic forcing is displayed in the CTRL-, BIG-, and SMALL-COM experiments (Fig. 1g,h,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.~~ icebergs are moved from the ice sheet ~~1h). Although the area covered by 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~~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). ~~combination of atmospheric and oceanic forcing,~~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 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~~ not transported southwards by 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 (Fig. 1h,~~ , but stay and melt in there. Overall, the amount of freshwater flux is comparable to the ~~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 (Fig. 1g,i and Fig. 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, b).~~ experiment, though over a much smaller area (CTRL-COM: 1.4×10^{13} m^2, CTRL-OCE: 0.8×10^{13} m^2, Fig. 2a) and over a longer time period. The CTRL-OCE icebergs melt up to 4 months slower than CTRL-COM bergs because they stay close to the GrIS margin and thus in colder water (Fig. 3).

3.1.2 ***The BIG Experiments (BIG-COM, BIG-ATM, BIG-OCE)***

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 stronger on big icebergs than on small ones. Second, the area covered by BIG-COM bergs is larger in the North Atlantic than in CTRL-COM (Fig. 2d). Over the mid-to high latitudes 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 three years longer (Fig. 3). But in total there are less BIG bergs generated than in the CTRL experiment because more mass is needed per berg (Table 2).

Applying only wind forcing on the BIG icebergs (BIG-ATM) transports less icebergs into the North Atlantic and especially the GIN Seas (Fig. 1e) where they cover about half the area of BIG-COM ($4x10^{12}m^2$ compared to $7x10^{12}m^2$), but release the same amount of freshwater ($150\ m^3/s$, Fig. 2c). The BIG-ATM icebergs are not transported as far as the BIG-COM bergs in all the regions considered and especially in the GIN Seas (Fig. 2c). There, the BIG-ATM bergs follow the strong southward component of the wind without being distributed further into the GIN Seas. Similar to the CTRL experiment, the BIG-ATM icebergs melt up to two years faster than the ones of BIG-COM or BIG-OCE (Fig. 3).

~~3.1.2~~ The impact of oceanic forcing on the iceberg distribution is simulated in BIG-OCE. Since the big icebergs melt slowly, they are transported further south than CTRL-OCE bergs (Fig. 1h). ~~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.~~In the GIN Seas the BIG-OCE bergs 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 ($125m^3/s$ compared to $75m^3/s$ and $95m^3/s$, 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 bergs 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 bergs over the mid-to high latitudes is clearly bigger than SMALL-, or CTRL-OCE (Fig. 2a) because of their lifetime, which is about two years longer compared to CTRL-OCE (Fig, 3).

The SMALL Experiments (SMALL-COM, SMALL -ATM, SMALL -OCE)

Generating only SMALL-COM icebergs results in a similar iceberg distribution as in CTRL-COM (Fig. 1c), but less widespread. The amount of freshwater that is released by SMALL-COM bergs is almost the same over the mid- to high latitudes as CTRL-COM, but over a smaller area (Fig. 2a) because all the SMALL-COM icebergs are melted within two years, compared to three 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 bergs 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 wide-spread 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 bergs 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' distribution and especially lifetime since 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.

3.2 Impact Of Forcing Fields 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. ~~3). This can be explained by the fact~~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: 75m^3/s, CTRL-OCE: 150m^3/s, Fig. 2b), but these differences do not result in an altered climate state due to the prevailing cold conditions that ~~the atmospheric forcing pushes the majority~~are less sensitive to the freshening and cooling effect of icebergs ~~into~~(not shown). Also in the GIN Seas and North Atlantic ~~where they are quickly spread into warmer waters and melt (Fig.~~ the SST and TAIR do not significantly differ between the experiments, even though these are sensitive areas because of the located convection sites. 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. Further, the~~2d). The~~ shorter lifetime of the atmospheric driven icebergs does not cause ~~alterations~~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), the oceanic and atmospheric conditions.

~~3.2 IMPACT OF INITIAL ICEBERG SIZE UNDER A CHANGING CLIMATE~~

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 ~~(CTRL, BIG, SMALL),~~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 (1120ppm) and LOW= ¼xCO_2 (70ppm~~) experiments,~~), 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 ~~3~~4°C and an increase of the Greenland ice sheet volume of up to ~~5~~4%, compared to the pre-industrial ice sheet volume (Table 3).

~~3.2.1~~3.3.1 ~~HighCO~~ *Experiments With High Radiative Forcing*

The ~~effects~~impact of the ~~boundary conditions~~enhanced radiative forcing on the Greenland ice sheet ~~are shown~~is displayed 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,b).

~~At the end of the simulations of constant 1120ppm 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~~Sv vs 0.02 ~~SV~~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~~20 (SMALL-, CTRL-HIGH) to ~~80m^3~~50m^3/s (BIG-HIGH, Fig. 2c), compared to 150m^3/s 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.~~In the Arctic Ocean the HIGH experiments result in a bigger spread between the

CTRL, BIG and SMALL runs than any other performed set-up. The BIG-HIGH bergs cover the smallest area because of the decreased calving flux much less BIG bergs are generated. Further, there are still SMALL bergs, 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. 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 volume (Table 3). ~~Also during~~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~~3.3.2 ~~Lowco~~ *Experiments* ***With Low Radiative Forcing***

~~Modelling~~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 coast line (Fig. 5c). Similar to the other experiments performed, the impact of different initial size distributions of the icebergs is negligible on the ~~evolution of the climate and the Greenland ice sheet during an up to 3°C colder climate (70ppm CO$_2$ constant over 1000 model years) shows that it does not affect the~~ resulting climate ~~(Fig. 4) or~~and ice sheet volume (Table 3).

Due to the increased ice sheet thickness, more calving ~~takes place~~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 300m^3/s in the mid-to high latitudes, compared to 150m^3/s in the pre-industrial experiments. The increase is seen almost everywhere around Greenland (Fig. ~~2). The~~ 2a,c,d), except in the Arctic Ocean (Fig. 2b). 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 ~~bigger~~big spread ~~than seen in~~between the ~~previous~~ experiments~~,~~

~~especially~~ with the BIG-LOW bergs being spread the furthest and releasing the most IMF (80m^3/s in BIG-LOW vs 45m^3/s in ~~the North Atlantic (~~CTRL-LOW; 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.~~This is also partly the case for the CTRL-LOW bergs thereby resulting in a higher iceberg melt flux than the SMALL-LOW (Fig. 2b). 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~~This thus indicates that the extreme boundary conditions have a stronger impact on the results than the used iceberg sizes.

4 *Discussion*

By testing the impact of the atmospheric versus 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 by 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, Table 2) melt within the first year, which ~~lies between~~is higher than in our SMALL-~~ATM and SMALL-~~COM ~~/ SMALL-OCE results~~set-up 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 of icebergs on ~~predicting specific iceberg ~~the prediction of their tracks. In their study they showed that most of the icebergs corresponding to size class 1 to 3 used in this study, disappear within 3 to 22 months, reassuring our results. The maximum lifetime of the BIG bergs is found to be ~~eight~~almost seven years, which is ~~up to two years~~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 ~~as well as strongly increased and decreased radiative forcing, respectively. We~~ conditions we find that independent of the forcing ~~and climate background, BIG~~, SMALL icebergs release less freshwater and spread over a smaller area ~~in the Arctic Ocean~~ than ~~SMALL~~BIG 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~~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 bergs, the overall effect on climate and especially on the Greenland ice sheet is negligible.

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. But we do not expect that the size of the icebergs released from Greenland have an impact on the Southern Hemisphere, thus, the uncertainty introduced by not actively coupling the Antarctic ice sheet is present and 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=1120ppm CO_2, LOW= 70ppm 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~~North American coast. The combined effect of the forces (control set-up) ~~allows for~~displays a ~~wide~~ lesser spread iceberg distribution in the Arctic Ocean and into the North Atlantic~~.~~ than the purely atmospheric driven bergs due to the restrictive effects of the oceanic forcing. The icebergs' spread depends on both the forcing fields and the icebergs size with the ~~control~~CTRL bergs being transported the furthest, followed by the ~~SMALL~~BIG bergs (size class ~~1~~8 to ~~3~~10). 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~~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 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 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.~~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~~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).~~didier.roche@lsce.ipsl.fr). The specific experimental set-up used for this study is available at ~~https://forge.ipsl.jussieu.fr/ludus.~~https://forge.ipsl.jussieu.fr/ludus.

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List of Tables

	PRE-INDUSTRIAL (ATM & OCE FORCING) = 280 ppm	ONLY ATMOSPHERIC FORCING	ONLY OCEANIC FORCING	~~PRE-INDUSTRIAL (ATM & OCE FORCING) = 280 ppm~~	4xCO$_2$ (ATM & OCE FORCING) = 1120ppm	¼xCO$_2$ (ATM & OCE FORCING) = 70ppm	~~NAME~~
~~EXPERIMENT NAME~~ALL SIZES	CTRL-COM	CTRL-ATM	CTRL-OCE	~~COM~~	CTRL-HIGH	CTRL-LOW	
BIG BERGS	~~X~~BIG-COM	~~X~~BIG-ATM	~~X~~BIG-OCE		~~X~~BIG-HIGH ~~X~~	BIG-~~EXP.NAME~~LOW	
SMALL BERGS	~~X~~SMALL-COM	~~X~~SMALL-ATM	~~X~~SMALL-OCE		~~X~~SMALL-HIGH ~~X~~	SMALL-~~EXP.NAME~~LOW	
~~**ALL SIZES**~~	~~X~~	~~X~~	~~X~~	~~X~~	~~X~~	~~CTRL-EXP.NAME~~	

Table 1: performed experiments

CLASS	HEIGHT (m)	WIDTH (m)	VOLUME (m^3)	PERCENTAGE of total available Volume	EXPERIMENT
1	67	67	5.16E05	0.15 / 0.33	CTRL / SMALL
2	133	133	4.07E06	0.15 / 0.33	CTRL / SMALL
3	200	200	1.38E07	0.2 / 0.33	CTRL / SMALL
4	267	267	3.28E07	0.15	CTRL
5	300	333	5.74E07	0.08	CTRL
6	300	400	8.28E07	0.07	CTRL
7	300	500	1.29E04	0.05	CTRL
8	300	600	1.86E08	0.05 / 0.33	CTRL / BIG
9	300	800	3.31E08	0.05 / 0.33	CTRL / BIG
10	300	1000	5.18E08	0.05 / 0.33	CTRL / BIG

Table 2: used initial iceberg classes

Experiment	Mean	STDEV	% diff
CTRL-COM	3,~~916E~~90E+15	~~4,794E+11~~2,53E+12	~~0,00~~-
BIG-COM	3,~~917E~~91E+15	~~5,925E+11~~2,61E+12	-0,~~03~~09
SMALL-COM	3,~~916E~~91E+15	~~6,805E+11~~1,96E+12	-0,~~01~~08
CTRL-ATM	3,~~917E~~91E+15	~~8,165E+11~~1,90E+12	~~0,00~~-
BIG-ATM	3,~~916E~~91E+15	~~4,654E+11~~2,14E+12	0,~~03~~02
SMALL-ATM	3,~~917E~~91E+15	~~5,222E+11~~1,99E+12	-0,~~01~~06

CTRL-OCE	3,~~917E~~91E+15	~~5,016E+11~~2,11E+12	~~0,00~~-
BIG-OCE	3,~~915E~~91E+15	~~4,984E+11~~1,29E+12	-0,03
SMALL-OC	3,~~916E~~91E+15	~~4,924E+11~~2,20E+12	-0,~~01~~14
CTRL-HIGH	3,~~576E~~50E+15	~~1,849E~~5,03E+12	~~0,00~~-
BIG-HIGH	3,~~583E~~49E+15	~~2,093E~~4,40E+12	~~-~~0,~~20~~32
SMALL-HIGH	3,~~585E~~49E+15	~~1,927E~~5,69E+12	~~-~~0,~~26~~14
CTRL-LOW	4,~~109E~~04E+15	1,~~005E~~90E+12	~~0,00~~-
BIG-LOW	4,~~110E~~06E+15	~~8,335E+11~~2,74E+12	-0,~~02~~41
SMALL-LOW	4,~~103E~~04E+15	~~1,531E~~3,20E+12	-0,~~15~~05

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

FIGURE CAPTIONS

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)

Figure 2: area (m^2) vs iceberg melt flux (m^3/s); 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 m3/s; b: Arctic Ocean: 80-90°N and 180°W-180°E, values of IMF: 60-140 m3/s; c: Greenland – Iceland – Norwegian (GIN) Seas: 50-85°N and 45°W-15°E, values of IMF: 40-240 m3/s; d: North Atlantic: 45-60°N and 60-20°W, values of IMF: 0-50 m3/s;

Figure 3: cumulative percentage of icebergs melted within a certain time; x – Axis corresponds to months, y-axis to cumulative percentage

Figure 4: Mean + 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

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