

Review of Revised Submission (gmd---2014---117)
Anonymous Referee #2 (report 18 May 2015)

In “Representing Icebergs in the iLOVECLIM Model (version 1.0) – A Sensitivity Study” Bügelmayer, Roche and Renssen assess the sensitivity of the North Atlantic and Arctic climate system to the effects of interactive icebergs under various greenhouse gas forcing scenarios. While the paper is well structured and easy to follow it lacks some scientific novelty. The iceberg model and its implementation to iLOVECLIM, an earth system model including coupled ice sheets, has been described in a paper by the same authors in *The Cryosphere*, 2015, 9, pp. 821---835. Nevertheless, a more detailed analysis of the effect of wind and ocean current forcing as well as initially prescribed iceberg size classes is a useful addition giving more insight to the behavior of the coupled iceberg model, which is well received by the scientific ice---ocean modeling community.

We would like to thank the reviewer for taking the time to thoroughly read the manuscript and to provide valuable suggestions to improve it and would like to react on the comment of the reviewer #3 concerning the novelty of the paper. We want to emphasize that in the paper of Bügelmayer et al. (2015) the coupling of the iceberg module to the ice-sheet – atmosphere – ocean – vegetation model is presented. Further, the skill of the coupled model to represent observations is tested as well as the validity of parameterizing icebergs by using freshwater fluxes. We thus first presented the model developments and performance (Bügelmayer et al., 2015 – TC) before designing sensitivity studies to further test its behavior (the present manuscript). As kindly mentioned by the reviewer, we have designed different experiments to better understand the different effects of the atmosphere and the ocean on the movement of the icebergs and the impact of the size classes used so far in iceberg modelling studies.

I recommend publication of this manuscript in GMD after minor though extensive revisions. My comments and suggestions all aim at sharpening the arguments in the manuscript. In general, I would like to ask the authors to more precisely formulate the goal of this study considering the limitations of using a coarse resolution model of intermediate complexity.

General comments:

My main concern is the obvious imbalance between the sensitivity experiments of initial iceberg size distribution and CO₂ forcing (climate scenarios) considering the variations in iceberg sizes and radiative forcing chosen. The change in radiative forcing seems overwhelming. As the authors state in line 100 the “chosen size distribution may not be a valid representation of calving events in past or future climate conditions”, i.e. iceberg sizes are always close to the present state of the climate. In contrast they apply relatively extreme CO₂ forcing of 70 and 1120 ppm (compared to the 280 ppm off the preindustrial control run, see lines 229ff). It can be expected without much reasoning that such changes to the GHG concentrations have significant impact on the climate state of the model, including the Greenland ice sheet, whereas the iceberg size distribution seems tailored to relatively small icebergs in general (max. iceberg length is 1 km, far below the 8 km lower size limit set for present day “giant icebergs” by Silva et al, 2006). With an intermediate complexity model such as iLOVECLIM one would have the right tool to quickly test a much larger range of iceberg sizes than done in the present study. Although “giant icebergs” are not seen around Greenland these days, they might have been more common during glacial times matching the “cold” state simulated here. Given the presented simulations, I am not surprised that differences between runs BIG, CTRL

and SMALL are not significant (see Fig. 4, bar diagram). Although this is an unfortunate and unnecessary weakness of the paper I am not insisting on additional model experiments considering the advanced state of the publication process. I recommend revising the associated discussion, however, and turning Fig. 4 into an addition to Table 3.

Silva, T.A.M., Bigg, G.R., Nicholls, K.W., 2006. Contribution of giant icebergs to the Southern Ocean freshwater flux. *J. Geophys. Res.*, 111.

As the reviewer correctly mentions, the chosen radiative forcing is very strong. This was done in order to investigate the icebergs' effect on the Northern Hemisphere climate and the Greenland ice sheet during periods of strong changes, thus non-equilibrated conditions, where we can expect altered calving sites and a modified amount of calved mass.

*Moreover, the reviewer points out that the BIG set-up does not represent "giant icebergs" that are, for example, of 8km length as seen in Antarctica. First, we didn't include giant icebergs in the present manuscript because we are interested in the sensitivity of the Greenland ice sheet to the initial iceberg sizes calved from Greenland, which are currently represented by the values of Table 2 of the present manuscript. Moreover, we explicitly want to test the models sensitivity to these sizes because in most iceberg modeling studies the size distribution of the icebergs is done according to Table 2 the only exceptions that we are aware of is in Green et al. (2010,2011, doi:10.1029/2010GL045299, 10.1029/2010PA002088) and Roberts et al. (2014). As we also state in the manuscript the sizes might have been different during previous cold periods, but we think that the BIG set-up is a valid test case for colder periods. Roberts et al (2014, doi: 10.1016/j.epsl.2013.10.020) investigated the tracks of icebergs that are almost 3 times the size of the current size class 10 coming from the Laurentide ice sheet during the Last Glacial. They find that the huge icebergs have similar tracks as smaller icebergs through Davis Strait. As soon as these huge icebergs enter the open ocean, they assume that the icebergs break up into smaller pieces corresponding to the 10 size classes. They find similar results for the experiments using only the 10 size classes compared to the one where giant icebergs are generated that break up later. Green et al. (2010, 2011) explicitly altered size class 10 to have a draft of 900m instead of 300m, but kept the length to 1350 m, similar to the 1500m stated in Bigg et al. (1997, 10.1016/S0165-232X(97)00012-8) to account for deep draft icebergs calved from the Barents Ice Sheet during MIS6 (Kristofferesen et al., 2007, doi: 10.1016/j.margeo.2007.04.012). Furthermore, there is evidence of deep draft icebergs in the West of Greenland (Kuijpers et al., 2007, doi:10.1016/j.margeo.2007.05.010) that indicates icebergs of approximately 1000m depth. Barker et al. (2004, NRC Publications Archive) found that the draft of an iceberg can be estimated to be 0.71 times the length ($D=0.71*L$) for icebergs of up to 250m lengths. Therefore, icebergs of 1000m draft would have a length of 1430m, although this ratio might change for bigger icebergs. The length of our BIG icebergs thus corresponds better to the 1430 m than to giant ones of 8km, but the draft of 300m underestimates the possible iceberg sizes during glacials. However, it is important to realize that the BIG experiments are extreme cases already because 100% of the calving mass is used to generate icebergs of the three biggest size classes, instead of 15% in the case of the CTRL set-up, see Table 2 in the manuscript. We agree that performing a "giant iceberg" experiment would probably result in more pronounced differences compared to the CTRL experiment, yet, we think that the BIG experiment is closer to glacial iceberg conditions than "giant" ones.*

Further, please test results in Table 3 and Figure 4 for statistical significance and indicate this in a revised Table 3. It seems that when calculating spatial integrals the differences between the CTRL,

SMALL, and BIG experiments are not statistically significant. Iceberg size still impacts spatial distribution, I think (Fig. 1).

*We tested whether the results differ significantly from internal variability as suggested by the reviewer. Therefore, we took the CTRL (-COM,-ATM,-OCE) experiment as reference and compared the mean difference of the last 100 years between the CTRL and the BIG/SMALL experiments to 2*stdev of the CTRL experiment (the standard deviation was computed over 200 years to have a longer control set-up). The difference is significantly different from internal variability if it is bigger than 2*stdev of the CTRL set-up. We performed this analysis for the air temperatures, sea surface temperatures, ice sheet thickness at the 4 different regions and the AMOC at 30°N. We present the results of the AMOC in Table 2 in this review. We didn't performed this analysis for the LOW and HIGH experiments because the climate system and ice sheet are not in equilibrium. None of the experiments caused variations bigger than internal variability.*

As suggested by the reviewer, we have added the absolute number of the difference between the experiments to Table 3. We didn't add the significance because none of the experiments was significantly different from internal variability.

ICE SHEET THICKNESS	Mean (1E+15)	STDEV (1E+12)	Difference (1E+12)	Difference in %
CTRL-COM	3.90	4.04*	-	-
BIG-COM	3.91	2.61	-3.50	-0.09
SMALL-COM	3.91	1.96	-2.97	-0.08
CTRL-ATM	3.91	2.79*	-	-
BIG-ATM	3.91	2.14	-2.58	-0.07
SMALL-ATM	3.91	1.99	-0.430	0,01
CTRL-OCE	3.91	3.18*	-	-
BIG-OCE	3.91	1.29	-1.20	-0.03
SMALL-OCE	3.91	2.20	-5.63	-0.14
CTRL-HIGH	3.50	5.03	-	-
BIG-HIGH	3.49	4.40	11.0	0.32
SMALL-HIGH	3.49	5.69	4.82	0.14
CTRL-LOW	4.04	1.90	-	-
BIG-LOW	4.06	2.74	-16.6	-0.41
SMALL-LOW	4.04	3.20	-1.85	-0.05

Table 1: Ice-sheet Volume (m³): Mean and Standard deviation of last 100 years, the *corresponds [1] to the CTRL stdev that was computed over the last 200 years to have a more representative range of internal variability as a reference; difference between the ice sheet volume of the CTRL experiment and the BIG/SMALL experiments in absolute numbers, if the value is above 2*sd of the CTRL experiments (*), then the difference is significantly different from internal variability (none of the experiments); % diff = difference between the ice sheet volume of the CTRL experiment and the BIG/SMALL experiments in percent.

Concerning Figure 4, it is correct that the spatial integral masks spatial differences between the runs, yet, we are interested in the overall response rather than in small changes in the spatial pattern. Therefore, we have chosen regions instead of presenting spatial plots. We would prefer to keep Figure 4 instead of adding the information to Table 3 because we think it is clearer to see at

once the results. We are however happy to change this into a Table if the editor agrees with the reviewer and move Figure 4 to supplementary information. The results in Figure 4 don't significantly differ from internal variability.

Unfortunately, effects on the ocean state are only discussed in terms of SST. What about the large-scale circulation, e.g. the North Atlantic Current, and deep convection sites with links to the Atlantic Meridional Overturning Circulation (AMOC)? Do they change in position or strength?

We have restricted our analysis to SST because we did not find any significant changes in the convection depth, or salinity or the AMOC, please see Table 2.

AMOC	Mean	STDEV	Difference
CTRL-COM	13.89	0.61*	-
BIG-COM	14.28	0.58	-0.39
SMALL-COM	13.50	0.59	0.39
CTRL-ATM	14.21	1.13*	-
BIG-ATM	13.48	0.95	0.74
SMALL-ATM	13.59	0.57	0.63
CTRL-OCE	13.64	1.14*	-
BIG-OCE	13.49	0.75	0.15
SMALL-OCE	13.34	0.52	0.15
CTRL-HIGH	5.96	0.33	-
BIG-HIGH	5.85	0.36	0.11
SMALL-HIGH	5.83	0.33	0.13
CTRL-LOW	17.21	2.18	-
BIG-LOW	17.60	1.89	-0.39
SMALL-LOW	16.89	2.04	0.32

Table 2: Atlantic Meridional Overturning Circulation (AMOC, Sv): Mean and Standard deviation of last 100 years, the *corresponds to the CTRL stdev that was computed over the last 200 years to have a more representative range of internal variability as a reference, difference between the AMOC of the CTRL experiment and the BIG/SMALL experiments in absolute numbers, if value is above 2*sd of the CTRL experiments (*), then the difference is significantly different from internal variability (none of the experiments)

We have modified lines 323-330:

Also in the GIN Seas and North Atlantic the difference in SST and TAIR between the experiments does not significantly differ from internal variability (Fig. 4). In all the pre-industrial experiments, we find that the differences in air and ocean temperature between the CTRL and the BIG, SMALL experiments do not significantly exceed the internal variability of the CTRL experiment. This is also the case for sensitive areas such as the GIN Seas or the North Atlantic, due to the located convections sites there. Therefore, the impact of the dynamical forcing and initial iceberg size is smaller than natural climate variability, which is also reflected in the deep ocean circulation (not shown).

For an improved structure I suggest to rename sections 2.4.1 and 2.4.2 to “Iceberg Dynamical Forcing” and “Initial Iceberg Size Distribution, respectively, and add a section 2.4.3 called “CO2 Forcing” or “Radiative Forcing”. Results are already presented according to this order in Section 3.

We have changed the structure of the methods section as suggested by the reviewer and added section 2.4.3 in lines 233-240:

2.4.3 Radiative Forcing

Using the three size distributions described in 2.4.2, we performed three sets of experiments. The first set was done under pre-industrial equilibrium conditions for 200 years. In the second one, a “high” experiment, we applied a CO2 concentration four times as strong as the pre-industrial value (1120 vs 280ppm CO2) and in the third, a “low” experiment, only a quarter of the pre-industrial CO2 concentration is used (70 vs 280ppm CO2). The latter two sets of experiments were done to analyze the effect of the size (CTRL/SMALL/BIG) distribution during periods of a strongly changing ice-sheet under non – equilibrated conditions.

Detailed comments:

15 delete “as well as on the icebergs’ size” (iceberg size changes are implied)

We have added “initial” to clarify, lines 15-17:

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 initial icebergs’ size.

21 “... oceanic forces on iceberg mass and melt flux distribution, and ...”

22 remove “used” and replace “as well as on” by “including” 25 please always use “icebergs” and not “bergs”

We changed lines 21 and 22 accordingly, which now read:

...1) the impact of the atmospheric and oceanic forces on the iceberg transport, mass and melt flux distribution, and 2) the effect of the initial iceberg size on the resulting Northern hemisphere climate including the Greenland ice sheet,...

25 please always use “icebergs” and not “bergs”

Thank you for pointing this out, we changed bergs to icebergs everywhere in the manuscript (lines 27/ 192 / 221 / 249 / 254/ 255 / 259 / 269 / 272 / 278 /281 / 286 /287 / 292 /293 / 297 /301 / 305 /310 / 316 / 320 /362 / 364/ 389 /393 / 402 /413 / 418 / 428 / 452 / 454 / 456 / 469 / 628 / 629)

27---29 shorten “These different characteristics ... North Atlantic waters.” to, for instance, “Icebergs remaining close to Greenland last up to two years longer as they reside in generally cooler waters”

We shortened lines 27-29 as nicely suggested by the reviewer.

35 replace “used initial size distribution of the icebergs” by “initial iceberg size distribution.”

We deleted the word “used”.

41 remove “1*”: “1 Sv = 10⁶ m³s⁻¹”

Line 42 has been changed as suggested.

41/42 "... affect the upper ocean by freshening and cooling due to melting and uptake of latent heat."

We changed line 43 as advised by the reviewer.

43/44 remove "the": "that freshening", "as cooling" and "whereas freshening"

Thank you for pointing this out, we deleted the articles.

48 delete "Therefore,"

We deleted "Therefore,".

50 suggest to replace ", consequently," with "thus"

We substituted "consequently" by "thus".

53 remove "the": "on air temperature and precipitation"

We removed the article.

57 "episodic massive discharges of icebergs" to emphasize unusual amount of calved mass

Thank you, we added "massive" to emphasize the point.

64 remove "and affected the global climate." or add reference.

We modified line 64 that now reads:

It has been suggested that the collapse was caused by the long duration (Marcott et al., 2011) and the increased amount of freshwater released (0.04 up to 0.4 Sv, Roberts et al., 2014) and coincided with globally altered climate conditions (Hemming, 2004).

67 replace "fed" with "forced"

We replaced "fed" with "forced" as kindly suggested (line 68).

67/68 "... and oceanic input fields from uncoupled model simulations."

As indicated by the reviewer, we changed line 69.

75 change "based on" to "from"

As correctly stated by the reviewer, we substituted "based on" with "from".

135 replace "consisting of" with "including"

Thank you, we changed "consisting of" to "including".

138 "consists of" ---> "uses"

As kindly suggested, we replaced "consists of" by "uses".

143 remove comma

We removed the comma.

146---148 I do not understand how this parameterization works. Please revise this sentence adding some more detailed information. Does it really only affect the heat budget ("uptake of latent heat") but the freshwater/salt budget? Which region is affected, what kind of geographic mask is applied? What are the prevailing ocean conditions: temperature, waves, ... ?

We tried to clarify paragraph 147-149. The parameterization only affects the temperature, not the salinity of the ocean. Only the ocean temperature is used to compute ice shelf melting. Unfortunately, we do not understand what the reviewer means with “geographic mask is applied”. But for the present manuscript, the parameterization of take up of latent heat used in the Southern Hemisphere is of minor importance. Lines 146-150 now read:

The Antarctic ice sheet is prescribed according to present-day conditions following the ETOPO5 topography (<http://www.ngdc.noaa.gov/mgg/fliers/93mgg01.html>). Icebergs are parameterized in the form of homogenous uptake of latent heat around Antarctica, thereby cooling the ocean without altering the salinity. Ice shelf melting is computed according to the prevailing ocean temperatures. The Greenland ice sheet is coupled actively using the GRISLI ice-sheet model.

156 “do not consider” ---> “exclude”

“do not consider” has been changed to “exclude”.

158 “... thickness at the ice shelf front is less ...”

We do not agree with the reviewer that calving occurs if the thickness at the “ice shelf front” is less than 150m because in Greenland there is mainly an ice sheet and only small areas of floating ice.

181 remove “Therefore,”

We removed “Therefore,”.

183/184 it appears there is an additional empty space in “air--- ,” and “water--- ,” because comma appears in next line.

Thank you for pointing this out, we removed the empty space.

197---200 “This initial ice sheet thickness ... the observed one. We consider this bias negligible for the present study because we focus on differences between our sensitivity runs using the same initial state for all experiments. The individual simulations are long enough to yield results that are independent of the initial conditions and only functions of the different forcing applied.”

We modified lines 201-204 as kindly suggested by the reviewer:

We consider this bias negligible for the present study because we focus on differences between our sensitivity runs using the same initial state for all experiments. The differences between the individual simulations are therefore independent of the initial conditions and only functions of the different forcing applied.

203 suggest to change title to “Iceberg Dynamical Forcing” (see also general comments) in order to separate these experiments from those of changed radiative forcing (cf. your section titles 3.3.1 and 3.3.2 and my comment on title of 3.1 and 3.2 below)

Thank you, we changed the headers of the subsections as indicated.

204/205 “... ocean and the atmosphere on iceberg dynamics, we separate the individual forcing terms of the iceberg momentum balance:

We modified lines 207/208 to:

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

208 “the air drag (F_a) and the wave radiation force ...”, parenthesis missing, add “the” before “wave”

Thank you, we added the missing parenthesis.

212 move reference to Table 1 to end of paragraph

We moved the reference to Table 1 as suggested to line 223.

217---219 “... was only applied to the momentum balance of the icebergs. The mass balance of icebergs, ... (AUTHOR et al., YEAR, Eq. ???), is the same in all experiments. ” Please add reference for mass balance of iceberg model; I didn’t find it in Bugelmayer et al., 2014, TC; I think Jongma et al., 2009, Ocn. Mod., which is referenced already, describes it for ECBilt---CLIO.

We modified lines 220-223

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

suggest to change title to “Initial Iceberg Size Distribution” (see general comments)

Thank you, we changed the headers of the subsections as indicated (line 224).

221 “By altering the initial size distribution of the icebergs we are able to investigate the potential sensitivity of the atmosphere, ocean and ice sheet to iceberg sizes.”

We changed line 225 as kindly suggested by the reviewer.

225 remove sentence: “The differences in the resulting ... and the ice sheet.”

We deleted the former line 225.

227 I strongly recommend introducing a new subsection “2.4.3 Radiative Forcing” here, which then begins with: “We conducted three sets of experiments, of which the first set was done under ... for 200 years. This set includes experiments with the CTRL, SMALL, and BIG iceberg size distributions as well as the experiments ATM and OCN with individually turned off dynamical forcing. In the second set, a ‘warm climate’ experiment, ...”

We added an additional subsection “Radiative Forcing” following the good advise of the Reviewer (lines 230-237).

231/232 “The ‘warm’ and ‘cold’ experiments were conducted to analyse the effect of the iceberg size distributions during periods ...

We modified lines 235-236 as indicated by the reviewer.

235 suggest to change title as follows to distinguish between dynamical (ATM, OCN) and radiative (CO₂) forcing: “Impact of Dynamical Forcing and Initial Size on the Transport and Lifetime of Icebergs Under Pre---Industrial Conditions”.

We changed the title 3.3.1 following the advise of the reviewer.

237 shorten sub---title “The CTRL Experiments”

We dropped the experiment names in all the subtitles (3.1.1 / 3.1.2 / 3.1.3).

248 remove reference "(Fig. 1d,f)" because Fig. 1d is linked in the previous sentence already and SMALL (Fig. 1f) is not yet discussed.

Thank you for pointing this out, we have removed the reference (line 253).

249 "... of the same magnitude and distributed over the same area as in CTRL--- COM (Fig. 2a)."

We rearranged the sentence as kindly suggested (line 254-255)

252 "... and into warmer waters."

We changed "conditions" to "waters" (line 258).

277---279 shorten: remove "The BIG---ATM icebergs ... (Fig. 2c)." and rewrite "The strong southward component of the wind keeps the icebergs from drifting farther into the GIN Seas."

We wrote lines 283-284 as advised by the reviewer.

298 "... melted within two years. This difference is much smaller than the difference to the lifetime of BIG icebergs (see Fig. 3)."

We unfortunately don't understand the reviewer's comment.

312 "Impact of Iceberg Dynamical Forcing and Initial Size on Pre---Industrial Climate"

We changed the title of 3.2 as kindly suggested.

315 I think that Fig. 4 should be turned into a table, probably added to Table 3 (see comments on Figures below). If this suggestion is followed, then the beginning of section 3.2 must be revised accordingly.

As stated above, we prefer to keep Figure 4 and Table 3 separated as it is because we think the information is easier to grasp for the reader. But we are happy to add Figure 4 to Table 3 if the editor agrees with the reviewer.

320 Good point to mention the deep convection sites in the North Atlantic: I think it is not enough to look at SST and surface air temperature, which are closely related anyway (except there is sea ice). How is the strength of the AMOC affected? Please check the streamfunction maximum at about 30°N in the all simulations. This would be interesting to show here in case iceberg size makes an impact in any of the three climate states.

Please see Table 3 and statement above.

345/346 "..., the calving flux from the GrIS is declining (...) especially in South Greenland. This has a direct impact on the iceberg melt flux."

Thank you for this suggestion, we modified lines 351-353 accordingly.

390 "... on the lifetime and motion of icebergs, we find ..."

We changed line 396-397 following the reviewer's comment.

402 "... small bergs of up to 200 m in diameter (size classes 1 to 3, Table 2) ...

We added "of up to 200m in diameter" to line 407 as kindly suggested.

409 Why do not compare the results (iceberg mass and melt distribution) with Jongma et al., 2009, Fig. 1 or Martin and Adcroft, 2010, Fig. 2?

We didn't discuss the studies of Jongma et al. (2009) or Martin and Adcroft (2010) because only the CTRL-COM experiment is comparable to these two studies and this comparison has already been done and discussed in Bügelmayer et al. (2015). In the present manuscript the focus lies on the impact of the background forces (atmosphere – ocean), the initial size distribution and prevailing climate. These were not investigated by either Jongma et al. (2009) nor by Martin and Adcroft (2010).

425 I am not convinced that icebergs from Greenland do not have a potential impact on the southern hemisphere, for instance by affecting deep convection in the North Atlantic and subsequently the AMOC. I agree that the iceberg size, varied within the range considered here, has likely no impact. It is probably rather due to significant changes in calving rates or calving of much larger icebergs that last longer and carry farther onto the ocean. These lines should be carefully revised.

We modified lines 432-442 to take clarify this paragraph:

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

434 What about much bigger icebergs of up to 10 km in diameter? Are they realistic in the North Atlantic under a much colder climate?

So far we have found 2 studies that found plow marks in the Arctic (Kristofferesen et al., 2007, doi: 10.1016/j.margeo.2007.04.012) and West of Greenland Greenland (Kuijpers et al., 2007, doi:10.1016/j.margeo.2007.05.010), which, according to a study by Barker et al. (2004, NRC Publications Archive) would correspond to icebergs of a 1.5km in diameter, which corresponds to the width of size class 10 in Table 2 of the manuscript. Moreover, Roberts et al. (2014) showed that generating huge icebergs (3 the mass of the current size class 10) results in a similar iceberg melt flux as generating icebergs of all size classes because of their break up.*

444 “The spread of iceberg mass on the ocean depends ...”

We changed “the icebergs’ spread” to “The spread of icebergs” as suggested.

445 “... by big icebergs of more than 500 m in diameter.” Conclusions should be understandable without checking tables and figures.

We deleted the reference to the size classes.

454 “... (1120 ppm or 70 ppm CO₂ over 1000 model years),...”

Thank you, we deleted “CO₂” after 1120ppm.

457 “... (all size classes, less than 200 m and more than 500 m in diameter only), ... does not differ significantly.” If significance tests are successful, then say “not digger strongly but significantly.”

We modified lines 466-468 that now state:

(all size classes, only size classes with less than 200m width, and only size classes with 600-1000m width, respectively), their impact on the northern hemispheric climate does not differ significantly from internal variability.

464 I am not entirely sure of that. What if iceberg size did vary beyond the current size distribution in past 'cold' climates? If one would test for, say nearly unrealistically giant icebergs and the response is still small compared to changes in radiative forcing, this would be much easier to believe.

By the way, just a thought, is there a stability limit to iceberg size based on first principles? This could limit the iceberg size distribution for all climate states.

Please note that we state that our results show that the response of the climate to the applied forcing is much stronger than its response to the chosen initial size distribution of the icebergs. We don't know if this is still correct if applying giant ($\geq 10\text{km}$ icebergs), but for the set-up we tested, this is correct. Moreover, it is an interesting thought to test if there exists a stability limit of icebergs, which will hopefully be investigated in future studies.

TABLES:

Table 1 provides a good overview of the various experiments; this is really useful.

Thank you.

Table 2: please change notation "5.16E05" to " $5.15 \cdot 10^5$ "; alternatively add " 10^5 " to column label and express numbers as factors of 10^5 . Also, I think numbers in column 5 represent "fraction" and not "percentage".

We modified Table 2 following the kind suggestions of the reviewer.

Table 3: The differences listed in column 4 appear to be puny. In most cases they are not significant at, say a 95% level (2 times the standard deviation) compared to the interannual variability given in column 3. I recommend listing the differences not only in percent but also in absolute numbers (10^{12} m^3) for comparison with the STDEV. Further, I suggest to move the order of magnitude to the label, i.e. remove "E+15" and "E+12" from all numbers but add 10^{15} and 10^{12} to Mean and STDEV respectively.

Thank you for pointing this out, we changed Table 3 accordingly, please see Table 1 above.

FIGURES

Figure 1: The nine panels provide a nice overview of iceberg size and atmosphere and ocean forcing. Why not presenting mean iceberg mass or meltwater influx per m^2 , i.e. quantities that are physically more meaningful than number of bergs? Apart from that, differences between rows, i.e. the impact of the forcing, is easy to see, differences between columns, i.e. impact of iceberg size, are much harder to detect. I thus recommend to plot panels b) and c) as difference to panel a), and similarly e,f) as difference of d) and panels h,i) as difference of g). In other words, present absolute values for the CTRL run but differences to CTRL otherwise.

Caption: "... icebergs passing through a grid cell ..."

We have changed Figure 1 to display the iceberg melt flux instead of the total number of icebergs as suggested by the reviewer and would like to keep the previous Figure 1 in the supplementary

information. If the editor agrees, we prefer to keep the total values in all panels because this allows the direct comparison between the BIG (SMALL)- OCE and BIG(SMALL)-ATM experiments.

Figure 2: I think it would be nice if one of these panels would represent the entire Northern Hemisphere. I also recommend adding a map on which the various regions are outlined. Maybe one could add these two displays to the present figure, which would then have a 2 by 3 arrangement instead of 2 by 2 panels.

Caption: "... all the grid cells that have at least 10 icebergs passing through per year on average (note area is given in 10^{12} m^2) ... Arctic Ocean: all area north of 80°N , IMF is ... "

We changed the panel of the Mid-to High Latitudes to one that covers the complete Northern Hemisphere. We deleted the figure with the Mid-to High Latitudes because the information was very similar to the Northern Hemisphere. If the editor doesn't agree with our choice, we are happy to include both panels.

Figure 3: Caption: "Cumulative iceberg melt distribution normalized to 100% as a function of time (months)."

We changed the caption.

Figure 4: I might not get the hang of this figure but in my view it does not show anything that I can conclude from the other figures or the text:

the differences between the CTRL, SMALL and BIG experiments are tiny, maybe even not significant as indicated by the black error bars in this plot, which always overlap and are bigger than the differences between the red, blue and green bars in each panel.

COM, ATM, and OCN results are extremely similar as well. It is not that obvious but they might also not be significant.

The only visible difference is between the runs of different CO₂ content. Please don't misunderstand me, this is a meaningful result, but it does not necessitate this Figure. A table might be more suitable, in fact differences in SST and Tair could be added nicely to Table 3.

This would still suite the discussion now linked to Figure 4.

As stated before, we prefer to keep Figure 4 because we think the results are clearer presented this way than adding them to Table 3. But we are happy to add them to Table 3 if the editor agrees with the reviewer.

Figure 5: As with Figure 1 I strongly recommend to plot absolute values only for panel a), COM and then show differences to COM in panels b) and c).

We changed Figure 5 according to the reviewer's suggestion.

1 *Representing Icebergs in the iLOVECLIM Model (version 1.0)- A Sensitivity* 2 *Study*

3
4
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11

12 Recent modelling studies have indicated that icebergs play an active role in the climate system as
13 they interact with the ocean and the atmosphere. The icebergs' impact is due to their slowly
14 released melt water, which freshens and cools the ocean and consequently alters the ocean
15 stratification and the sea ice conditions. The spatial distribution of the icebergs and their melt
16 water depends on the atmospheric and oceanic forces acting on them as well as on the initial
17 icebergs' size. The studies conducted so far have in common that the icebergs were moved by
18 reconstructed or modelled forcing fields and that the initial size distribution of the icebergs was
19 prescribed according to present day observations. To study the sensitivity of the modelled iceberg
20 distribution to initial and boundary conditions, we performed 15 sensitivity experiments using the
21 climate model iLOVECLIM that includes actively coupled ice-sheet and iceberg modules, to analyse
22 1) the impact of the atmospheric and oceanic forces on the ~~icebergs' distribution~~ iceberg transport,
23 mass and melt flux distribution, and 2) the effect of the ~~used~~ initial iceberg size on the resulting
24 Northern ~~hemisphere~~ Hemisphere climate ~~as well as on~~ including the Greenland ice sheet, due to
25 feedback mechanisms such as altered atmospheric temperatures, under different climate
26 conditions (pre-industrial, high/low radiative forcing). Our results show that, under equilibrated
27 pre-industrial conditions, the oceanic currents cause the ~~bergs~~ icebergs to stay close to the
28 Greenland and North American coast, whereas the atmospheric forcing quickly distributes them
29 further away from their calving site. ~~These different characteristics strongly affect the lifetime of~~
30 icebergs, since the wind - driven icebergs melt icebergs remaining close to Greenland last up to

31 two years ~~faster~~longer as they ~~are quickly distributed into the relatively warm North Atlantic~~reside
32 in generally cooler waters. Moreover, we find that local variations in the spatial distribution due to
33 different iceberg sizes do not result in different climate states and Greenland ice sheet volume,
34 independent of the prevailing climate conditions (pre-industrial, warming or cooling climate).
35 Therefore, we conclude that local differences in the distribution of their melt flux do not alter the
36 prevailing Northern Hemisphere climate and ice sheet under equilibrated conditions and
37 continuous supply of icebergs. Furthermore, our results suggest that the applied radiative forcing
38 scenarios have a stronger impact on climate than the ~~used~~-initial size distribution of the icebergs.

39 **1 Introduction**

40 Icebergs are an important part of the climate system as they interact with the ocean, atmosphere
41 and cryosphere (e.g. Hemming, 2004; Smith et al., 2011; Tournadre et al., 2012). Most
42 importantly, icebergs play an important part in the global fresh water cycle since currently up to
43 half of the mass loss of the Antarctic (Rignot et al., 2013) and Greenland ice sheets is due to
44 calving (approx. 0.01 Sv, 1 Sv = $1 \cdot 10^6 \text{ m}^3 \text{ s}^{-1}$, Hooke et al., 2005). As icebergs are melting, they
45 affect the upper ocean ~~not only~~ by freshening, ~~but also by~~ and cooling due to their uptake of
46 latent heat. Several studies have revealed that ~~the~~ freshening and cooling have opposing effects
47 on ocean stratification, as ~~the~~ cooling enhances the surface density, promoting deep mixing,
48 whereas ~~the~~ freshening decreases the water density, stabilizing the water column (Jongma et al.,
49 2009, 2013, Green et al., 2011).

50 Moreover, the implementation of dynamical icebergs in climate models has revealed that icebergs
51 enhance the formation of sea ice (Jongma et al., 2009, 2013; Wiersma and Jongma 2010;
52 Bügelmayer et al., ~~2014~~2015), which forms a barrier between the ocean and the atmosphere.
53 ~~Therefore, on~~On the one hand sea ice shields the ocean from being stirred by atmospheric winds,
54 and on the other hand from losing heat to the relatively cold atmosphere, ~~consequently~~thus,
55 reducing mixing of the upper water column. Further, this reduced oceanic heat loss leads, in
56 combination with an increase in surface albedo, to a changed atmospheric state (Bügelmayer et
57 al., ~~2014~~2015). Thus, icebergs indirectly alter the ice sheet's mass balance through their effect on
58 ~~the~~ air temperature and precipitation (Bügelmayer et al., ~~2014~~2015).

59 The amount of icebergs calved and their effects on climate depend on the calving flux provided by
60 the ice sheets, which is altered by the prevailing climate conditions. For instance, in the relatively

61 | cold climate of the last glacial massive episodic discharges of icebergs into the North Atlantic
62 | Ocean, so-called Heinrich events, have been recorded in distinct layers of ice rafted debris
63 | (Andrews 1998; Hemming 2004). These periods of enhanced ice discharge have been proposed to
64 | be caused by ice shelf collapses (e.g. MacAyeal, 1993; Hulbe et al., 2004; Alvarez-Solas et al., 2011)
65 | and happened during periods of a (partial) collapse of the thermohaline circulation (Broecker et
66 | al., 1993; McManus et al. 2004; Gherardi et al., 2005; Kageyama et al., 2010). It has been
67 | suggested that the collapse was caused by the long duration (Marcott et al., 2011) and the
68 | increased amount of freshwater released (0.04 up to 0.4 Sv, Roberts et al., 2014) and ~~affected the~~
69 | ~~global climate coincided with globally altered climate conditions (Hemming, 2004).~~

70 | So far, different approaches have been taken to incorporate icebergs from the Antarctic and
71 | Greenland ice sheets into numerical models for different time periods. Bigg et al. (1996, 1997)
72 | presented an iceberg module, which was ~~fed~~forced with present-day atmospheric and oceanic
73 | input fields from uncoupled model simulations. The forcing was provided off-line by atmospheric
74 | and oceanic models to investigate the drift patterns of icebergs in the Northern Hemisphere. Their
75 | approach was further developed for the Southern Ocean by Gladstone et al. (2001), who used
76 | modelled oceanic ~~forcing~~ and modern reconstructed wind fields, as well as observed calving
77 | amounts to seed the iceberg module. Subsequently, the same iceberg module was implemented
78 | in an earth system model of intermediate complexity (EMIC) by Jongma et al. (2009) to investigate
79 | the impact of icebergs on the Southern Ocean under pre-industrial conditions. In the latter study,
80 | the icebergs were seeded based on a prescribed constant calving flux ~~based on~~from observational
81 | estimates, but moved according to the modeled winds and currents and interacted with the model
82 | atmosphere and ocean. Martin and Adcroft (2010) then implemented the iceberg model into a
83 | coupled global climate model (CGCM) using the model's variable runoff as a calving flux though
84 | still lacking an ice sheet component. Most recently, Bügelmayer et al. (~~2014~~2015) took the next
85 | step by using an EMIC with both dynamically coupled ice sheet and iceberg model components. In
86 | their model setup, the climate – ice-sheet – iceberg system was fully interactive, with the icebergs'
87 | calving positions and amounts being determined by the ice sheet model, and with the ice sheet
88 | responding to the icebergs' effect on climate.

89 | Coupled climate-iceberg models have been used for several specific purposes, such as the
90 | investigation of drift patterns of icebergs under present-day (Venkatesh and El-Tahan, 1988; Bigg
91 | et al., 1996) and glacial climate conditions (Death et al., 2005). In addition, these models have

92 been utilized to study the effect of icebergs on the climate during present (e.g. Gladstone et al,
93 2001; Martin and Adcroft, 2010), pre-industrial (Jongma et al., 2009 Bügelmayer et al., ~~2014~~2015)
94 and past times (Levine and Bigg, 2008; Wiersma and Jongma, 2010; Green et al., 2011; Jongma et
95 al., 2013; [Roberts et al., 2014](#)) using both prescribed and interactively modelled forcing fields, and
96 have shown that icebergs and their melt water have an impact on climate. The spatial distribution
97 of the icebergs' freshwater flux is according to the atmospheric and oceanic forces acting on the
98 icebergs as they determine the icebergs' movement.

99 Computing iceberg melting and tracks is linked to various types of uncertainties. First, the
100 iceberg's drift and melting, as computed in the iceberg module, are based on empirical parameters
101 and simplifications (e.g. Jongma et al., 2009) that would need further observations to be
102 improved. Second, uncertainties in the reconstructed and modelled wind fields and ocean
103 currents, used to force the icebergs, directly affect the distribution of the freshwater. Third, the
104 initial size distribution of the icebergs is prescribed and based on present day observations
105 (Dowdeswell et al., 1992). Yet, this chosen size distribution may not be a valid representation of
106 calving events in past or future climate conditions.

107 We therefore propose in this study to extend the approach of Bügelmayer et al. (~~2014~~2015),
108 evaluating in detail the impact of the modelled forcing fields and iceberg size distributions. We use
109 the same earth system model of intermediate complexity (*i*LOVECLIM) coupled to an ice sheet/ice
110 shelf model (GRISLI) and an iceberg module to answer the following research questions.

- 111 1. How do atmospheric and oceanic forcing fields affect the icebergs (their lifetime and
112 movement) in the ~~northern hemisphere~~Northern Hemisphere under pre-industrial
113 conditions?
- 114 2. How sensitive is the pre-industrial ~~northern hemisphere~~Northern Hemisphere climate and
115 Greenland ice sheet to spatial variations in the iceberg melt flux?
- 116 3. Do the ~~northern hemisphere~~Northern Hemisphere climate and the Greenland ice sheet
117 respond differently to icebergs of different initial size distributions?
- 118 4. Is the ~~northern hemisphere~~Northern Hemisphere climate and the Greenland ice sheet
119 response to icebergs of different initial size distribution dependent on the prevailing
120 climate conditions (pre-industrial (PI), warmer than PI and colder than PI)?

121 We will address these questions by presenting results from 15 different sensitivity experiments
122 (Table 1) that differ in the applied forcing (atmospheric, oceanic, pre-industrial, warmer, colder
123 climate) and the initial size distribution (CTRL (standard sizes), BIG, SMALL, Table 2) of the
124 icebergs.

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

127 **2 Methods**

128 We use the earth system model of intermediate complexity *i*LOVECLIM (version 1.0) which is a
129 code fork of the LOVECLIM climate model version 1.2 (Goosse et al., 2010). *i*LOVECLIM differs in
130 the ice sheet module included (Roche et al., 2014) and the further developed iceberg module
131 (Bügelmayer et al., ~~2014~~2015), but shares some physical climate components (atmosphere, ocean
132 and vegetation) with LOVECLIM.

133 **2.1 Atmosphere – ~~Ocean – Vegetation Model~~ocean – vegetation model**

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

140 *i*LOVECLIM includes the sea-ice and ocean model CLIO, which is a 3D ocean general circulation
141 model (Deleersnijder and Campin, 1995; Deleersnijder et al. 1997; Campin and Goosse, 1999)
142 ~~consisting of~~including a dynamic – thermodynamic sea-ice model (Fichefet and Morales Maqueda,
143 1997, 1999). Due to its free surface, the freshwater fluxes related to iceberg melting can be
144 directly applied to the ocean’s surface. The horizontal resolution is 3°x3° in longitude and latitude
145 and the ocean is vertically divided into 20 unevenly spaced layers. CLIO ~~consists~~uses of a realistic
146 bathymetry. The oceanic variables (e.g., sea surface temperature and salinity) are computed once
147 a day.

148 The vegetation (type and cover) is calculated by the vegetation model VECODE (Brovkin et al.,
149 1997), which runs on the same grid as ECBilt. VECODE accounts for fractional use of one grid cell
150 because of the small spatial changes in vegetation. It simulates the dynamics of two plant
151 functional types (trees and grass) as well as bare soil, in response to the temperature and
152 precipitation coming from ECBilt.

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

159 2.2 GRISLI – ~~Ice Sheet Model~~ ice sheet model

160 The ice-sheet model included in iLOVECLIM is the Grenoble model for Ice Shelves and Land Ice
161 (GRISLI), which is a three-dimensional thermomechanical model that was first developed for the
162 Antarctic (Ritz et al., 1997, 2001) and was further developed for the ~~northern hemisphere~~ Northern
163 Hemisphere (Peyaud et al., 2007). GRISLI consists of a Lambert azimuthal grid with a 40x40km
164 horizontal resolution. In the present study, it computes the evolution of the thickness and
165 extension of the Greenland ice sheet (GrIS) only, as we ~~do not consider~~ exclude the ~~southern~~
166 ~~hemisphere~~ Southern Hemisphere grid. GRISLI distinguishes three types of ice flow: inland ice, ice
167 streams and ice shelves. Calving takes place whenever the ice thickness at the border of the ice
168 sheet is less than 150 metres and the points upstream do not provide enough inflow of ice to
169 maintain this thickness. After one model year, the total yearly amount of calving is given to the
170 iceberg module where icebergs are generated daily, as described in detail in Section 2.3. The
171 runoff of GRISLI is calculated at the end of the year by computing the difference between the ice
172 sheet thickness at the beginning of the model year and the end of the year, and taking into
173 account the mass loss due to calving. The runoff is then given to ECBilt where it is re-computed to
174 fit its time-step (4 hours) and incorporated into the land routing system. GRISLI is run for one
175 model year and then provides the runoff and calving, as well as the updated albedo- and
176 topography fields to the atmosphere – ocean – vegetation component. A more detailed

177 explanation of the coupling between ECBilt, CLIO and the ice sheet model GRISLI is provided in
178 Roche et al. (2014) and Bügelmayer et al. (~~2014~~2015).

179 **2.3 Iceberg ~~Module~~module**

180 As discussed in detail in Bügelmayer et al. (~~2014~~2015), the dynamic – thermodynamic iceberg
181 module (Jongma et al., 2009; Wiersma and Jongma, 2010) included in *i*LOVECLIM is based on the
182 iceberg-drift model of Smith and co-workers (Smith and Banke, 1983; Smith, 1993; Loset, 1993)
183 and on the developments done by Bigg et al. (1996, 1997) and Gladstone et al. (2001). According
184 to the calving mass and locations calculated by GRISLI over one model year, icebergs of up to ten
185 size classes are generated. The provided ice mass is re-computed to fit the daily time-step of the
186 iceberg module, taking into account the seasonal calving cycle, with the maximum calving
187 occurring from April to June and the minimum occurring in late summer (Martin and Adcroft,
188 2010). The control size distribution of the icebergs is according to Bigg et al. (1996) and based on
189 observations of Dowdeswell et al. (1992) that represent the Greenland present day distribution
190 (Table 2). It does not take into account huge tabular icebergs as those calved from Antarctica, but
191 is a valid representation for icebergs calving from the Greenland ice sheet. ~~Therefore, the~~The
192 thickness and width of the calving front as defined in GRISLI affects the amount of ice mass
193 available to generate icebergs, but not the icebergs' dimensions. Icebergs are moved by the
194 Coriolis force, the air ~~-,~~ water-, and sea-ice drag, the horizontal pressure gradient force and the
195 wave radiation force. The forcing fields are provided by ECBilt (winds) and CLIO (ocean currents)
196 and are linearly interpolated from the surrounding grid corners to the icebergs' positions. The
197 icebergs melt over time due to basal melt, lateral melt and wave erosion and may roll over as their
198 length to height ratio changes. The heat needed to melt the ~~bergs~~icebergs is taken from the ocean
199 layers corresponding to the icebergs' depth and the freshwater fluxes are put into the ocean
200 surface layer of the current grid cell. The refreezing of melted water and the break-up of icebergs
201 is not included in the iceberg module.

202 **2.4 Experimental ~~Set – Upset - up~~**

203 We have performed 15 sensitivity experiments that differ in the initial size distribution (CTRL /
204 SMALL / BIG, Table 2), in the applied CO₂ forcing (pre-industrial =280ppm, 4xCO₂ =1120ppm,
205 ¼xCO₂ =70ppm) or in the forces that move the icebergs (atmosphere and ocean). A summary of
206 the experiments performed is given in Table 1. All runs were started from an equilibrated climate

207 and Greenland ice sheet under pre-industrial conditions that has already been used in the study of
 208 Bügelmayer et al. (2014, 2015). The ~~fact that the~~ initial ice sheet thickness is about $1/3$ bigger than
 209 the observed one ~~does not impact our results~~. We consider this bias negligible for the present
 210 study because we focus on differences between our sensitivity runs using the same initial state for
 211 all the experiments. The differences between the individual simulations are started from the same
 212 ice sheet and climate therefore independent of the initial conditions and ~~thus changes at the end~~
 213 ~~of the model runs are only due to~~ functions of the different forcing fields ~~or iceberg size~~
 214 ~~distribution applied~~. The model runs were conducted for 200 model years (pre-industrial) and 1000
 215 model years ($4\times\text{CO}_2$, $1/4\times\text{CO}_2$), respectively. The last 100 years are presented in the results.

216 2.4.1 Iceberg Dynamical Forcing

217 To differentiate between the impact of the ocean and the atmosphere, we separate the individual
 218 forcing terms of the equation of horizontal motion (Eq. 1) of an iceberg ~~is used~~:

$$219 \quad M \frac{d\mathbf{v}_i}{dt} = -Mf_k \times \mathbf{v}_i + F_a + F_r + F_w + F_p + F_s \quad (1)$$

220 with M being the Mass of the iceberg, \mathbf{v} its velocity, the first term ($-Mf_k \times \mathbf{v}_i$) on the right side
 221 corresponds to the Coriolis force, the second and third are the air drag (F_a) and wave radiation
 222 force (F_r) and therefore depend on the atmospheric winds; the last three terms represent the
 223 oceanic forcing namely water drag (F_w), horizontal pressure gradient (F_p) and sea-ice drag (F_s).

224 In the so-called “COM” experiments, the icebergs are moved according to Equation 1, thus by the
 225 combined atmospheric and oceanic forcing. In the so-called “ATM” set-up (~~Table 1~~), all the forcing
 226 terms corresponding to ocean currents are set to zero, thereby ensuring that the icebergs are only
 227 moved by the Coriolis and the atmospheric forcing. In the “OCE” set-up on the contrary, the air
 228 drag and the wave radiation force are defined to be zero, thus only the Coriolis force and the
 229 ocean currents are acting on the ~~bergs~~ icebergs.

230 The differentiation between atmospheric and oceanic forces was only made in the equation of
 231 motion of an iceberg. ~~The melting of icebergs, The mass balance (Jongma et al., 2009),~~ which
 232 depends on bottom- and lateral melt (oceanic forcing) and the wave erosion (atmospheric
 233 forcing), ~~was not altered~~ is the same in all experiments. All the experiments are described in Table
 234 1.

235 2.4.2 *Iceberg Initial Size Distribution*

236 By ~~comparing the CTRL, SMALL and BIG experiments,~~altering the initial size distribution of the
 237 icebergs we are able to investigate the ~~impact of the initial size distribution~~potential sensitivity of
 238 the atmosphere, ocean and ice sheet to iceberg sizes. In the CTRL experiments, depending on the
 239 available mass, icebergs of all 10 size classes can be generated (Bügelmayer et al., ~~2014~~2015). In
 240 the SMALL (BIG) experiments, the available mass is used to generate an equal amount of the three
 241 smallest (biggest) iceberg sizes (Table 2). ~~The differences in the resulting atmosphere and ocean~~
 242 ~~conditions as well as the ice sheet allow us to identify the different impact of the BIG and the~~
 243 ~~SMALL icebergs on the climate and the ice sheet.~~

244 2.4.3 *Radiative ~~Forcing~~forcing*

245 Using the three size distributions described in 2.4.2, we performed three sets of experiments. The
 246 first set was done under pre-industrial equilibrium conditions for 200 years. In the second one, a
 247 “high” experiment, we applied a CO₂ concentration four times as strong as the pre-industrial value
 248 (1120 vs 280ppm CO₂) and in the third, a “low” experiment, only a quarter of the pre-industrial
 249 CO₂ concentration is used (70 vs 280ppm CO₂). The ~~latter two sets of~~“high” and “low” experiments
 250 were ~~done~~conducted to analyse the effect of the size (CTRL/SMALL/BIG) distribution during
 251 periods of a strongly changing ice-sheet under non – equilibrated conditions.

252 3 *Results*

253 ~~3.1 Impact Of Forcing Fields And Initial Iceberg Size On The Transport And~~ 254 ~~Lifetime Of Icebergs (Pre-Industrial)~~

255 ~~3.1.1 The Control Experiments (CTRL-COM, CTRL-ATM, CTRL-OCE)~~

256 ~~3.1 The iceberg Impact of dynamical forcing and initial iceberg size on the~~ 257 ~~transport and lifetime of icebergs under pre-industrial conditions~~

258 ~~3.1.1 The CTRL experiments~~

259 ~~The~~ distribution of the CTRL-~~COM~~experiment~~COM's iceberg melt flux~~ displays the general
 260 transport of icebergs of all size classes due to atmospheric and oceanic forces (Fig. 1a). We find
 261 that most ~~icebergs are transported~~iceberg melt flux is distributed along the eastern and western

262 | coast of Greenland, ~~following~~displaying that the icebergs' movement follows the oceanic currents.
 263 | Further, they are moved southward along the North American coast and spread into the North
 264 | Atlantic. In the Arctic, most ~~bergsicebergs~~ are found close to Ellesmere Island as indicated by the
 265 | freshwater flux, due to the calving sites in this region (not shown) and are then widely distributed
 266 | by the Beaufort Gyre and the prevailing winds.

267 | By applying only atmospheric forcing, we find that CTRL-ATM icebergs ~~are transported~~distribute
 268 | their meltwater further into the North Atlantic and Arctic Ocean (Fig. 1d) than seen in CTRL-COM.
 269 | After calving, they are quickly pushed away from the Greenland ice sheet (GrIS) margin. -In CTRL-
 270 | ATM less ~~bergsicebergs~~ than in CTRL-COM ~~movemelt~~ along the coast of Greenland ~~as can be seen~~
 271 | ~~in the number of bergs travelling along the coast (Fig. 1d, f),,~~ highlighting the lack of ocean
 272 | currents. Overall, the amount of iceberg melt flux released in CTRL-ATM (~~mid to high latitudes:~~
 273 | ~~150~~Northern Hemisphere: 30 m³/s, please note that this is an area weighted mean) is of the same
 274 | magnitude ~~as,~~ but distributed over a broader area than in CTRL-COM ~~and over the same area~~ (Fig.
 275 | 2a). Yet, the lifetime of CTRL-ATM icebergs, that is the time (in months) it takes to completely melt
 276 | the ~~bergsicebergs~~, is up to one year shorter than in CTRL-COM (Fig. 3) because they are
 277 | transported faster away from the ice sheet and into warmer ~~conditions~~waters of the North
 278 | Atlantic.

279 | The effect of the oceanic forcing is in strong contrast to the atmospheric one as it causes the CTRL-
 280 | OCE icebergs to stay closer to the GrIS margin (Fig. 1g). The icebergs ~~movement~~melt flux reflects
 281 | the prevailing ocean currents, mainly the Beaufort Gyre, the East Greenland and the Labrador
 282 | Current. Much less icebergs are moved from the ice sheet into the Greenland – Iceland –
 283 | Norwegian (GIN) Seas and the North Atlantic in CTRL-OCE compared to CTRL-COM (Fig. 1a,g) due
 284 | to the lack of wind forcing, which is also reflected in the area that they cover (Fig. 2c,d). Also In the
 285 | Arctic Ocean the CTRL-OCE icebergs do not spread as much, but a slightly larger iceberg melt flux
 286 | (IMF) is released because the ~~bergsicebergs~~ are not transported southwards by the wind, but stay
 287 | and melt ~~in~~ there. Overall, the amount of freshwater flux is comparable to the CTRL-COM
 288 | experiment, though over a much smaller area (CTRL-COM: ~~12.4~~12.4 $\times 10^{13}$ m², CTRL-OCE:
 289 | ~~0.8~~0.8 $\times 10^{13}$ ~~1.2~~1.2 $\times 10^{13}$ m², Fig. ~~2a2b~~) and over a longer time period. The CTRL-OCE icebergs melt up to 4
 290 | months slower than CTRL-COM ~~bergsicebergs~~ because they stay close to the GrIS margin and thus
 291 | in colder water (Fig. 3).

292 | 3.1.2 *The BIG Experiments (BIG-COM, BIG-ATM, BIG-OCE) experiments*

293 | The spatial distribution of the BIG-COM icebergs displays, first, the effect of the Coriolis force since
 294 | there is an eastward movement in the North Atlantic (Fig. 1b). The Coriolis force depends on the
 295 | size and velocity of the icebergs and thus, is acting stronger on big icebergs than on small ones.
 296 | Second, the area covered by BIG-COM bergsicebergs is larger in the North Atlantic than in CTRL-
 297 | COM (Fig. 2d). Over the mid-to-high latitudesNorthern Hemisphere the area covered by more than
 298 | 10 BIG-COM icebergs is only slightly bigger than the one of- CTRL-COM (Fig.2a), even though their
 299 | lifetime is up to three years longer (Fig. 3). But in total there are less BIG bergsicebergs generated
 300 | than in the CTRL experiment because more mass is needed per berg (Table 2).

301 | Applying only wind forcing on the BIG icebergs (BIG-ATM) transports less icebergs into the North
 302 | Atlantic and especially the GIN Seas (Fig. 1e) where they cover about half the area of BIG-COM
 303 | ($4 \times 10^{12} \text{m}^2$ compared to $7 \times 10^{12} \text{m}^2$), but release the same amount of freshwater ($150 \text{m}^3/\text{s}$, Fig. 2c).
 304 | ~~The BIG-ATM icebergs are not transported as far as the BIG-COM bergs in all the regions~~
 305 | ~~considered and especially in the GIN Seas (Fig. 2c). There, the BIG-ATM bergs follow the~~ strong
 306 | southward component of the wind without being distributed keeps the icebergs from drifting
 307 | further into the GIN Seas. Similar to the CTRL experiment, the BIG-ATM icebergs melt up to two
 308 | years faster than the ones of BIG-COM or BIG-OCE (Fig. 3).

309 | The impact of oceanic forcing on the iceberg distributionmelt flux is simulated in BIG-OCE. Since
 310 | the big icebergs melt slowly, they are transported further south than CTRL-OCE bergsicebergs (Fig.
 311 | 1h). In the GIN Seas the BIG-OCE bergsicebergs are spread from the coast and cover almost the
 312 | same area as the BIG-ATM (Fig. 2c). In the Arctic Ocean the BIG-OCE icebergs release a higher
 313 | averaged melt flux than BIG-COM and BIG-ATM ($125 \text{m}^3/\text{s}$ compared to $75 \text{m}^3/\text{s}$ and $95 \text{m}^3/\text{s}$,
 314 | respectively; Fig. 2b), but over a smaller area. This is because of the missing wind forcing which
 315 | prevents the icebergs from being distributed out of the Arctic Ocean, ~~instead.~~ Instead the
 316 | bergsicebergs are stuck close to their calving sites. The higher IMF in BIG-OCE does not strongly
 317 | impact the Arctic climate because of the prevailing cold conditions. Thus, more IMF, which is
 318 | released to the ocean surface layer at 0°C and consequently cools and freshens it, does not cause
 319 | noticeable changes. —The area covered by BIG bergsicebergs over the mid-to-high
 320 | latitudesNorthern Hemisphere is clearly bigger than SMALL-, or CTRL-OCE (Fig. 2a) because of their
 321 | lifetime, which is about two years longer compared to CTRL-OCE (Fig. 3).

3.1.3 ~~The SMALL Experiments (SMALL-COM, SMALL-ATM, SMALL-OCE) experiments~~

Generating only SMALL-COM icebergs results in a similar iceberg melt flux distribution as in CTRL-COM (Fig. 1c), but less widespread. The amount of freshwater that is released by SMALL-COM bergsicebergs is almost the same over the ~~mid-to-high latitudes~~ Northern Hemisphere 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 bergsicebergs 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 meltwater distribution of SMALL-ATM is in strong contrast to the one of SMALL-OCE (Fig. 1i). The oceanic forcing restricts the icebergs' transport to the shore and due to their smaller size SMALL-OCE bergsicebergs melt before being distributed as far as CTRL-OCE and especially BIG-OCE (Fig 2a).

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

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

The resulting sea surface and air temperatures (SST, TAIR) are comparable between the CTRL-COM, ~~-ATM, and -OCE~~ experiments (Fig. 4a,b), despite the different spatial distribution of the iceberg melt flux. The biggest spread in IMF is found in the Arctic Ocean (BIG-COM: $75\text{m}^3/\text{s}$, CTRL-OCE: $150\text{m}^3/\text{s}$, Fig. ~~2b2c~~), but these differences do not result in an altered climate state due to the prevailing cold conditions that are less sensitive to the freshening and cooling effect of icebergs

351 (not shown). Also in the GIN Seas and North Atlantic the ~~SST and TAIR do not significantly differ~~
352 ~~between the experiments, even though these are sensitive areas because of the located~~
353 ~~convection sites.~~ difference in SST and TAIR between the experiments does not significantly differ
354 from internal variability (Fig. 4). In all the pre-industrial experiments, we find that the differences
355 in air and ocean temperature between the CTRL and the BIG, SMALL experiments do not
356 significantly exceed the internal variability of the CTRL experiment. This is also the case for
357 sensitive areas such as the GIN Seas or the North Atlantic, due to the located convections sites
358 there. Therefore, the impact of the dynamical forcing and initial iceberg size is smaller than natural
359 climate variability, which is also reflected in the deep ocean circulation (not shown). This indicates
360 that since the amount of freshwater released is comparable in the model runs, the exact location
361 of the release does not have a strong impact on the prevailing climate conditions- or the ocean
362 circulation. Further, the shorter lifetime of the atmospheric driven icebergs does not cause
363 differences in the resulting climate and the GrIS because the calving flux provided by GRISLI is
364 almost constant over the years and comparable in all the pre-industrial experiments. Therefore,
365 the same amount of freshwater is supplied to the ocean. Under pre-industrial equilibrium
366 conditions the atmospheric and oceanic forcing do transport the icebergs differently, but the
367 resulting spatial patterns of the iceberg melt flux cause only local differences in the Greenland ice
368 sheet volume (Table 3), ~~the oceanic and atmospheric conditions.)~~ that are within the internal
369 variability of the ice sheet.

370 ~~3.3 Impact Of Initial Iceberg Size Under A Changing Climate~~

371 3.3 Impact of initial iceberg size under a changing climate

372 To have more confidence in using the present day iceberg distribution also for simulations of past
373 and future climates, we conducted two more sets of experiments with enhanced or reduced
374 radiative forcing to obtain warmer and colder climate states. This change in radiative forcing was
375 applied through adjustment of the atmospheric CO₂ concentration in two experiments, the so-
376 called HIGH = 4xCO₂ (1120ppm) and LOW= ¼xCO₂ (70ppm), with a duration of 1000 years. For each
377 of these settings, we performed experiments with CTRL, BIG and SMALL icebergs. The HIGH
378 experiments resulted in an up to 4°C warmer global mean temperature and caused the Greenland
379 ice sheet to lose 10% of its volume, whereas the LOW experiments caused the mean global
380 temperatures to decrease about 4°C and an increase of the Greenland ice sheet volume of up to
381 4%, compared to the pre-industrial ice sheet volume (Table 3).

382 | 3.3.1 *Experiments ~~With High Radiative Forcing~~with high radiative forcing*

383 | The impact of the enhanced radiative forcing on the Greenland ice sheet is displayed in Fig. 5,
384 | where the resulting CTRL-HIGH ice sheet extensions and thickness are shown ~~compared to the~~
385 | ~~equilibrated CTRL-COM ice sheet (Fig. 5a,b)~~(Fig. 5b).

386 | As the ice sheet is shrinking and retreating from the coast (Fig. 5b), the ~~amount of~~ calving flux
387 | from the GrIS is decaying (0.003 Sv vs 0.02 Sv in the CTRL-COM), ~~which is reflected in the IMF and~~
388 | ~~the area that they cover (Fig. 2b).~~~~especially~~ ~~The strong retreat of the ice sheet~~ in South Greenland,
389 | ~~and so is~~ ~~has a direct impact on~~ the icebergs melt flux. The released iceberg melt flux in the GIN
390 | Seas is in the range of 20 (SMALL-, CTRL-HIGH) to 50m³/s (BIG-HIGH, Fig. 2c), compared to
391 | 150m³/s in the CTRL-COM. Moreover, there are hardly any icebergs entering the North Atlantic,
392 | independent of the used size distribution (Fig. 2d). In the Arctic Ocean the HIGH experiments
393 | result in a bigger spread between the CTRL, BIG and SMALL runs than any other performed set-up-
394 | (Fig. 2b). The BIG-HIGH ~~bergsicebergs~~ cover the smallest area because of the decreased calving
395 | flux much less BIG ~~bergsone~~s are generated. Further, there are still SMALL ~~bergsicebergs~~, but due
396 | to their size and the warmer conditions they melt faster than seen in the SMALL experiments
397 | performed under pre-industrial conditions. The CTRL-HIGH experiment covers a slightly smaller
398 | area than the CTRL-COM,-OCE or -ATM, but much bigger than BIG-, and SMALL-HIGH- (Fig. 2b).
399 | This is because the different iceberg sizes allow for the production of a higher number of icebergs
400 | than in BIG and the existence of icebergs bigger than size 3 (as in SMALL) allows for a longer
401 | lifetime.

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

408 | 3.3.2 *Experiments ~~With Low Radiative Forcing~~with low radiative forcing*

409 | In contrast to the experiments with high radiative forcing, the low radiative forcing causes up to
410 | 4°C lower global mean temperatures and consequently the ice sheet's volume is thickening and
411 | extending further down to the coast line (Fig. ~~5e)-5c~~), ~~especially along the western margin and in~~

412 South Greenland. Similar to the other experiments performed, the impact of different initial size
413 distributions of the icebergs is negligible on the resulting climate and ice sheet volume (Table 3).

414 Due to the increased ice sheet thickness, more calving flux is released (0.05 Sv in CTRL-LOW
415 compared to 0.02 Sv in CTRL-COM) and so the iceberg melt flux increases to $300\text{m}^3\sim 40\text{m}^3/\text{s}$ ~~in over~~
416 the ~~mid-to-high latitudes~~ Northern Hemisphere, compared to $150\text{m}^3\sim 15\text{m}^3/\text{s}$ in the pre-industrial
417 experiments. The increase is seen almost everywhere around Greenland (Fig. ~~2a,c,d2~~), except in
418 the Arctic Ocean (~~Fig. 2b~~). In the Arctic Ocean the released IMF is in the same range as in the
419 experiments performed under pre-industrial conditions because the ice sheet's thickness and
420 consequently the calving sites in North Greenland are not strongly altered by the colder climate
421 (Fig. 5c). In the North Atlantic the released iceberg melt flux displays a big spread between the
422 experiments with the BIG-LOW bergsicebergs being spread the furthest and releasing the most
423 IMF ($80\text{m}^3/\text{s}$ in BIG-LOW vs $45\text{m}^3/\text{s}$ in CTRL-LOW; Fig. ~~2b2d~~). Since the cold conditions prevent the
424 BIG-LOW icebergs from melting quickly, almost all of them are transported into the North Atlantic
425 where they finally melt. This is also partly the case for the CTRL-LOW bergsicebergs thereby
426 resulting in a higher iceberg melt flux than the SMALL-LOW (Fig. ~~2b2e~~). Independent of the chosen
427 size distribution, the resulting temperatures are about 5°C lower than during pre-industrial
428 conditions in the North Atlantic and the GIN Seas (Fig. 4), displaying the strong CO_2 forcing.

429 ~~These results show that~~ During a strongly changing climate, the used initial size distributions
430 ~~do not alter the climate response (temperatures, ocean circulation) stronger than~~
431 internal variability. The BIG-LOW set-up causes a slightly larger mean ice sheet volume at the end
432 ~~of the climate and the GIN Seas to the applied forcing. This thus~~ 1000 years (Table 3), which indicates
433 that the extreme boundary case of BIG icebergs impacts the resulting ice sheet thickness, even
434 though the climate conditions have a stronger impact on the results than the used iceberg
435 sizes are similar to the CTRL- and SMALL-LOW runs.

436 **4 Discussion**

437 By testing the impact of the atmospheric versus the oceanic forcing on icebergs' the lifetime and
438 movement motion of icebergs, we find that the atmospheric forcing causes the bergsicebergs to
439 travel further away from their calving sites and into the North Atlantic, whereas the ocean
440 currents lead to iceberg tracks closer to shore. It is difficult to compare our results to previous
441 studies, since the studies that investigated the impact of the background forcing (Smith 1993;
442 Keghouche et al., 2002) focused on observations of single icebergs and the ability of models

443 reproducing their specific tracks. Bigg et al. (1997) noted that the modelling of specific iceberg
444 tracks is very unlikely to be successful and it is important to notice that we do not expect our
445 model to resolve single tracks due to its coarse resolution, but to reflect the wide spread effect of
446 icebergs on climate.

447 In our model, the impact of icebergs on climate does not strongly depend on the two types of
448 forcing (atmospheric and oceanic), yet their lifetime is shortened by up to two years when they
449 are transported by atmospheric forces only. Bigg et al. (1997) showed that about 80% of the small
450 bergsicebergs of up to 200 m diameter (size class 1 to 3, Table 2) melt within the first year, which
451 is higher than in our SMALL-COM set-up where about 60% are melted. Also Venkatesh and El-
452 Tahan (1988) conducted a study to investigate the impact of modelling complete deterioration of
453 icebergs on the prediction of their tracks. In their study they showed that most of the icebergs
454 corresponding to size class 1 to 3 used in this study, disappear within 3 to 22 months, reassuring
455 our results. The maximum lifetime of the BIG bergsicebergs is found to be almost seven years,
456 which is slightly longer than modelled by Bigg et al. (1997). This discrepancy can be due to the pre-
457 industrial climate conditions used in our study that are slightly colder than the present day
458 conditions applied by Bigg et al. (1997).

459 To better understand the response of the modelled climate to the initial size distribution, we
460 performed different sensitivity experiments. First, using pre-industrial conditions we find that
461 independent of the forcing, SMALL icebergs release less freshwater and spread over a smaller area
462 than BIG and CTRL icebergs. In the North Atlantic the impact of the Coriolis force is especially
463 pronounced in the BIG-ATM and BIG-COM runs, confirming the findings of Roberts et al. (2014). In
464 their study they noted that BIG icebergs travel further south than small icebergs due to the
465 stronger impact of the Coriolis force. Even though the SMALL icebergs cause locally different
466 ocean and atmospheric conditions than the BIG bergsicebergs, the overall effect on climate and
467 especially on the Greenland ice sheet is negligible within the natural climate variability.

468 Second, we repeated the experiments under a strongly increased and decreased radiative forcing
469 for 1000 years. During this time scale changes in the Southern Ocean can impact the Northern
470 Hemisphere. Jongma et al. (2009) showed that including active icebergs increases the net
471 production of Antarctic Bottom Water by 10% under pre-industrial conditions. We do neglect this
472 direct effect of icebergs here since icebergs and Antarctic ice-sheet runoff are computed using
473 parameterizations that depend on the prevailing climate conditions. But Concerning the icebergs

474 ~~released from Greenland~~, we do not expect that the size of the icebergs ~~released from Greenland~~
475 have an impact on the Southern Hemisphere, ~~thus through altered ocean circulation because the~~
476 ~~Atlantic Meridional Overturning Circulation is comparable within all the experiments (not shown).~~
477 ~~Thus~~, the uncertainty introduced by not actively coupling the Antarctic ice sheet is ~~present and~~
478 comparable in all the radiative forcing experiments.

479 There might be different reasons why the climate conditions and the GrIS are not strongly affected
480 by the initial size distribution during strong radiative background conditions. One reason could be
481 that the ice sheet and the climate model are too insensitive to the experienced changes as they
482 have a relatively coarse resolution. Therefore, it would be interesting to repeat this study with a
483 finer model grid. Another reason might be that in the experiments where really strong forcing was
484 applied (HIGH=1120ppm CO₂, LOW= 70ppm CO₂), the feedbacks related to calving have a smaller
485 signal than the forcing and are therefore overruled.

486 5 Conclusions

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

490 We find that, under pre-industrial conditions, the wind forcing pushes the icebergs further away
491 from their calving sites and further into the North Atlantic, whereas the ocean currents transport
492 the ~~bergsicebergs~~ close to Greenland and southward along the North American coast. The
493 combined effect of the forces (control set-up) displays a lesser spread iceberg distribution in the
494 Arctic Ocean and into the North Atlantic than the purely atmospheric driven ~~bergsicebergs~~ due to
495 the restrictive effects of the oceanic forcing. The ~~icebergs'~~ spread ~~of icebergs~~ depends on both the
496 forcing fields and the icebergs size with the CTRL ~~bergsicebergs~~ being transported the furthest,
497 followed by the BIG ~~bergs (size class 8 to 10)-icebergs~~. The amount of released iceberg melt flux is
498 comparable in all the experiments, though locally different. In our model set-up, the biggest
499 impact of the applied forcing (atmospheric or oceanic) is on the icebergs' lifetime which is up to
500 two years shorter if the icebergs are only transported by winds.

501 In the presented model framework, the implementation of icebergs of different size classes under
502 equilibrated pre-industrial conditions reveals that there are local differences in the released

503 freshwater flux. However, these differences do not cause significant changes in the resulting
504 Greenland ice sheet volume and climate conditions.

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

508 Even though the iceberg and freshwater distribution differ between the conducted experiments
509 (all size classes, only SMALL, less than 200m width, and only BIG ~~bergs~~ icebergs, 600-1000m width,
510 respectively), their impact on the ~~northern hemispheric~~ Northern Hemispheric climate does not
511 differ ~~strongly~~ significantly from internal variability. We can therefore conclude that for the
512 resulting climate and ice sheet small spatial differences between the runs do not have a strong
513 impact as long as there is a wide spread impact of icebergs (cooling and freshening) around
514 Greenland. Furthermore, our results show that the response of the climate to the applied radiative
515 forcing is much stronger than its response to the ~~used~~ chosen initial size distribution of the
516 icebergs.

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

519 Code availability

520 The iLOVECLIM source code is based on the LOVECLIM model version 1.2 whose code is accessible
521 at <http://www.elic.ucl.ac.be/modx/elic/index.php?id=289>. The developments on the iLOVECLIM
522 source code are hosted at <https://forge.ipsl.jussieu.fr/ludus>, but are not publicly available due to
523 copyright restrictions. Access can be granted on demand by request to D. M. Roche
524 (didier.roche@lscs.ipsl.fr). The specific experimental set-up used for this study is available at
525 <https://forge.ipsl.jussieu.fr/ludus>.

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650

651 LIST OF TABLES

	PRE-INDUSTRIAL (ATM & OCE FORCING) = 280 ppm	ONLY ATMOSPHERIC FORCING	ONLY OCEANIC FORCING	4xCO ₂ (ATM & OCE FORCING) = 1120ppm	½xCO ₂ (ATM & OCE FORCING) = 70ppm
ALL SIZES	CTRL-COM	CTRL-ATM	CTRL-OCE	CTRL-HIGH	CTRL-LOW
BIG BERGSICEBERGS	BIG-COM	BIG-ATM	BIG-OCE	BIG-HIGH	BIG-LOW
SMALL BERGSICEBERGS	SMALL-COM	SMALL-ATM	SMALL-OCE	SMALL-HIGH	SMALL-LOW

652 Table 1: performed experiments

CLASS	HEIGHT (m)	WIDTH (m)	VOLUME (m ³) 1E+05	PERCENTAGE FRACTION of total available Volume	EXPERIMENT
1	67	67	5.16E0516	0.15 / 0.33	CTRL / SMALL
2	133	133	4.07E0607	0.15 / 0.33	CTRL / SMALL
3	200	200	1.38E07138	0.2 / 0.33	CTRL / SMALL
4	267	267	3.28E07328	0.15	CTRL
5	300	333	5.74E07574	0.08	CTRL
6	300	400	8.28E07828	0.07	CTRL
7	300	500	1.29E041297	0.05	CTRL
8	300	600	1.86E081860	0.05 / 0.33	CTRL / BIG
9	300	800	3.31E083310	0.05 / 0.33	CTRL / BIG
10	300	1000	5.18E085180	0.05 / 0.33	CTRL / BIG

653 Table 2: used initial iceberg classes

654

Experiment ICE SHEET THICKNESS	Mean (1E+15)	STDEV (1E+12)	%-diff-Difference (1E+12)	Difference in %
CTRL-COM	3,90E+15.90	2,53E+124.04*	-	-
BIG-COM	3,91E+15.91	2,61E+12.61	-3.50	-0,7.09
SMALL-COM	3,91E+15.91	1,96E+12.96	-2.97	-0,7.08
CTRL-ATM	3,91E+15.91	1,90E+122.79*	-	-
BIG-ATM	3,91E+15.91	2,14E+12.14	-2.58	-0,7.02.07
SMALL-ATM	3,91E+15.91	1,99E+12.99	-0,06.430	0,01
CTRL-OCE	3,91E+15.91	2,11E+123.18*	-	-
BIG-OCE	3,91E+15.91	1,29E+12.29	-1.20	-0,7.03
SMALL-OCE	3,91E+15.91	2,20E+12.20	-5.63	-0,7.14
CTRL-HIGH	3,50E+15.50	5,03E+12.03	-	-
BIG-HIGH	3,49E+15.49	4,40E+12.40	11.0	0,7.32
SMALL-HIGH	3,49E+15.49	5,69E+12.69	4.82	0,7.14
CTRL-LOW	4,04E+15.04	1,90E+12.90	-	-

Icebergs in a fully coupled climate model

BIG-LOW	4,06E+15.06	2,74E+12.74	-16.6	-0,41
SMALL-LOW	4,04E+15.04	3,20E+12.20	-1.85	-0,05

655

656 Table 3: Ice-sheet Volume (m³): Mean and Standard deviation of last 100 years, the *corresponds
 657 to the CTRL stdev that was computed over the last 200 years to have a more representative range
 658 of internal variability as a reference; difference between the ice sheet volume of the CTRL
 659 experiment and the BIG/SMALL experiments in absolute numbers, if the value is above 2*stdev of
 660 the CTRL experiments (*), then the difference is significantly different from internal variability
 661 (none of the experiments); % diff =– difference between the ice sheet volume of the CTRL
 662 experiment and the BIG/SMALL experiments in percent.

663 FIGURE CAPTIONS

664 ~~Figure 1: Number of icebergs passing by a grid cell per year (icebergs that are grounded are only~~
 665 ~~counted once~~Figure 1: Iceberg melt flux (m³/s); first row: atmospheric forcing only (CTRL-, BIG-,
 666 SMALL-ATM); second row: oceanic forcing only (CTRL-, BIG-, SMALL-OCE), third row: the default
 667 set-up (icebergs are moved by both, atmospheric and oceanic forcing; CTRL-, BIG-, SMALL-COM)

668 Figure 2: area (m²) vs area weighted iceberg melt flux (m³/s-); the area is computed by taking into
 669 account all the ~~gridcells~~grid cells that ~~are passed by more than~~have at least 10 icebergs passing
 670 through per year (be aware that the area is 10¹³m² in panel a), 10¹² m² otherwise); a: ~~Mid to High~~
 671 ~~Latitudes~~Northern Hemisphere: mean computed over 40-90°N and 80-180°W-15-180°E, values of
 672 IMF: ~~30-180 m~~30-40m³/s; (area weighted IMF); b: Arctic Ocean: 80-90°N and 180°W-180°E, values
 673 of IMF: 60-140 m³/s; c: Greenland – Iceland – Norwegian (GIN) Seas: 50-85°N and 45°W-15°E,
 674 values of IMF: 40-240 m³/s; d: North Atlantic: 45-60°N and 60-20°W, values of IMF: 0-50 m³/s;

675 Figure 3: cumulative ~~percentage~~iceberg melt distribution normalized to 100% as a function of
 676 ~~icebergs melted within a certain time;~~ (months); x – Axis corresponds to months, y-axis to
 677 cumulative percentage

678 Figure 4: Mean + Standard deviation of last 100 years of the performed experiments: Sea Surface
 679 Temperature (SST, °C) and air temperature (TAIR, °C); red = BIG ~~bergs~~icebergs, blue = CTRL, green
 680 = SMALL ~~bergs~~icebergs; a: North Atlantic: mean computed over: 45-60°N and 60-20°W; b:
 681 Greenland – Iceland – Norwegian (GIN) Seas: 50-85°N and 45°W-15°E

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