We have revised our manuscript 'Last Interglacial climate and sea-level evolution from a coupled ice sheet-climate model'.

We would like to thank all four reviewers for their constructive comments that helped to improve the manuscript.

Please find below the reviewer's comments in regular italic and a point-by-point rebuttal in bold font.

Reviewer 1

General comments:

The submitted manuscript by Goelzer et al. investigates a new transient simulation of the last interglacial (LIG) period with a bi-directionally coupled climate-ice sheet model. More precisely, the authors use LOVECLIM1.3, an earth system model of intermediate complexity including interactive components for Greenland and Antarctica, i.e., the solely remaining ice sheets during the LIG. Consequently, the focus of the paper lies on climate and ice sheet changes in Greenland and Antarctica and the resulting sea level evolution throughout the LIG. The simulation is compared to previous experiments which exclude ice sheet changes or use a one-way coupling approach. Furthermore, they analyze different sensitivity experiments where specific climate processes are modified or omitted in the experimental setup. The main result of the paper is that the evolution of the Greenland ice sheet (GrIS) is dominated by changes in the surface mass balance whereas the Antarctic ice sheet (AIS) is mainly governed by melting of the shelf area driven by sea-level rise and reduced ice shelf viscosity in a warming climate. A valuable outcome of the model effort is also the temporal and spatial evolution of both the GrIS and the AIS generated within the same climate-ice sheet simulation and thus a consistent experimental setting.

The baseline of the paper is the remarkable technical effort to produce a fully-coupled climate-ice sheet model simulation for the LIG, i.e., a simulation which allows feedbacks between all components of the climate system and hence somewhat represents the "best possible estimate" of the LIG climate with a modeling approach. To my knowledge, the simulation is the first of its kind for the LIG and certainly a valuable contribution for the paleoclimate science community. However, in the present manuscript I am missing a comparison of the simulated climate with proxy records, at least for the two key regions Greenland and Antarctica, as this comparison would have the role of an evaluation of the novel model setup. Moreover I expect a more critical discussion of the chosen model approach regarding remaining improvements and challenges.

Concerning the formal aspects, I think the manuscript needs to be improved in several aspects. Whereas Sections 1-4 are mostly well-written, the results

(Section 5) are sometimes hard to follow and need a revision to become more complete and comprehensive. Some figures are only partly described and very poorly referenced in the text (Table 1 is not mentioned a single time in the text). As you will see, I have many minor comments where I feel the language could be more precise to make the manuscript more reader-friendly.

We thank the reviewer for the detailed comments that we have all considered for the revised version of the manuscript. Please find our response to the individual comments below.

Please find below the full list of major and minor issues.

Major issues:

1. Critical discussion of experimental setup

As stated above I expect a section which critically reflects on the quality of your model setup. I think as much as your reference simulation deserves credit for having a pioneering role as a fully-coupled simulation of the LIG it asks for a discussion of its strengths and weaknesses as well as of remaining challenges and possible improvements. This additional section could be in form of a "discussion" or an "outlook" section which both are non-existent at the moment. The discussion should also include a comparison to Helsen et al. 2013 CP, who previously assessed the GrIS retreat during the LIG with a bi-directionally coupled model approach.

We have included a new discussion section to discuss in more detail comparison with former work (including the mentioned reference), limitations of the model and possible improvements. Please find details in response to individual comments.

Regarding modeling the climate in Greenland I further wonder if your setup includes the relevant feedbacks on temperature and precipitation found in response to a retreating Greenland ice sheet (Merz et al. 2014 CP, Merz et al, 2014 JGR, Hakuba et al. 2012 JGR). I suspect that the limited spatial resolution of the EMIC in the atmosphere (T21) might be a problem here. Furthermore, the authors should address the use of the positive-degree-day method (PDD) for the ice sheets as this is a serious issue for the LIG as shown by van de Berg et. al. 2011 NatGeo.

Feedbacks arising from the coupling between ice sheets and climate are in principle included in the model, in particular the albedo-temperature feedback for a retreating ice sheet and for changing surface properties due to surface melting. However, resolution of the atmospheric model is indeed a limiting factor, a so far unavoidable side effect of running a fully coupled model for several thousands of years. The katabatic wind effect discussed by Merz et al. (2014) is therefore likely underrepresented. A quantification of how much the feedback strength depends on spatial resolution of the

climate model would be an interesting study, but is not something we can add to with our model set-up.

Possible limitations of the model due to its spatial resolution and of the applied PDD scheme are now discussed in a new discussion section in the manuscript:

"A so far unavoidable side effect to running a fully coupled model for several thousands of years is the limited horizontal resolution of the atmospheric model. The katabatic wind effect discussed by Merz et al. (2014) and other small-scale circulation patterns are therefore likely underrepresented. A quantification of how much the strength of ice sheet-climate feedbacks depends on spatial resolution of the climate model would be an interesting study, but is not something we could add to with our model set-up.

The applied PDD scheme has been extensively validated with results of more complex Regional Climate Models for simulations of the recent past (e.g. Vernon et al., 2013), but several studies point to limitations of this type of melt model when applied for periods in the past with a different orbital configuration (e.g. van de Berg et. al., 2011; Robinson and Goelzer, 2014). Their results indicate that the stronger northern summer insolation during the LIG should result in additional surface melt on the Greenland ice sheet compared to simulations based on temperature changes alone. We note that this suggests an underestimation of LIG melt with the PDD model and increased melt if it was corrected for. Thus, including an additional melt contribution due to insolation would further increase the contrast of the NEEM paradox in our simulation. Our modelling therefore provides no arguments to support the contention that the limited LIG warming implied over Greenland would be indicative of an overly sensitive ice sheet and mass balance model."

2. Scaling factor

You use the scaling factor (described on lines 192-203) as a necessary tuning factor to avoid a complete loss of the Greenland ice sheet during the LIG. I wonder if the scaling factor is necessary due to the simplified representation of the climate in LOVECLIM over Greenland as I guess that the climate-ice sheet feedbacks previously mentioned in major issue 1 (described in Merz et al. 2014 CP, Merz et al, 2014 JGR, Hakuba et al. 2012 JGR) are probably not included.

Our understanding is that the predominant (temperature-related) feedbacks that are discussed in the mentioned publications and have an impact on the scaling are included in our model. Furthermore, any missing positive feedback, especially if acting in the summer, would further increase the need for scaling we have encountered. Hence, the scaling is needed in any case. See also response to the point before.

How do you feel that this artificial control affects your result concerning Greenland ice sheet evolution and consequently its contribution to the LIG sea level?

It is clear that the scaling has a large effect on the sea-level contribution and that it strongly limits the predictive capability of the model in this regard. We have clarified that further in the manuscript:

"Instead, the applied scaling of the temperature anomaly forcing for the GrIS is a necessity to keep the ice sheet from losing too much mass during the warm period and to maintain ice sheet retreat to within limits of reconstructions. Clearly, this implies a limited predictive capability of our model, which is now forced to comply with the given constraints on minimum ice extent during the LIG. However, the Antarctic simulation would not be strongly affected by changes in the melt model due to the limited role of surface melting for the evolution of the AIS during the LIG."

Do I understand it correctly that no scaling factor is applied for the Antarctic ice sheet?

Yes, correct. We have not identified a physical process that would justify a similar procedure for the Antarctic ice sheet. Since surface mass balance changes have generally a minor effect for the AIS, we would also not have constraints that could be used to evaluate a scaling on the AIS. See also text above.

Another clarifying sentence has been added to the text:

"The scaling is only applied for the GrIS, since we have not identified a physical process that would justify a similar procedure for to the AIS."

Line 274: I think you should state clearly here that the choice of the scaling factor crucially affects the contribution of the GrIS to the sea-level high stand of the LIG.

OK, made that explicit:

"For the two sensitivity experiments (High, Low) with modified scaling (R=0.5, 0.3), the contribution changes to 2.7 m and 0.65 m, respectively, crucially controlled by the scaling factor (Table 2). "

3. Additional part describing all (sensitivity) experiments

Currently, the manuscript presents results from various sensitivity experiments at different occasions, which makes it hard for the reader to keep the overview. Therefore, it would be much more reader-friendly to add a subsection to Section 4 describing all (sensitivity) experiments and their purpose. I think this subsection could be complemented with a respective list in a table.

OK. We have included a new section 4.2, which describes the reference and sensitivity experiments with reference to a new table that lists all discussed experiments.

I further advise to clearly state in the text that you define the two-way coupled simulation as "reference". Similar definitions might be worth for the stand-alone experiments etc. Make sure that you use these terms consistently in all text and figures.

OK. We have defined the reference simulation in a new section 4.2 as suggested and now consistently refer to "reference" throughout the text. Standalone experiments are now consistently referred to as "forced".

4. Extended analysis/description of results

I think the manuscript would greatly profit from an extended analysis and some additional figures in order to present a complete picture of your two-way coupled simulation rather than just showing selected aspects.

Specifically I request:

As I like Figure 3 showing the gained value of the two-way coupling, I think a similar figure for temperature in Greenland and Antarctica would be highly appreciated as these two regions are the main areas of interest in your paper.

We have now included additional figures (S1, S2) for Greenland and Antarctic temperature evolution in comparison with ice core records. These are discussed in the new version of the manuscript.

Moreover, I am missing a clear statement in the text regarding the results shown in Fig. 3: (i) the simulation with two-way coupling only marginally differentiates from the simulation with one-way coupling with respect to global mean temperature throughout the LIG. (ii) Excluding ice sheet changes and freshwater forcing as done in the noIS simulation leads to a decreased glacial-interglacial temperature contrast and an earlier warming going into the LIG. However, there is only a small difference to the one-way and reference simulation after ca. 128ka! I wonder whether the latter result also applies for temperatures in Greenland and Antarctica?

For a discussion of the temperature response over the ice sheets, see response to previous comment. We have extended the interpretation and discussion of Figure 3 following the reviewer's suggestion. The section now reads as follows:

"The fully-coupled experiment exhibits a global mean temperature evolution during the LIG, which is very similar to One-way (Figure 3). A much larger temperature contrast at the onset of the LIG in the reference experiment compared to noIS arises mainly from changes in surface

albedo and melt water fluxes of the Northern Hemisphere ice sheets, which freshen the North Atlantic and lead to a strong reduction of the Atlantic meridional overturning circulation (Loutre et al., 2014). All three simulations show only small differences in the global mean temperature evolution after 127 kyr BP. "

In order to evaluate your two-way simulation against data I strongly suggest a comparison of the simulated Greenland and Antarctic temperature evolution with respective ice cores (e.g., NEEM, EPICA). As the NEEM delta18O-based temperature reconstruction likely assumes an overestimated delta18O-temperature relationship you could also include the NEEM temperature curve based on the recent delta18O-temperature relationship presented in Masson-Delmotte et. al. 2015 Cryosphere.

Comparison with ice core data is included in the additional figures (S1, S2) showing the temperature response over the ice sheets. See previous comments.

It might also be worth to show the evolution of the freshwater fluxes throughout the LIG to complement your findings presented at Line 353pp and Line 429pp.

We have instead added a reference to Goelzer et al. (2016), where the climate response to freshwater forcing is discussed in more detail (line 353pp in the manuscript). We estimate that the discussion on thermal expansion (line 429pp) does not warrant a new figure and we have kept the (not shown) there.

5. Mass balance of Greenland and Antarctic ice sheet

I think a proper definition of the (surface) mass balances for the Greenland and the Antarctic ice sheet is required. Please clearly state what you refer to as accumulation, ablation, runoff, (surface) melting, calving flux and how they combine to the mass balance. Please use the same terms in the text as in the axis labels of Figs. 4 & 7.

We have revised the manuscript to be consistent in our terminology and have e.g. replaced all occurrences of "ablation" by "runoff".

We have also added a reference to Huybrechts et al. (2011), where the mass balance components of the ice sheet models are described in detail.

I think it would be a valuable addition to show the net mass balance as a further panel in Figs. 4 & 7 so the reader can reconstruct the evolution of the ice volume shown in Figs. 4e and 7e. Whenever possible use the same scales for the different terms of the mass balance in Figs. 4 and 7.

We have included additional panels in Figures 4 and 7 that show the net mass balance. Display of the different variables on the same scale would

render the panels difficult to read, because of the different magnitudes (no change).

6. References to figures in text

Throughout the paper I miss many references to the corresponding figures, which would substantially help the reader to understand the descriptions in text-form. Please be more precise when discussing panel plots, e.g. put reference to Fig. 4a rather than just to Fig. 4.

We have revised the entire manuscript to include sufficient and precise referencing to figures and individual panels.

Some examples of missing/imprecise figure references:

Line 365: Fig. 7b

OK.

Line 375: Fig. 7a,d

OK.

Line 382: Fig. 7d

OK (Fig. 7e).

Line 393: Fig. 9b after "experiments"

OK, included in next sentence.

Line 402: Fig. 7a and 2c

OK.

Line 427: Fig. 3 after "evolution"

OK.

Line 445: Fig. 10c

OK.

Line 446: Fig. 10b

OK.

Minor issues:

Lines 23: Please be more specific than "surface mass balance changes"

OK. Specified surface meltwater runoff as the governing component.

Lines 24-25: "Our results indicate" could be replaced with "The comparison of fully-coupled with stand-alone Greenland ice sheet simulations emphasizes"

Not changed.

Line 68: change "lower bound of 5.5m" to "lower bound of Eemian sea level rise of 5.5 m above present-day levels"

OK, changed to:

"lower bound of 5.5 m for the LIG sea-level high-stand"

Lines 75-78: This sentence is misleading as it implies that any Southern Ocean warming is induced by the interhemispheric seesaw effect.

OK, added "possibly" to allow for other interpretations.

Line 104: Wrong reference: Robinson et al. 2011's ice sheet model uses output of a transient EMIC simulation as input but does not give feedback to the climate model. Helsen et al. 2013 CP would be a more appropriate reference here.

The reference is correct as confirmed by the comment from reviewer 3 (cp-2015-175-RC4). We have included a reference to Helsen et al. (2013) as another example of a transient LIG simulation of the GrIS.

Line 111: "climate and oceanic conditions over the ice sheets and in their proximity" seems not to be a correct/precise statement.

OK, removed "over the ice sheets and in their proximity".

Lines 109-118: Whereas I like the rest of the introduction, this last paragraph should be improved to better stress the focus and strategy of the paper. I think you should highlight here that you generate the first transient simulation of the LIG with a bi-directional coupling of climate and GrIS/AIS model components. Furthermore, please clarify that you study key mechanisms and feedback processes with the aid of sensitivity experiments and with the comparison to one-way coupled and stand-alone ice sheet simulations. I would also state here that you focus on climate and ice sheet changes in Greenland and Antarctica and the resulting sea-level evolution throughout the LIG.

OK. We have extended the last paragraph of the introduction following the reviewer's suggestions.

“Here, we present modelling results from the first fully coupled climate-ice sheet simulation of the LIG period (135 kyr BP to 115 kyr BP) using ice sheet models of the GrIS and AIS and a climate model of intermediate complexity. In this set-up LIG sea-level evolution and climate-ice sheet interactions can be modelled in a consistent framework. With focus on climate and ice sheet changes in Greenland and Antarctica and corresponding sea-level changes, we compare results from the fully coupled model to former climate simulations with prescribed ice sheet changes and uncoupled ice sheet experiments.”

Lines 170-171: specify “ice loading changes” e.g., with “ice loading changes coming out of the penultimate glacial period”.

OK. Modified as suggested.

Line 184-191: You use the sea-level reconstruction by Grant et al. 2012 as boundary condition for your simulations. Wouldn’t it be more consistent to use the “internal” sea level corresponding to the simulated global ice sheet changes?

What would be the consequences for the melting of the AIS which apparently most strongly responds to sea level changes? What are the reasons for driving the model with a respective sea-level reconstruction instead?

Ultimately, it would indeed be desirable to apply a consistent ‘internal’ sea-level forcing. However, there are a number of complications that led us to use a prescribed forcing. 1) The predominant sea-level forcing is the NH contribution, which we currently do not model prognostically. 2) The GrIS and AIS models need forcing well before the modelled period for the spin-up, which would require some sort of anomaly method. 3) For the AIS, where sea-level change is a dominant forcing and the AIS contribution itself would have to be accounted for, regional sea-level changes would also need to be estimated.

Line 205: introduce the abbreviation “(SA)” here.

We have revised the terminology and now consistently refer to the additional experiments as “forced” experiments. The term “stand-alone” is only used for former experiments and ice sheet model runs in the spin-up.

Line 215: The title of this subsection could be more specific, e.g., “Initialisation of the reference simulation”

OK.

Line 241: might be more precise to replace “importance of ice sheet changes” with “importance of two-way coupling between the climate model and the ice sheet models for the GrIS and the AIS”

Not changed. Comparison here includes a case without NH ice sheet forcing, thus not limited to GrIS and AIS.

Line 247-251: This finding is somewhat hard to understand. May be it would help if you show the freshwater fluxes in a figure (as also requested in major issue 4) and put a respective reference.

These results are largely based on mechanisms well documented in the studies of Loutre et al. (2014) and Goelzer et al. (2016). We have made that clear in the text and added the references again.

Line 264: Rather put the reference to Fig. 4e here.

OK. Modified to include references to both Fig. 5 (showing the retreat) and Fig. 4e (showing the volume and area change).

Lines 334-336: I think you could add here that the ice-albedo feedback is a positive feedback.

OK.

Line 351pp: “The warming necessary....” This sentence is not easy to comprehend. Please revise.

OK, passage revised:

“The warming before the peak is around a factor two faster than the cooling afterwards, with both transitions being near linear on the millennial time scale. ”

Line 365: show the freshwater fluxes in a figure or add (not shown) after “hemispheres”.

OK, added “not shown”.

Line 367: You speak of “ablation” but in Figure 7 you name it runoff – is this the same? Please be consistent with all terms describing the mass balance of the GrIS and the AIS (see also major comment 5)

OK. We have replaced “ablation” by “runoff” everywhere in the manuscript.

Line 376: add (not shown) after “130 kyr BP”.

OK, added “(not shown)”.

Line 380: add (not shown) at end of sentence or put a reference to Goelzer et. al. 2015.

OK, included reference to Goelzer et al. (2016).

Line 418-419: Is "their model" equal to the simulation you termed "one-way" at other occasions in the script?

Yes, modified the text accordingly:

"The main retreat in their one-way coupled climate model run happened ~129.5 kyr BP, a timing predating the time of retreat in the fully coupled model by ~2 kyr due to the difference in atmospheric and oceanic forcing."

Line 470-472: I think this sentence should be rephrased to state more clearly that you artificially limit the melting of the GrIS to conform to existing ice core constraints.

OK. Added some clarifications to describe this limitation:

"However, this result is strongly controlled by the need to scale the climate forcing to match existing ice core constraints on minimal ice sheet extent. This shortcoming in our modelling reflects the NEEM paradox, that strong warming over the ice sheet coincides with limited mass loss from the GrIS, indicative of a fundamental missing link in our understanding of the LIG ice sheet and climate evolution. "

Line 477-478: Please be more specific. I think "ice-climate feedback" is a too general term for a take-home message in the conclusions.

OK. reformulated:

"The treatment of albedo changes at the atmosphere-ice sheet interface play an important role for the GrIS and constitute a critical element when accounting for ice sheet-climate feedbacks in our fully-coupled approach."

Line 482: I think it should also be stated here that an unconstrained fully-coupled climate-ice sheet simulation does not fully agree with data, e.g., the GrIS would melt away completely during the LIG. This implies deficiencies in the model physics or unknown/excluded processes. It also emphasizes the NEEM paradox of strong warming coinciding with limited GrIS melting that can hardly be understood in a model perspective.

We have included statements in the conclusion following the suggestion of the reviewer. Please see response to comment for Line 470-472 above.

Table 1: Needs to be discussed in the text or should be removed.

OK, now referring to Table 1 in two places in the results section, where the results in Table 1 were already discussed.

Figure 1: The references (Opsteegh et al. 1998, Brovkin et al. 1997 and Goosse and Fichefet, 1999) mentioned in Fig. 1 should also be added to the reference list.

OK, references included.

Fig. 4b,c,d: Does the horizontal stippled line represents the pre-industrial level? Please clarify in figure caption.

Yes, have included a clarification:

“Horizontal dashed lines give the pre-industrial reference values.”

Fig. 6b: This schematic is somewhat difficult to comprehend and it is only mentioned once in the text. Should be revised or removed.

Most of the last paragraph of 5.1 is relying on this schematic, which aims to illustrate the main controls on albedo changes in the model. We prefer to keep it in.

Figure 7d and text: Is there a difference between shelf melting and sub-shelf melting? Please be consistent in text and figures

OK, we now consistently refer to sub-shelf melting throughout the manuscript.

Figure 9b: Does the blue curve represent the experiment with excluded surface AND sub- shelf melting or just the latter? In line 392 you mention both. Please revise to be consistent in text and figures.

OK. The blue curve denotes an experiment with no sub-shelf melting. Added clarifications in the figure caption and in the text.

Figure 10: please number the panels with a,b,c. Furthermore, the figure caption should include additional information, e.g., the meaning of the stippled lines.

OK, added panel indicators (a,b,c) and description of the median and percentiles.

Technical corrections:

Line 89: remains

OK.

Line 96: van de Berg

OK.

Line 256: “is retreating” rather than “has retreated”

No change. Surface melt water runoff is the dominant mass loss for a predominantly land-based ice sheet because the calving flux is close to zero.

Line 379: a weakening

OK.

Caption of Fig. 8: move listing of (a), (b), (c) in front of description as done in all other figure captions.

We have added alphabetic panel indicators in all multi-panel figures and now consistently refer to panels in the captions with in-line indicators.

Reviewer 2

This study assesses the Last Interglacial climate and ice sheet evolution in a two-way coupled approach. The novelty is in the fully coupled method. Especially promising is the simulated evolution of both the Greenland and the Antarctic ice sheet in one overarching climate-ice sheet framework, which allows for assessing their relative contributions to the global mean sea-level highstand during the Last Interglacial. As such the study is interesting as should be published. However, some parts are unclear and lack information and/or discussion.

Please discuss the comments below before publication in CP.

Many thanks for the detailed comments that have helped to improve the manuscript. Please find our answers to the comments below.

<u>*GENERAL COMMENTS*</u>

1) Sea-level forcing from a Red Sea record is prescribed. Are the simulated sea-level changes from the Greenland and Antarctic ice sheet somehow added to this during the simulation?

No. Interpreted as a global sea-level record, the Red Sea record already includes the contributions of the ice sheets. See also discussion of point by reviewer 1 (Line 184-191).

How certain is the Red Sea record? And how much does it affect the sea-level contributions of the two ice sheets and the total sea-level changes simulated? The discussion on this (lines 420-424) is too short.

The sea-level contribution of the GrIS is largely independent from the sea-level forcing. For the AIS, however, a comparison with a sea-level forcing based on a benthic δ18O record shows a large influence on the timing of the WAIS retreat. We have not attempted to formally quantify the uncertainty associated with the sea-level forcing but note that there are large uncertainties in the timing. This was already described in the manuscript, but we have included clarifications to improve on that point:

"It is noteworthy in this context that the prescribed sea-level forcing imposes an important control for the timing of the Antarctic retreat and is a source of large uncertainty. We have only used the central estimate of the Grant et al. (2012) sea-level reconstruction, but propagated dating uncertainties could accommodate a shift of the forcing by up to 1 kyr either way."

2) Related to this: Would it be possible to fit your model results better to the Kopp et al. (2009) reconstructions if uncertainties in the Red Sea sea-level record are included, or if you use the benthic d18O-stack? In other words can you suggest improvements to the NH ice sheet retreat records, based on the comparison between your simulations and the Kopp reconstructions?

As suggested in response to the previous comment, uncertainty in the age model of the Grant et al. sea-level reconstruction could in principle be used to force the AIS to an earlier retreat, better in line with the Kopp reconstructions. We have not attempted that, since other uncertainties, in particular in the climate forcing are large and do not warrant to attempt a precise chronology. Conversely, using the benthic d18O-stack would lead to a later retreat of the AIS and thus increase the mismatch to the Kopp reconstruction.
We have included a discussion item of similar content in the text.

Earlier work (Loutre et al., 2014; Goelzer et al., 2016) has shown that the NH ice sheet reconstruction based on Lisiecki and Raymo (2005) is preferable to other reconstructions. We refer to these publications, with detailed discussion on this aspect.

In both cases (AIS and NHIS) the climate response (to ice sheet retreat and resulting FWF) was our main guideline in evaluating model performance, which renders comparison to the Kopp et al. (2013) an additional, independent validation, rather than a tuning goal in itself.

3) Why is the temperature forcing over Greenland so high that it melts away the Greenland ice sheet entirely? What are the summer and annual mean temperature anomalies for the Last Interglacial? Please compare and discuss this with respect to proxy data, and previous climate model simulations (see e.g.

Bakker et al. (2013) and Lunt et al. (2013) for global intercomparisons). The method of uniform scaling is a bit eccentric, and needs better argumentation.

Please compare response to comment 4. of reviewer 1.

4) Related to this: the experimental set-up misses a section that describes how the simulated temperatures (and accumulation) are converted to (surface) mass balance. Which scheme do you use? With which parameter settings? The latest studies simulating the Last Interglacial Greenland ice sheet evolution show that differences in parameter settings have a huge effect on how much the ice sheet melts (e.g. Robinson et al., 2011; Stone et al., 2013; Langebroek and Nisancioglu, 2016).

We have added a description of the surface mass balance treatment in the model description. The model parameters remain unmodified from earlier studies with the same model (e.g. Huybrechts et al., 2011) and have been extensible validated against other SMB models (e.g. Vernon et al., 2013). See also next point:

"The surface mass balance model is based on the positive degree-day (PDD) method (Janssens and Huybrechts, 2000) and distinguishes between snow accumulation, rainfall and meltwater runoff, all parameterized as a function of temperature. Surface melt is estimated based on two distinct PDD factors for ice and snow and may be retained and refreeze in the snow pack. Melt model parameters are unmodified compared to earlier studies (Goosse et al., 2010; Huybrechts et al., 2011) and have been extensively validated for the present day (e.g. Vernon et al., 2013)."

5) These studies validate their ice sheet model results to the present-day observed ice sheets. I think this is what you need to do as well. Compare your present-day or pre-industrial climate and ice sheet configuration to observations and discuss the differences. This will validate the model set- up, and increase confidence in your model results.

The same has been done for our model in earlier studies (e.g. Huybrechts and de Wolde, 1999). For the GrIS the model has been validated recently for present day simulations (Fürst et al., TC 2015) with parameters very close to the ones in our study.
We have included figures of the simulated present day configurations of both ice sheets at the end of this rebuttal for information. Since our focus in this study is the LIG and large-scale changes in the ice sheets, we estimate that a close match to present-day observations is less of an issue and we would not include these figures in the manuscript.

How do you deal with the differences between the atmospheric and ice sheet model grids?

The ice sheet models are forced in anomaly mode. We have included additional information in the model description:

“Climate anomalies are interpolated to the ice sheet grids using Lagrange polynomials and the SMB-elevation feedback is accounted for natively in the PDD model on the ice sheet grid.”

6) Also for Antarctica some discussion is lacking:

a. Lines 375-380: Can you show model “evidence” for the see-saw effect taking place in your model results? E.g. assess Atlantic meridional ocean circulation or heat transport. Do they really decrease?

This result pertaining mainly to the climate response to the NH freshwater forcing is discussed in Goelzer et al. (2016) and not repeated here. A reference has been added in the text.

b. Lines 381-390: What do you mean with “overshoot behaviour”? Is the Antarctic ice loss not related to the positive temperature anomaly? Which part is overshoot?

The main mass loss from the AIS in that period is due to grounding-line retreat, not due to surface melting. The overshoot behaviour discussed in the manuscript concerns this mechanism. Please see also response to comment 5, reviewer 3.

c. Also, how does the present-day/pre-industrial simulated Antarctic ice sheet look like? Is this not too sensitive to the temperature forcing, as is the case for Greenland? So in other words, no correction is needed for the temperature forcing over Antarctica?

No correction needed. See response to comment reviewer 1.

d. Lines 391-402: these sensitivity experiments need more explanation, and a reference to Figure 9b.

We have included an additional sub-section 4.2 in the Experimantal setup to extend the description of the sensitivity experiments.

OK, reference to Figure 9b included.

7) The Section about freshwater input and thermal expansion of the ocean is very interesting, but also lacking information. How large is the freshwater input (Sv) and how long do the episodes take? Another figure or table would be useful.

See response to similar comment by reviewer 1.

8) Concerning the "double" peak in the Kopp reconstruction: Do you have suggestions why your model results do not reproduce this? Is it because of too constant the climate forcing, too slow regrowth of the ice sheets, or other missing feedbacks? Please discuss.

Our model results do not provide evidence for a double peak, mainly because the forcing does not show such variations. However, while the median projections in Kopp et al., (2009) visually suggest a double-peak structure, the uncertainty range is wide enough to accommodate a global sea-level trajectory without intermediate low stand. Our discussion in the manuscript has been extended in that regard to clarify that we are not convinced reproducing a double peak structure is a necessity:

"While the median projections in Kopp et al., (2009) visually suggest a double-peak structure in the global sea-level evolution during the LIG, our results show that the uncertainty range is wide enough to accommodate a global sea-level trajectory based on physical models without intermediate low stand. The simulated climate forcing in our case does not favour the presence of such variability, which admittedly could be due to missing processes or feedbacks in our modelling. Nevertheless, based on our own modelling results and the Kopp et al., (2009) reconstruction we are not convinced reproducing a double peak structure is a given necessity."

SPECIFIC AND TECHNICAL COMMENTS

1) Greenland and Antarctic ice sheets are abbreviated in line 59, please use these abbreviations in the remainder of the text

OK, used abbreviations consistently throughout the text.

2) A bit more information on the coupling procedure is necessary (Section 4.2). How often do they interact or are the components updated, every day/year/1000 years?

No change. This information is already present in section 3.

3) Lines 275-293: You can also use the reconstructed limits for the Last Interglacial surface elevation change at the ice core locations compared to PI (e.g. NGRIP-members, 2004, Johnsen and Vinther, 2007, NEEM community members, 2013) to evaluate your model results.

In our estimate reconstructed elevation changes are highly uncertain. This was already mentioned in the text.

"Elevation changes from that ice core are however not very well constrained and even if they were, would leave room for a wide range of possible retreat patterns of the northern GrIS (e.g. Born and Nisancioglu, 2012)"

4) Lines 294-305: I don't understand the need of such a speculative section. What is the surface mass balance evolution over the Greenland ice sheet? The resulting ice volume changes are shown in Fig. 4.

No change. The timing of the GrIS contribution to sea-level is a key question of this paper. It is important in how far the evolution can be constrained by existing data and model evidence. However, we have moved this part to the new discussion section.

5) Lines 325-346: This section is difficult to read. It would be better to better explain the sensitivity experiments. Is "forced" the same a "stand-alone" as you call it earlier in the text? Better also to discuss the simulated maximum sea-level contribution in two steps: 1) effect of temperature scaling factor on resulting ice volume changes, 2) effect of coupling ("forced/stand-one" vs "coupled") on ice volume change.

We have revised the use of "stand-alone" and "forced" throughout the document, the latter referring now exclusively to the forced repeat-experiments using climate data from the fully coupled run.

6) Lines 360-365: comparing the Last Interglacial accumulation to pre- industrial is a bit difficult if you base the calculation on differently sized areas. Maybe the accumulation actually didn't increase in many locations? What happens over NEEM? Maps for certain time slices would be much more helpful.

We agree with the reviewer that time resolved maps would be better suited to reveal details of the accumulation change. However, as a minor contribution to the overall ice sheet mass balance we prefer to keep accumulation change treated in condensed form as is the case now. NEEM is not on the Antarctic ice sheet discussed here.

Line 24: "reference experiment", either describe the reference experiment, or omit the mentioning of this and change the values to express the full range of your results (0.62-2.77m)

Replaced "the reference experiment" by "our reference experiment".

Lines 32-33: would be nice to add which part of the ~5m is due melting of the Greenland and which due to the Antarctic ice sheet

Numbers for the GrIS and AIS are given for the individual peaks just before. Although the timing of the two ice sheets is not identical, we believe this is sufficient information for an abstract.

Line 63: skip "e.g."

OK.

Line 71: “mean” instead of “central”

Not changed. Estimates are given in different form, not always as a mean with standard deviation.

Line 77: add “possibly” caused by

OK.

Lines 84-86: make new section, and add “evidence” for possible reduction of the LIG AIS

No change. We are not aware of direct evidence of an AIS reduction as discussed. The whole paragraph is dedicated to the uncertain AIS contribution.

Line 87: better constrained than ...? (I assume AIS evolution)

OK.

Line 102: also mention latest work (Langebroek and Nisancioglu, 2016)

We have updated our reference list to include recent publications (e.g. DeConto and Pollard, 2016; Langebroek and Nisancioglu, TCD, 2016); Rasmus et al., CPD 2016), Merz et al., CPD 2016) and Landais et al. CPD, 2016). Discussion papers are foreseen to be included as they get finally published.

Line 99: correct reference is Born and Nisancioglu, 2012; please also update in rest of text

OK. Corrected throughout the manuscript.

Line 104: incorrect reference, maybe you meant regional climate model, or a different reference

No change. See Reviewer comment 4 in CP discussion.

Line 106: reformulate “results” – what results?

We meant results from “Ice sheet modelling studies on the Antarctic ice sheet during the LIG” as mentioned in the sentence before. Added some clarification:

“However, some results on the AIS during the LIG have been presented in studies with main focus on other time periods (e.g. Huybrechts, 2002) or with interest on longer time scales (e.g. Pollard and DeConto, 2009; de Boer et al., 2013, 2014).”

Line 108: check correct reference in reference list for Pollard and DeConto, 2009 or 2015?

No change. Correct reference for an Antarctic ice sheet simulation spanning the Last Interglacial, but without specific focus on it.

Lines 113-114: skip “high-resolution”, grid boxes of 10 or 20 km is normal, not high for ice sheet models

OK.

Line 121: EMIC description with capital letters or not – make consistent with abstract

OK. Abbreviation is not used anymore:

“Earth system model of intermediate complexity”

Lines 123-124: “The model has been utilised ...” – but without dynamic ice sheets, and two-way coupling, right? Rewrite to make clear.

No change. All listed references used the fully coupled model.

Lines 133-134: what is the resolution of T21 in degrees or km, approximately? “high-resolution ice sheet models”, see earlier comment

OK. Replaced “high-resolution” by “higher resolution” to focus on the relative difference.

Lines 137-138: are the freshwater fluxes etc the same as in the earlier version of the model, or is the set-up the same? Please rewrite.

OK. Sentence split and rewritten:

“The ice sheet models in turn provide the climate model with changing topography, ice sheet extent (albedo) and spatially and temporally variable freshwater fluxes. The coupling procedure for these variables is unmodified to earlier versions of the model (Goosse et al., 2010), while recent model improvements for the ice-climate coupling interface are described in Appendix A.”

Section 3.1: Would make more sense to make Section 3.1 a part of 3.2

No change. Section 3.1 is about forcing, while 3.2 is about the model response.

Line 157: change to “sea-level equivalents (SLE)”

OK. Changed to "sea-level equivalent", but SLE only used in Table 1 and defined there.

Lines 158-160: sentence very unclear, please rewrite

OK. Sentence split and reformulated:

"The Antarctic contribution to global sea-level change is calculated taking into account corrections for ice replacing seawater, ice being replaced by seawater and seawater being replaced by isostatic bedrock movement. These effects are mainly of importance for the marine sectors of the WAIS."

Lines 181-183: Is insolation calculated for each latitude and for each month? Not entirely clear, especially because figure only shows 2 months and 2 latitudes.

Insolation is spatially and temporally resolved. Added clarification in caption to Figure 2 that the two curves are for illustration:

"Average monthly insolation anomaly (a) at 65° North in June (black) and 65° South in December (blue) to illustrate the spatially and temporally resolved forcing (Berger, 1978) …"

Line 186: change "the latter" to "this data"

OK.

Would be nice to explain what this reconstruction is based on.

This sentence has been revised according to comment by reviewer 4:

"The chronology of this data is thought to be superior compared to sea-level proxies based on scaled benthic δ18O records (Grant et al., 2012; Shakun et al., 2015)."

Line 193: Skip "As a measure"

OK.

Line 208: skip "comparison between"

OK, reformulated.

Line 209: skip "recorded"

No change. Important to mention that the climate forcing is recorded.

Lines 208-210: The ice sheet response to what?

OK, replaced "response" by "evolution".

Line 211: Are these "Additional experiments" stand-alone experiments or coupled?

Yes, stand-alone experiments. We are still describing the same "forced" experiments. Added clarifications in the text.

Lines 217-219: What is the climate forcing for this initialisation? And how large are the 'initial' Greenland and Antarctic ice sheets, so at 135ka?

This was done following established procedures, recently updated in Goelzer et al. (2016). References have been included in the text to clarify that (Huybrechts and de Wolde, 1999; Huybrechts, 2002; Goelzer et al. 2016).

We have included additional panels for the initial Greenland and Antarctic ice sheets at 135 kyr BP in figures 5 and 8.

Line 231: The first section of the Result should be named "5.1 Climate evolution" or something similar

OK, added section header "5.1 Climate evolution"

Lines 231-235: and what are the differences to Loutre et al., 2014?

Comparison to Loutre et al. (2014) and Goelzer et al. (2016) are given in the first section.

Line 249: Southern Ocean (SO)

OK.

Lines 250-251: I don't see this cooling event in the one-way experiment, please rewrite.

Added reference to Goelzer et al. (2016), where the one-way experiment is described.

Line 254: change to "mass balance dominated by ablation"

OK. Also refer to runoff instead of ablation now following comments of the other reviewers.

Section 5.1: What do you call "ablation"? runoff + calving or only runoff? Need for some definitions here.

OK. Have revised the terminology. "Ablation" is replaced by "runoff" or "surface meltwater runoff".

Lines 254-255: "Marginal" could mean "just a bit" or "on the rim", please clarify.

OK. Replaced “Marginal … runoff” by “runoff from the margins”;

Section 5.1: “Temperatures”, are these summer mean or annual mean? Surface or air temperatures? Please be more precise.

OK, further specified “air” temperatures. We are describing a physical process here. Physically, accumulation increase is due to increased temperature not due to increased mean temperature, or for that matter, annual temperature.

Figure 4: are the dashed lines the pre-industrial values? Would be great to have these numbers also for the ice area and volume.

Yes, see also comment of reviewer one.
Reference values for volume and area have been included in Figure 4.

Line 268: change “furthest” to “maximum”

No change. We mean the furthest retreat as “over the largest distance”. “Maximum” retreat could mean the maximum attainable retreat.

Line 269: change “Conversely” to “At the same time”

OK.

Line 317: Not sure if Merz et al., 2014 is the correct reference here, as they focus on the effect of topography on precipitation during the Last Interglacial.

No change. There are two papers of Merz et al., in 2014. The one we refer to is the one about temperature.

Line 334: “Figure 6, left” should be “Figure 6a”, check also rest of section.

OK. Also replaced twice “(Figure 6, right)” by “(Figure 6b)”

Line 340: skip “therefore”

OK.

Line 365, “Figure 7b”

OK.

Line 367: so ablation is runoff?

Yes, replaced “ablation” by “runoff” throughout.

Figure 7: what is the present-day ice area and volume in your model set-up?

OK. Reference values for volume and area have been included in Figure 7.

Line 375: include reference to Figure 7d

OK.

Line 414: “included” instead of “attempted”

OK.

Line 428: “Ocean expansion is rapid during ...”

OK.

Line 439: skip “well”

OK.

Lines 439-440: the estimated LIG ocean thermal expansion is 0.4+0.3m according to the IPCC report, they use McKay et al., 2011 as a reference. Please rewrite.

Thank you for spotting this mistake. Corrected.

Line 443: “AIS and thermal expansion”

OK.

Lines 443-445: add reference to Figure 10

OK.

Figure 10: add information on confidence levels to figure caption

OK.

Line 453: change “hiatus” to “regrowth” or similar

OK.

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Reviewer 3 – Andrey Ganopolski

The manuscript by Goelzer et al. presents results of the first fully interactive simulation of climate and ice sheet evolution during the penultimate glacial termination and the last interglacial (LIG) using an Earth system model of intermediate complexity. The authors show that reconstructed temporal dynamics of sea level during the LIG can be successfully reproduced by their model. The authors for the first time demonstrated that disintegration of the last fraction of the West Antarctic ice sheet (WAIS) at the beginning of LIG can be solely explained by the dynamical response of the ice sheet to sea level rise. The manuscript presents in depth analysis of the processes and feedbacks operating in the system supported by a set of sensitivity experiments. The manuscript is well-written and properly illustrated. I believe this is an important scientific contribution and I would recommend it for publication in CP after minor revision.

Thank you very much for the comments and suggestions that we have responded to in detail below.

General comments

1. Although the manuscript by Goelzer et al. is not the first paper produced in the framework of the same project and many technical details have been already described in Loutre et al (2014) and Goelzer et al (2015), for the readers' convenience a more detailed description of experimental design would be helpful. In particular I would suggest (i) provide information of how surface mass balance of ice sheets was simulated and give in the table the values of semi-empirical parameters; (ii) explain how temperature and precipitation anomalies from low-resolution climate component were applied to high resolution ice sheet models and how changes in ice sheet elevation and extent were accounted for; (iii) how simulated ocean temperature anomalies were used to compute submarine melt of ice shelves; (iv) how one-way coupling experiments have been performed; (v) how "present" GrIS and AIS have been simulated.

We have included additional information in the model description as follows. i) A PDD model is used to calculate the SMB with unchanged parameters compared to other studies (included references). ii) Climate anomalies are interpolated to the ice sheet grids using Lagrange polynomials. The SMB-elevation feedback is accounted for on the high-resolution ice sheet model grid.

iii) The submarine melt parameterisation is described in Appendix A.

iv) Forced experiments (as we now refer to consistently) are identical to the fully coupled experiments except that climate forcing is read from file (from an earlier simulation) rather than dynamically calculated. We have included an additional sub-section 4.2 describing these experiments in more detail.

v) It is not feasible to run the fully coupled model from 135 kyr BP all the way to the present day. Our present-day ice sheet simulations are therefore the result of standalone ice sheet experiments continuing from the standalone spin-up simulations to the present day following established procedures (references to Huybrechts and de Wolde, 1999; Huybrechts, 2002 and Goelzer et al., 2016 have been included).

2. I have a question concerning scaling technique to reconstruct Northern Hemisphere (NH) continental ice sheets during penultimate termination. According to the manuscript, evolution of NH ice sheets were prescribed using Lisiecki and Raymo (2005) benthic stack L&R04 and the Fig. 4 from Goelzer et al. (2015) shows that according to L&R04 the termination was only half-way at 130 ka with the global sea level still ca. 50 m below present. This would imply existence of large continental ice sheets in the NH which is consistent with the Fig. 2 from Goelzer et al. (2015). How- ever, according to the Figure 10 (top) from the new manuscript, the volume of NH ice sheets at 130 ka was only 10 meters in sea level equivalent which is only 10% of their LGM value. If I misunderstood your approach, please clarify.

In the final version of Goelzer et al. (2016), we have included an extended description of the reconstruction methods used for the NH ice sheets, which explains our approach. "Our method does not guarantee that the sea-level contribution of the reconstructed NH ice sheets closely follows the global ice volume curve. This is generally due to the mismatch between global ice volume and NH ice sheet reconstruction during the post-LGM period, and in part related to the unconstrained contribution of other components (AIS, thermal expansion)."

3. To prevent GrIS from complete melt, the authors scaled down simulated temperature anomalies used for calculation GrIS surface mass balance. This is somewhat surprising in a view that simulated glacial-interglacial global temperature change in the model is only about 2C which is much less than results of PMIP2 and 3 models which simulated global LGM cooling of 4-5C. Moreover, uncorrected simulated GrIS temperature anomalies during LIG are only about 3C which is still well below "NEEM temperature reconstructions". It would be useful to show simulated summer temperature anomalies over the GrIS because summer temperatures are the most important for ice sheet mass balance.

The global mean temperature anomaly is not a good measure for the LOVECLIM model, which exhibits a relatively strong polar amplification. Furthermore, summer temperature anomalies are larger than annual mean anomalies because of the quasi- instantaneous albedo-temperature feedback, which is predominant at the margins of the ice sheet.
We have now included an extra figure (S2) showing annual mean and summer temperatures in comparison.

4. While I have no problem with the pragmatic decision to scale GrIS temperature anomalies down, I am missing an explanation why the authors decided to use the factor 0.4 as the reference value and considered 0.3 and 0.5 as the upper and lower limits. I wonder whether simulation for scaling factor 0.4 is better than for other two, can the value 0.5 can be accepted or rejected by empirical constraints and whether any larger scaling factors can (or cannot) be ruled out? I believe that at present the only thing we can say with some confidence about GrIS during LIG is that melting of more than half of modern GrIS would be difficult to reconcile with the existing empirical constraints. Any number below 3 meters is equally probable and therefore implied accuracy of reported "1.4 m" significantly underestimates uncertainties of this estimate. I also found it noteworthy that three numbers for the range of GrIS contribution during LIG (0.6, 1.4, 2.8 m) given by the authors are almost identical to the values given in the recent paper by Calov et al. (2015, CP): 0.6, 1.4, 2.5 m.

We have included explanations in the experiment description as follows. "The range of parameter R is chosen to retain an acceptable agreement of the minimum GrIS extent during the LIG with reconstructions. In practice, the high scaling factor is chosen to produce the smallest minimum ice sheet extent, which still has ice at the NEEM site. The low scaling factor was adopted to produce the smallest minimum ice sheet extent still covering Camp Century."

The match of our results with the numbers in Calov et al. (2015) is purely coincidental.
We have added a note on that fact in the discussion section:

"Incidentally, our range of modelled GrIS sea-level contribution is in very close agreement with recent results from a large ensemble study of the LIG sea-level contribution constrained against present-day simulations and elevation changes at the NEEM ice core site (Calov et al., 2015). Despite a possible degree of coincidence in this particular case, the overlap between results reached by largely different methods is indicative of the lack of better constraining data needed to arrive at much narrower uncertainty ranges."

5. While the estimates of GrIS contribution fall well within the range reported in a number of previous studies, dynamical collapse of the WAIS during LIG is new and very important finding presented in the manuscript. Thereby it would be interesting to learn more about the mechanisms. The authors show that Antarctic ice volume overshoot is not related to enhanced surface or subsurface melting, as was proposed in some previous studies, but mostly of dynamical WAIS response to prescribed global sea level rise. In this relation I have a question. What is the crucial difference between the penultimate and the last glaciations which explains this overshoot: much faster sea level rise during the penultimate glaciation or the fact that sea level from Grant et al. (2012) overshoots Holocene sea level by ca. 10 m already at the beginning of LIG? The authors mentioned *that they performed similar simulations with the L&R04 sea level reconstruction. Since L&R04 stack suggests a slower rate of sea level rise and does not overshoot present sea level during LIG, I wonder what is the WAIS dynamics in this experiment.*

The main difference between Termination II and Termination I is indeed the speed of sea-level rise (faster for the penultimate deglaciation than for the most recent deglaciation) and to a lesser extent the fact that the sea-level forcing by itself overshoots the Holocene sea-level stand. A similar experiment with L&R04 sea-level forcing brought to light that the Antarctic ice volume overshoot is reduced by 50% as the rate of sea-level rise is smaller in L&R04 than in the Grant record. The sensitivity experiments discussed in Huybrechts (2002) showed the importance of the speed of bedrock rebound with respect to the speed of sea-level rise to generate overshoot behaviour. With slow isostatic rebound during the last deglaciation (characteristic time scale of 10000 years as compared to 3000 years in the reference experiment having no overshoot), the Antarctic ice volume overshoot was ~4 m SLE, while with very fast isostatic rebound (characteristic time scale of 1000 years), WAIS grounding line retreat got stuck halfway the present-day Ross and Ronne-Filchner ice shelves (or an 'undershoot' of ~ 4 m SLE). This behaviour is easily understood as both sea-level change and bedrock elevation change have a similar effect on grounding-line migration being controlled by hydrostatic equilibrium. If the bedrock rebound after ice unloading is faster than the sea-level rise, this will dampen grounding-line retreat. If on the contrary, the sea-level rise is faster than the bedrock uplift, grounding line retreat will be enhanced, as was the case during the penultimate deglaciation.

We have added this discussion as section 6.3 in the manuscript.

6. Although the mechanism for the WAIS disintegration found in the study by Goelzer et al. differs from that proposed by Holden et al. (2010), I do not believe that the modeling results presented in the manuscript under consideration can be used to rule out completely importance of submarine melt for stability of the WAIS. The reason is that simulated in the current study bipolar see-saw is very weak compare to other modeling results and paleoclimate data. The later reveal significant temperature overshoots at the beginning of LIG essentially everywhere in the SH, and the magnitude of temperature overshoots (above present) in different Antarctic locations was at least several degrees. At the same time, in the work by Goelzer et al. (2015) only a tiny (0.2C) temperature overshoot is seen in subsurface South Ocean temperature (Fig 7b) and essentially nothing in SH or Antarctic temperatures. This seems to be a typical feature of the LOVECLIM model (e.g. Menviel et al., 2015, EPSL). I believe, this potential caveat of the current study should be mentioned in the discussion.

We have included a discussion on this point in the revised manuscript:

"The sea-saw effect evoked by NH freshwater forcing leads to millennial time scale temperature variations in the SO, but the surface climate over the AIS is hardly affected in our simulations. Despite some improvement when ice sheet changes are included, the limited Antarctic temperature response appears to be a general feature of the LOVECLIM model (e.g. Menviel et al., 2015), which fails to reproduce a several degree warming during the LIG reconstructed at deep ice core locations."

Specific comments

L 82 It should be Pollard et al. (2015)

OK.

L 182 What is the meaning of "dynamically computed"?

The meaning is that insolation is calculated at run time. Removed 'dynamically' to avoid confusion.

L 183 Does "governing" means here "major"?

Yes. Greenhouse gas forcing is of minor importance and ice sheets have retreated at that time.

L 187 "... assumes ice volume to be independent of deep-sea temperatures" This incorrect formulation. In fact, the sea level reconstruction based on Red Sea d18O, unlike benthic d18O, does not require information about deep-sea temperature because it based on planktonic forams. It is also affected by temperature (sea surface temperatures) but to a lesser degree than benthic d18O.

OK, reformulated.

L 223 Would be useful to clarify how the "stand-alone ice sheet forcing" was defined for penultimate glacial cycle.

This was done following established procedures. References have been included in the text to clarify that (Huybrechts and de Wolde, 1999; Huybrechts, 2002).

L 255 Would be interesting to know why "the retreat of the WAIS" in the interactive experiment "occurs 2 kyr later compared to the one-way experiment"

The reason is differences in atmospheric and oceanic forcing as described in section 5.3.

L 310 I fully agree that if "NEEM temperature reconstruction is applied uniformly in space and over seasons, than in any model GrIS will melt completely. However, if Eemian warming had strong seasonality, as proposed by Merz et al. (2015, CP) with large warming in winter and small warming in summer, then in combination with some other factors, "NEEM paradox" can be resolved.

L 322 See my previous comment

Yes, this is what our discussion in this paragraph is about.

L 355. As I already stated in general comment, not much happened in the Southern Hemisphere in response to freshwater forcing in the Northern Hemisphere. This is why it is not surprising that Antarctic temperature is so flat.

The amplitude of climate changes in the SH is indeed lower than in the NH. However, the point we are making here is that the Antarctic ice sheet surface climate appears to be largely isolated from those (millennial time scale) changes in the surrounding oceans.

L. 370 Would be useful to show also ocean (subsurface) temperature in the respective figure.

Instead, we refer now to Goelzer et al 2016, where the ocean response is discussed in detail.

L. 411 Which "environmental forcing" is meant here?

OK, replaced "environmental" by "climatic".

L. 412 It should be Pollard et al. (2015)

OK.

L. 428 "Ocean expansion is steep. . ." Rather I would say "the fastest sea level rise due to thermal expansion . . ."

OK. Replaced "steep" by "rapid" as suggested by other reviewer.

L. 440 "0.42+-0.11" This is a typo. Chapter 5 of AR5 does not contain this number. Instead it referrs to the only available estimate of thermal expansion during the LIG of 0.4 +-0.3 m by McKay et al. (2011). In such case I would recommend to cite original publication rather than IPCC report.

Thank you for spotting this mistake. Corrected.

L. 452 "0.42+-0.11" m is not the estimate of glacier contribution to sea level during the LIG but rather the maximum possible sea level rise due to melting of all existing at present glaciers and small ice caps. Obviously, there is no reason *to believe that all glaciers melted completely during the LIG and therefore real contribution of glaciers and ice caps during LIG was probably much smaller than 0.4 m.*

OK. Reformulated to “maximum possible contribution”.

L. 523 “. . .by preventing tundra warming affecting proximal ice sheet margins”. This is not very clear.

OK, reformulated:

“This is accomplished by calculating surface temperatures independently for different surface types (ocean, ice sheet, tundra), which most importantly prevents tundra warming to affect proximal ice sheet margins.”

L. 539 Please correct doi of Berger’s paper

We have verified the record, this appears to be the correct doi.

L 575. Correct reference is “Science, 349, doi: 10.1126/science.aaa4019, 2015”

OK.

Figure 1. Brovkin et al (1997) is not in the reference list

OK. Added reference.

L 717 I suppose this is not original Grant et al. (2012) reconstruction but its smoothed version. Please, make it clear.

No smoothing has been applied. The maximum probability curve given by Grant et al. (2012) is already as smooth.

L 746 Does “forced” here means the same as “one-way”?

Yes, modified throughout the manuscript.

Reviewer 4 – Eric Wolff

<u>General comments:</u>

This paper does represent something of a technical achievement, succeeding in making a coupled run of climate and both Greenland and Antarctic ice sheets across the last interglacial (LIG). To demonstrate that ability, and highlight the steps that are needed to improve on it, I think the paper should eventually be published in CP. How- ever it does need quite a lot of work to explain both details and its limitations correctly. I notice that the paper has already achieved several *reviews, so I will not go into huge detail but just give some overall comments, with a little more emphasis on data aspects of the study.*

The strength of the paper, as I have indicated, comes from the achievement of making such a study. However I think it is important that it is correctly labelled. It is really a demonstration simulation, not a testable prediction. The Greenland ice sheet coupling is achieved only after applying a randomly chosen scaling to the temperature data (it's a tuning in the sense of aiming at a Greenland SL contribution the authors think is sensible, but random in the sense that there is no reason at all to think that a linear tuning is correct). The Antarctic ice sheet apparently responds despite the ice dynamics processes that many glaciologists consider paramount for West Antarctica not being present (or at least I don't think they are). Given these two issues, the actual values that are achieved seem almost meaningless. I don't suggest they should not be explored, and the relative timing of the contributions is of interest for example, but the paper should make much clearer that it does not in any way represent a success in explaining LIG sea level, rather it is a demonstration of how one might start to assess that in a consistent manner.

Another significant issue I would like to see addressed concerns data. This is in two senses; firstly some critical data seem a little misquoted, and others seem to be ignored. But also there is an opportunity here to test different aspects of the model results rather than just the SL response. In particular the climate response in both polar regions could be well-tested using the recent Capron et al (2014, QSR) compilation; but in fact this paper is not even cited. I suspect for example that this paper would allow the authors less room to suggest that the Greenland temperature response is overestimated in the model, and force them instead to consider that the ice sheet may be too sensitive, which is quite a critical issue.

A final major issue I think the authors need to address concerns the mechanism by which they achieve a significant loss of WAIS – this seems to be global SL and ice shelf viscosity. This seems really surprising to me: global sea level is higher than today really only because of the loss of WAIS in these expts, so it is hard to see why this should be a part of provoking such a loss. That leaves us having to accept that Antarctic temperature in Fig 7a apparently provokes a change in viscosity and loss of ice just a few tenths of a degree above present: this would be a very alarming result, but seems quite at odds with the mechanisms that usually concern people about WAIS (they generally worry about dynamic loss through the major ice streams and glaciers on the Amundsen Sea side, which have little or no ice shelf restraint, rather than the ice flowing into the large ice shelves). Perhaps I have not understood your mechanism but this definitely needs exploring: either your model is way too sensitive to this process, or glaciologists are worrying about the wrong thing and should be very urgently concerned about ice shelf viscosity. I rather suspect the former as I can't see how there can be such a sharp breakpoint in ice shelf viscosity that a couple of degrees would drain the whole of WAIS and destroy the Ross and Ronne-Filchner Ice Shelves. In any case this certainly needs a discussion.

Thank you very much for the comments. The referee raises important issues, not all of which can reasonably be answered within the scope of the present paper.

We first of all note that a rather detailed comparison of the climate response of LOVECLIM during the LIG with data (without considering Antarctic or Greenland ice-sheet changes) was presented in Loutre et al. (2014), which paper had Emily Capron as co-author, and made extensive reference to Capron et al. (QSR, accepted at that time). In Goelzer et al. (2016) the emphasis was on the effects of prescribed Antarctic and Greenland ice sheet changes on the oceans and atmospheres, and in that paper more comparisons with data were made, also explicitly referring to Capron (2014). The present paper concentrated more on the ice sheets and sea level, and emphasized less the comparison with climate data.

We also agree that the possibility of a too sensitive Greenland ice sheet model should not be discarded a priori, but we found little additional elements to support that. As noted further below in reply to the detailed comments, our results are very much in line with other Greenland model studies on the LIG, regardless of the mass balance model (e.g. Huybrechts, 2002; Robinson et al., 2011; van de Berg et al., 2013; Calov et al., 2015). Moreover, our PDD surface mass balance model was compared with the Polar MM5, RACMO, and MAR models over Greenland for the period 1960-2008 and found to be even slightly less sensitive than the other models (Vernon et al., 2013), which does not seem indicative of a suspiciously sensitive modelling approach in the present study.

As already mentioned in our reply to question 5 of reviewer 3, we found the main mechanism for WAIS retreat during Termination II to be sea-level rise. The ice volume ‘overshoot’ of ca. 4 m is primarily a consequence of the delayed bedrock response with respect to the rising sea level, and secondly, of the overshoot in the sea-level forcing itself. Ice shelf viscosity changes also play a role during the deglacial retreat and the sea-level overshoot, but are not dominant. The comparison with future climate warming conditions is however hard to make because of different forcing and different response times. The response time of viscosity changes in the ice shelves is governed by vertical heat conduction, having a characteristic time scale of order 500 years with respect to surface temperature (Huybrechts and de Wolde, 1999). In future warming scenarios, the effect of shelf viscosity changes is therefore usually too slow compared to the anticipated direct effect of increased surface and basal melting rates. For instance, in future warming scenarios with LOVECLIM under 4xCO2 conditions (Huybrechts et al, 2011), we found the ice shelves to be largely gone from melting before they had a chance to warm substantially, and found shelf melt rates to increase 5-fold, compared to the +20% increase for the LIG found here.

More detailed comments:

Line 47: Turney and Jones compiled data that were not contemporaneous, ie they combined the maximum temperature at each site over a long time slab. It is therefore impossible to deduce a global mean temperature anomaly from their paper. Probably better to acknowledge this.

OK, we have modified the text to take this comment into account and have used the opportunity to refer to Capron et al., 2014.

"During the LIG, global mean annual surface temperature is thought to have been 1°C to 2°C higher and peak global annual sea surface temperatures 0.7°C ± 0.6°C higher than pre-industrial (e.g. Turney and Jones, 2010; McKay et al., 2011), with the caveat that warmest phases were assumed globally synchronous in these data syntheses (Masson-Delmotte et al., 2013). These numbers are largely confirmed by a recent compilation, which resolves the temporal temperature evolution (Capron et al., 2014)."

Line 56. I think the most commonly cited numbers for LIG sea level are 5-10 m from IPCC AR5, and 6-9 m from the recent Dutton et al (2015, Science) review paper. There is not a great basis for emphasising 6 m in particular.

Not changed. The IPCC AR5 literally states "The best estimate is 6 m higher than present" in Section 13.2.1.3, page 1146.

Page 4. Here is a first place one could mention the Capron et al compilation which could act as a check on your climate outputs or as a forcing in standalone experiments.

We have added a reference to Capron et al. (2014) in the section before (see comment 1) and in the following:

"Despite recent advances (e.g. Capron et al., 2014), the fundamental shortcoming at present for improving modelled constraints on the LIG ice sheet contribution to sea level with physical models is the sparse information on LIG polar climate and oceanic conditions."

Line 186-188 is badly worded. The Grant et al paper uses an approach that doesn't use synchronisation to a mixed record of SL and deep sea temperatures but it doesn't assume anything about their independence or otherwise does it?

OK, reformulated:

"The chronology of this data is thought to be superior compared to sea-level proxies based on scaled benthic δ18O records (Grant et al., 2012; Shakun et al., 2015)."

Line 192-203. While I understand your decision to scale I think it needs more discussion. From Fig 4a I read off that without forcing you would estimate a Greenland warming of about 3 degrees. This is not only below the NEEM estimate, it's below other NEEM lower estimates (such as Masson-Delmotte et al 2015), and I am pretty sure it is already similar to other model estimates. Your preferred estimate allows only a one degree warming and this would be really hard to reconcile with NEEM data or with compiled SST data in Capron et al. So, for pragmatic reasons, Ok use the scaling, but I feel you should admit that this might be telling you that your Greenland model is too sensitive, and at least discussing your model in the context of others.

The crucial temperature for ice-sheet changes is summer temperature at the margin where the melting takes place, and these are higher than 3°C, which we are showing in a new figure (S2) now. We don't think our model is too sensitive, or at least not more sensitive than other models. For one thing, the melt model has been compared with other surface mass balance models and found to be even slightly less sensitive to recent late-20th century climate changes (Vernon et al. 2013). See also reply to comment 3 of reviewer 3 and below in response to comment line 314.

Line 277. While the elevation at NEEM is not perfectly constrained, I suspect its equally important that ice sheet elevation at NEEM is not a strong constraint on the size/area of GrIS. Perhaps re-word.

OK, sentence reworded:

"Elevation changes from that ice core are however not very well constrained and even if they were, would leave room for a wide range of possible retreat patterns of the northern GrIS (e.g. Born and Nisancioglu, 2012)."

Line 284. I am not sure what point you want to make here about Cap Century. The same paper also suggests no ice older than 115 ka at Summit but this is clearly not taken to mean there was no Eemian ice there.

Yes, agreed. Sentence removed.

Line 314 and around. While we don't understand how an ice sheet at +8 degrees could survive, I still question whether your result illustrates a NEEM paradox or an oversensitive Greenland ice sheet model. You should at least discuss both options.

We agree that without further information the results could initially be interpreted as illustrating a too sensitive ice sheet model. However, other elements leave little room for that interpretation. Other surface mass balance models of similar and of higher complexity show a similar or larger sensitivity for the LIG period (e.g. van de Berg et al., 2011). In a comparison and validation for the recent past, the applied melt model is within the

range and even slightly less sensitive than the other models (Vernon et al. 2013).

We have now included discussion of these aspects in the manuscript. See also response to comment 1 of reviewer 1.

Line 353-359 and beyond is really confusing. Firstly you say that "Antarctic surface climate is isolated from millennial fluctuations". But then later you agree with previous authors in ascribing the warm Antarctic to the bipolar seesaw. Please make your text consistent. I assume in fact you do think it is the bipolar seesaw response to NH melting that is important in warming the Antarctic at a time when orbital forcing would cool it.

The temperature evolution over the Antarctic ice sheet is not showing millennial time-scale variations, which is the case for the surrounding ocean subject to the bipolar see-saw. We have modified the text to clarify that and added a reference to Goelzer et al., 2016, where the SH temperature evolution in response to freshwater fluxes is discussed in detail:

"The surface climate over the AIS appears to be largely isolated from millennial time scale perturbations occurring in the Southern Ocean in response to changing freshwater fluxes in both hemispheres (Goelzer et al., 2016)."

Fig 6b: I could not follow this figure, please explain it better.

We have include additional information in the figure caption and in the main text to improve the explanation:

"The underlying surface type with different characteristic albedo values for tundra and ice sheet is determined by the relative amount of ice cover, which is modified when the area of the ice sheet is changing. On much shorter time scales, the albedo can change due to changes in snow depth and also due to changes of the snow cover fraction, which indicates how much surface area of a grid cell is covered with snow (Figure 7b).“

Fig 10 is really not comprehensible. It needs a much better caption. In any case I am not sure it serves any purpose since the NHIS evolution dominates everything. This means that while the extent of the highstand above present is a prediction that can be aimed at, the shape of the deglacial rise is really dominated by your (prescribed) NHIS loss.

Figure 10 is given to show that with our modelling approach we can roughly match the reconstructed range of LIG sea-level evolution. The NHIS reconstruction is part of this approach. It was not prescribed to fit with Kopp, but chosen between two alternative reconstructions to give the best climate response (Loutre et al., 2014).

The caption has been updated to explain the percentile curves in the Kopp et al. (2009) reconstruction:

“Modelled sea-level contributions from this study (colour lines) compared to probabilistic sea-level reconstructions (black lines) from Kopp et al. (2009) for the NH (a) the SH (b) and global (c). For the reconstructions, solid lines correspond to the median projection, dashed lines to the 16th and 84th percentiles, and dotted lines to the 2.5th and 97.5th percentiles.”

Modified figures

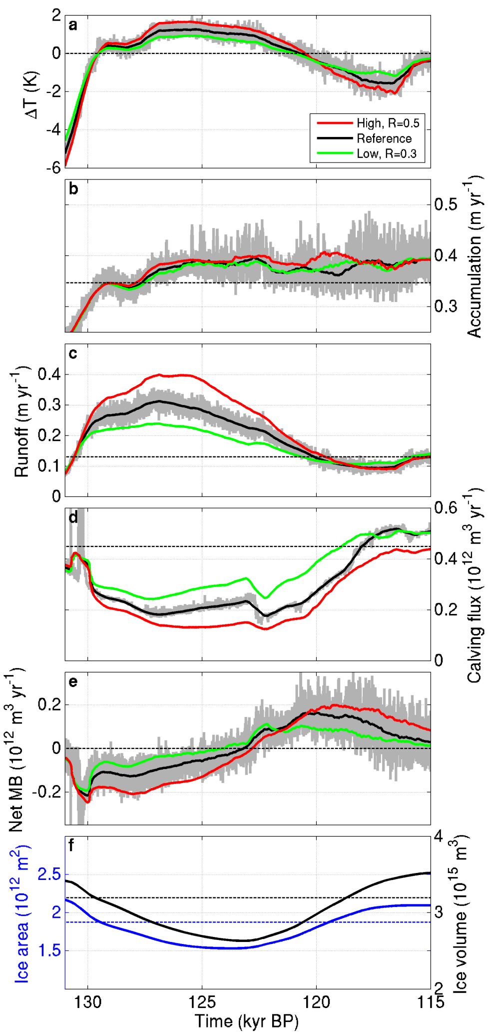

Fig. 4. Greenland ice sheet forcing characteristics for the reference run (black) and with higher (red) and lower (green) temperature scaling. Climatic temperature anomaly relative to pre-industrial (a). Accumulation rate (b) and runoff rate (c) given as ice sheet wide spatial averages over grounded ice. Calving flux (d), net mass balance (e) and other mass balance terms (b, c) given in water equivalent. Ice area (blue) and ice volume (black) for the reference run (f). All lines are smoothed with a 400 years running mean except for the grey lines giving the full annual time resolution for the reference run. Horizontal dashed lines give the pre-industrial reference values, except for panel e, where it is the zero line.

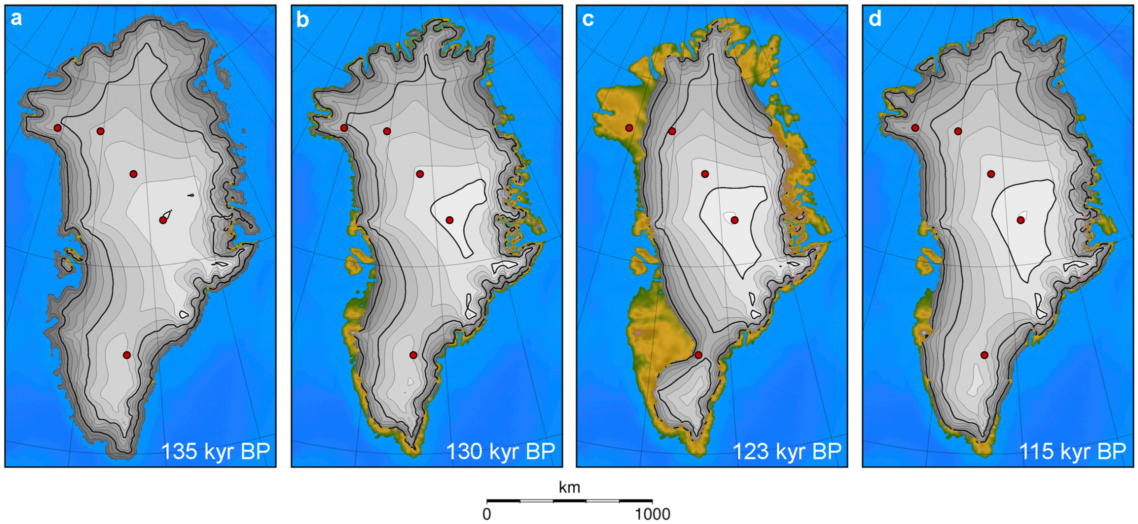

Fig. 5. Greenland ice sheet geometry at 135 kyr BP (a), 130 kyr BP (b), for the minimum ice sheet volume at 123 kyr BP with a sea-level contribution of 1.4 m (c) and at the end of the reference experiment at 115 kyr BP (d). The red dots indicate the deep ice core locations (from south to northwest: Dye-3, GRIP, NGRIP, NEEM, Camp Century).

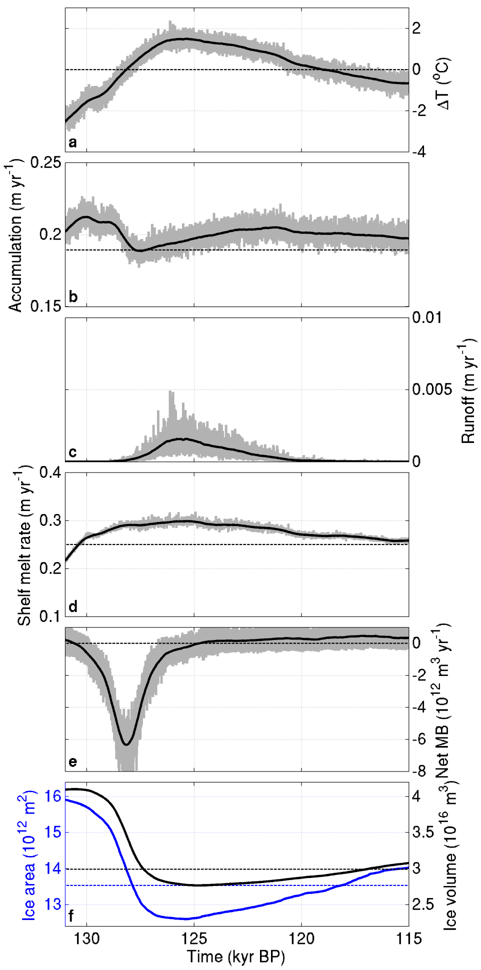

Fig. 8. Antarctic ice sheet forcing and characteristics. Temperature anomaly relative to pre-industrial (a), average ice sheet wide accumulation rate (b), average ice sheet wide runoff rate (c), average sub-shelf melt rate diagnosed for the area of the present-day observed ice shelves (d) and net mass balance of the grounded ice sheet (e). Mass balance terms (b-e) are given in water equivalent. (f) Grounded ice sheet area (blue) and volume (black). Grey lines give full annual time resolution, while black lines (and blue in f) are smoothed with a 400 years running mean. Horizontal dashed lines give the pre-industrial reference values, except for panel e, where it is the zero line.

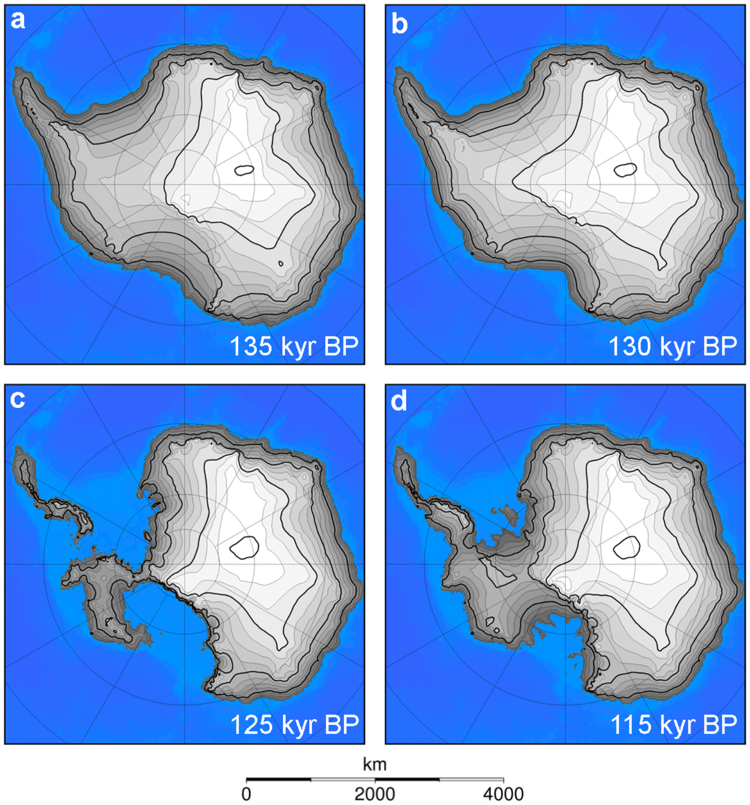

Fig. 9. Antarctic grounded ice sheet geometry at 135 kyr BP (a), 130 kyr BP (b), for the minimum ice sheet volume at 125 kyr BP with a sea-level contribution of 4.4 m (c) and at the end of the reference experiment at 115 kyr BP (d).

Additional figures

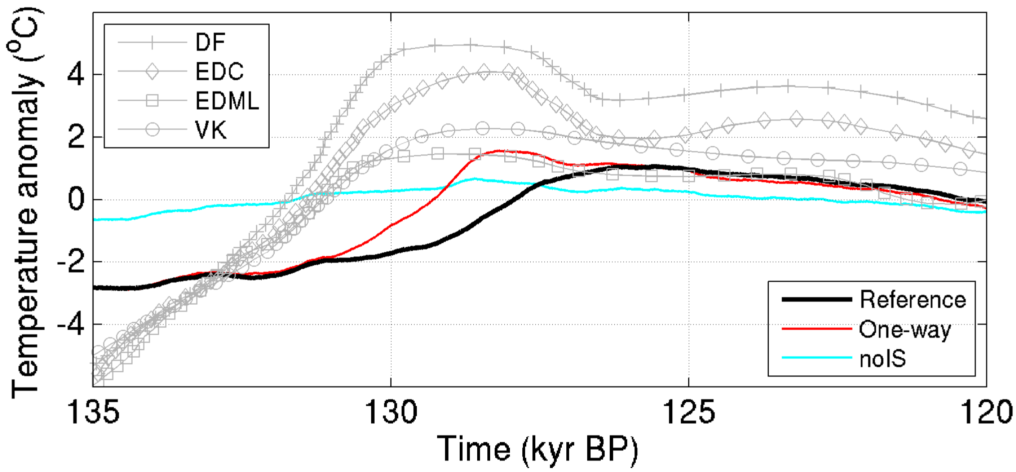

Figure S1 Comparison of modelled East Antarctic temperature evolution with reconstructed temperature changes at deep ice core sites. Modelled temperature anomalies are averaged over a region 72° - 90° S and 0° - 150° E. Ice core temperature reconstructions for the sites EPICA Dronning Maud Land (EDML, 75°00′ S, 00°04′ E), Dome Fuji (DF, 77°19′ S, 39°40′ E), Vostok (VK, 78°28′ S, 106°48′ E) and EPICA Dome C (EDC, 75°06′ S, 123°21′ E) are from Masson-Delmotte et al. (2011).

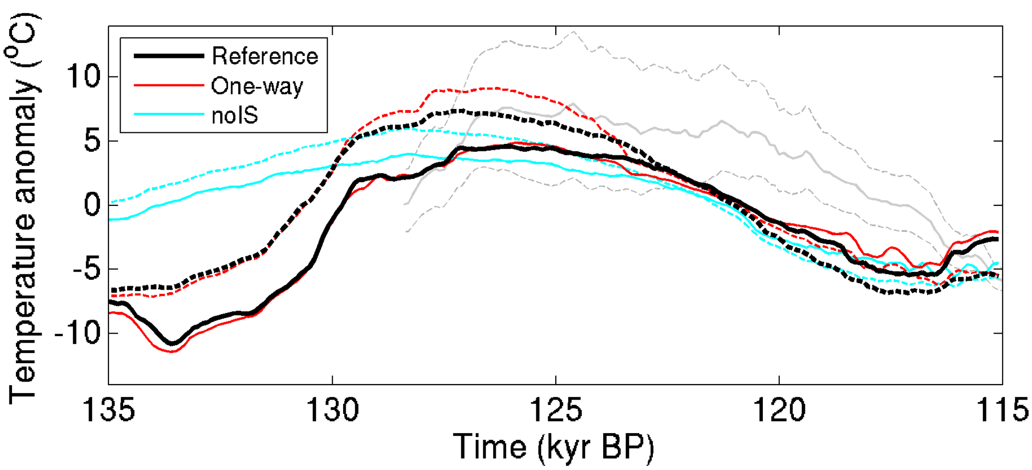

Figure S2 Comparison of modelled North-East Greenland annual mean (solid) and summer (June-July-August, dashed) surface temperature evolution (72° - 83° N and 306°33′ - 317° 48′ E) with reconstructed temperature changes (grey) at deep ice core site NEEM (77°27′ N, 308°56′ E). The solid grey line is the central estimate and grey dashed lines give the estimated error range for NEEM.

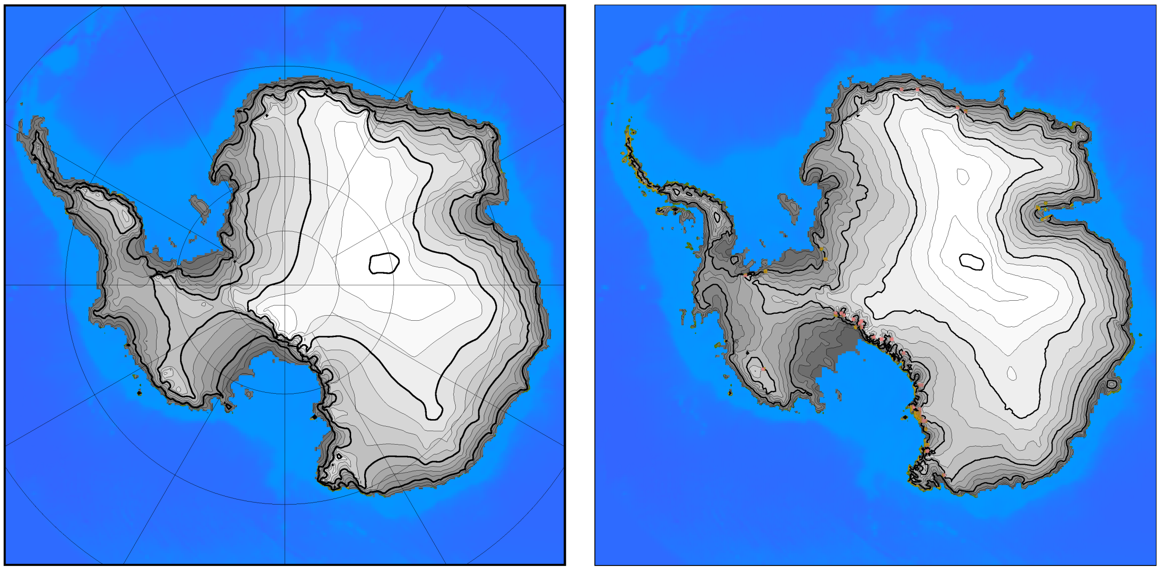

Figure S3: Present-day Antarctic ice sheet configuration from the model (left) compared to observations (right).

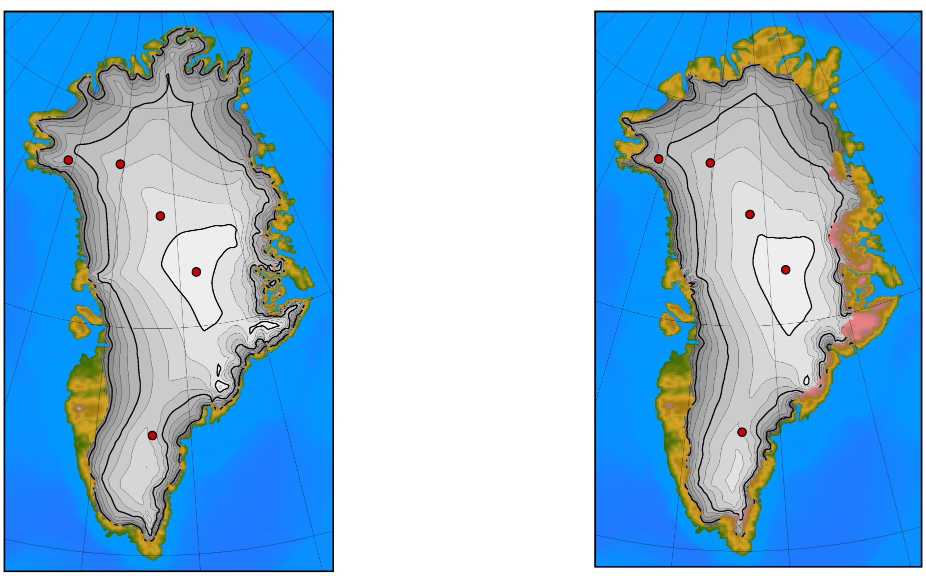

Figure S4: Present-day Greenland ice sheet configuration from the model (left) compared to observations (right). Note that the observations omit peripheral glaciers and ice caps that are included in the model.

Last Interglacial climate and sea-level evolution from a coupled ice sheet-climate model

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1 Abstract

As the most recent warm period in Earth's history with a sea-level stand higher than present, the Last Interglacial ~~period~~ (~130 to 115 kyr BP) is often considered a prime example to study the impact of a warmer climate on the two polar ice sheets remaining today. Here we simulate the Last Interglacial climate, ice sheet and sea-level evolution with the Earth system model of intermediate complexity LOVECLIM v.1.3, which includes dynamic and fully-coupled components representing the atmosphere, the ocean and sea ice, the terrestrial biosphere and the Greenland and Antarctic ice sheets. In this set-up, sea-level evolution and climate-ice sheet interactions are modelled in a consistent framework.

Surface mass balance change~~s,~~ governed by changes in surface meltwater runoff is~~are~~ the dominant forcing for the Greenland ice sheet, which shows a peak sea-level contribution of 1.4 m at 123 kyr BP in the reference experiment. Our results indicate that ice sheet-climate feedbacks play an important role to amplify climate and sea-level changes in the Northern Hemisphere. The sensitivity of the Greenland ice sheet to surface temperature changes considerably increases when interactive albedo changes are considered. Southern Hemisphere polar and sub-polar ocean warming is limited throughout the Last Interglacial and surface and sub-shelf melting exerts only a minor control on the Antarctic sea-level contribution with a peak of 4.4 m at 125 kyr BP. Retreat of the Antarctic ice sheet at the onset of the LIG is mainly forced by rising sea-level and to a lesser extent by reduced ice shelf viscosity as the surface temperature increases. Global sea level shows a peak of 5.3 m at 124.5 kyr BP, which includes a minor contribution of 0.35 m from oceanic thermal expansion. Neither the individual contributions nor the total modelled sea-level stand show fast multi-millennial time scale variations as indicated by some reconstructions.

2 Introduction

The climate and sea-level evolution of past warm periods in the history of the Earth can give important insights into expected changes in the future. The Last Interglacial (LIG) in particular is often considered as a prime candidate for a potential, albeit limited, analogue for a warmer future world, due to a wealth of available reconstructions of climate and sea level for this period ~130-115 thousand years (kyr) ago (e.g. Dutton et al., 2015). Problems for the direct comparison between LIG and future climates arise mainly from the different forcing responsible for the warming, which can be ascribed to orbital variations during the LIG and to elevated levels of greenhouse gases in the future. During the LIG, global mean annual surface temperature is thought to have been 1°C to 2°C higher and peak global annual sea surface temperatures 0.7°C ± 0.6°C higher than pre-industrial (e.g. Turney and Jones, 2010; McKay et al., 2011), with the caveat that warmest phases were assumed globally synchronous in these data syntheses (Masson-Delmotte et al., 2013). These numbers are largely confirmed by a recent compilation, which resolves the temporal temperature evolution (Capron et al., 2014). Due to polar amplification, high latitude surface temperatures, when averaged over several thousand years, were at least 2°C higher~~larger~~ than present (Masson-Delmotte et al., 2013) and were up to 5°C higher~~larger~~ over the ice sheets (EPICA community members, 2004; Masson-Delmotte et al., 2015). These high temperatures had severe consequences for the evolution of the ice sheets at the onset and during the LIG as evidenced in large variations of sea level (Rohling et al., 2014; Grant et al., 2012). Coming out of the penultimate glaciation with a sea-level depression of up to 130 m, the global sea level has peaked during the LIG, estimated at 5.5 to 9 m higher than today (Dutton and Lambeck, 2012; Kopp et al., 2009;

2013), with a current best estimate of 6 m above the present level (Masson-Delmotte et al., 2013).

A higher-than-present sea-level stand almost certainly implies a complete melting of the Laurentide and Fennoscandian ice sheets and a contribution from the Greenland ice sheet (GrIS), from the Antarctic ice sheet (AIS), or from both. However, ice sheet retreat should not be assumed synchronous in the Northern and Southern hemispheres and between individual ice sheets. Fluctuations in global sea-level during the LIG period (Thompson et al., 2011;~~,~~ Kopp et al., 2013) could be a consequence of differences in the timing of retreat and regrowth ~~e.g.~~ between the ~~Greenland~~ GrIS and ~~Antarctic ice sheets~~AIS.

Because thus far direct evidence for an ~~Antarctic ice sheet~~AIS contribution to the LIG sea-level high-stand is elusive, support for a contribution from the AIS is usually given as a residual of total sea-level stand minus contributions from the GrIS, thermal expansion (THXP) and glaciers and small ice caps~~ (GIIC.).~~ This illustrates that the attribution problem is so far largely underdetermined. It appears that the lower bound of 5.5 m for the LIG sea-level high-stand (Dutton and Lambeck, 2012; Kopp et al., 2013) could be fully explained by maximum values given in the IPCC AR5 (Masson-Delmotte et al., 2013) for the contributions of the GrIS (1.4 - 4.3 m), ~~GIIC~~ glaciers and small ice caps (0.42 ± 0.11 m) and THXP (0.4 ± 0.3 m) combined. However, assuming central estimates for all individual components and the total would indicate an Antarctic contribution of ~ 3 m, which would be in line with the contribution estimated for a collapse of the West Antarctic ice sheet (WAIS) alone (Bamber et al., 2009). An Antarctic component is generally assumed to have foremost come from the WAIS, which is thought to be vulnerable due to its marine-based character. It is often speculated to be sensitive to ocean warming and increased sub-shelf melting (e.g. Duplessy et al., 2007; Holden et al., 2010), possibly caused by the interhemispheric see-saw effect (Stocker, 1998). However, a combination of partial WAIS collapse and some East Antarctic ice sheet (EAIS) retreat is also a possibility due to the large size of the latter. High-end estimates of sea-level change can only be reconciled with an additional ~~East Antarctic ice sheet~~EAIS contribution, supposedly from marine-based sectors in the Wilkes and Aurora basins (Pollard et al.,~~and DeConto,~~ 2015; DeConto and Pollard, 2016). One issue complicating the residual argument is the aforementioned possibility of different timing of the GrIS and AIS contributions. Indirect evidence of a WAIS reduction or collapse may come from climate modelling studies that attempt to explain stable-isotope ratios from ice (core) records (Holden et al., 2010;~~,~~ Steig et al., 2015).

The ~~Greenland ice sheet~~GrIS evolution is somewhat better constrained than the AIS evolution by ice core records both in the central part (GRIP, NGRIP, NEEM) and at the periphery (Dye-3, Camp Century), even if interpretation of the lower parts of the records ~~remain~~remains ambiguous. To this date, none of the Greenland ice cores shows continuous and undisturbed information back in time through the LIG and into the penultimate glacial maximum. The relatively high temperatures during the LIG as reconstructed from the folded lower parts of the NEEM ice core (NEEM community members, 2013; Landais et al., 2016) seem to be incompatible with the general view that the ice sheet has lost rather little volume during the LIG (e.g. Robinson et al., 2011; Colville et al., 2011~~; Rybak and Huybrechts, in prep.~~). Several studies have therefore attempted to identify possible biases in the NEEM reconstructions (e.g. van ~~De~~de Berg et al., 2013; Merz et al., 2014; Sjolte et al., 2014; Steen-Larsen et al.,~~,~~ 2014;~~,~~ Masson-Delmotte et al., 2015; Merz et al., 2016; Rasmus et al., 2016). Furthermore, the minimum extent and margin position of the northeastern part of the ice sheet is not well constrained, leaving room for alternative retreat scenarios (e.g. Born and Nisancioglu~~et al.~~, 2012).

Modelling studies of the GrIS~~Greenland ice sheet~~ for the entire LIG period so far often use parameterised representations of the climate forcing (e.g. Huybrechts, 2002), ~~or~~ forcing based on time slice climate experiments (e.g. Born and Nisancioglu~~Born et al.~~, 2012; Stone et al., 2013; Langebroek and Nisancioglu, 2016) or asynchronous coupling (Helsen et al., 2013), while full coupling between ice and climate models is still a challenge and limited to models of intermediate complexity (e.g. Robinson et al., 2011). Ice sheet modelling studies with specific focus on the ~~Antarctic ice sheet~~AIS during the LIG are rare due to the aforementioned lack of climate and geomorphological constraints for that period. However, some results on the AIS during the LIG have been presented in studies with main focus on other time periods (e.g. Huybrechts, 2002) or with interest on longer time scales (e.g. Pollard and D~~d~~eConto, 2009; de Boer et al., 2013, 2014). A recent study by DeConto and Pollard (2016) utilizes simulations ~~i~~of the AIS during the LIG to constrain future sea-level projections.

Despite recent advances (e.g. Capron et al., 2014), t~~T~~he fundamental shortcoming at present for improving modelled constraints on the LIG ice sheet contribution to sea level with physical models is the sparse information on LIG polar climate and oceanic conditions~~ over~~

~~the ice sheets and in their proximity~~. Consequently, our effort is directed towards studying key mechanisms and feedback processes in the coupled climate-ice sheet system during the LIG. ~~-~~Here, we present modelling results from the first ~~high resolution ice sheet models of the Greenland and Antarctic ice sheets~~ fully coupled climate-ice sheet simulation of the LIG period (135 kyr BP to 115 kyr BP) using ice sheet models of the GrIS and AIS~~to a~~ and a climate model of intermediate complexity~~ run for the time period 135 kyr BP to 115 kyr BP~~. In this set-up LIG sea-level evolution and climate-ice sheet interactions can be modelled in a consistent framework. With focus on climate and ice sheet changes in Greenland and Antarctica and corresponding sea-level changes, we compare results from the fully coupled model to former climate simulations with prescribed ice sheet changes and uncoupled ice sheet experiments. In the following, we describe the model (section 3) and the experimental setup (section 4) and present results (section 5) and conclusions (section 6).

3 Model description

We use the Earth s~~S~~ystem m~~M~~odel of i~~I~~ntermediate c~~C~~omplexity~~ (EMIC)~~ LOVECLIM version 1.3, which includes components representing the atmosphere, the ocean and sea ice, the terrestrial biosphere and the Greenland and Antarctic ice sheets (Fig. 1~~Figure 1~~). The model has been utilised in a large number of coupled climate-ice sheet studies (e.g. Driesschaert et al., 2007; Swingedouw et al., 2008; Goelzer et al., 2011; 2012~~a~~). Version 1.2 is described in detail in Goosse et al. (2010). The present set-up of the climate model component is identical to the model used in Loutre et al. (2014) and Goelzer et al. (2016~~5~~). Where in the latter study the ice sheet components were prescribed and used as forcing for the climate model, in the present work, they are fully two-way coupled with information exchanged every full year. The model components for the ~~Greenland~~ GrIS and ~~Antarctic ice sheets~~AIS are three-dimensional thermomechanical ice-dynamic models (Huybrechts and de Wolde, 1999), which have been utilised for long-term stand-alone ice sheet simulations in the past (Huybrechts, 2002). Their behaviour in the coupled system and detailed analysis of the ice sheet mass balance components are described in Huybrechts et al. (2011).~~.~~ The surface mass balance model is based on the positive degree-day (PDD) method (Janssens and Huybrechts, 2000) and distinguishes between snow accumulation, rainfall and meltwater runoff, all parameterized as a function of temperature. Surface melt is estimated based on two distinct PDD factors for ice and snow and may be retained and refreeze in the snow pack.

Melt model parameters are unmodified compared to earlier studies (Goosse et al., 2010; Huybrechts et al., 2011) and have been extensively validated for the present day (e.g. Vernon et al., 2013).

Because of the relatively coarse resolution of the atmosphere in LOVECLIM (T21), the higher ~~-~~resolution ice sheet models (10x10 km for Greenland and 20x20 km for Antarctica) are forced with temperature anomalies and precipitation ratios relative to the pre-industrial reference climate. Climate anomalies are interpolated to the ice sheet grids using Lagrange polynomials and the SMB-elevation feedback is accounted for natively in the PDD model on the ice sheet grid.

The ice sheet models in turn provide the climate model with changing topography, ice sheet extent (albedo) and spatially and temporally variable freshwater fluxes.~~,~~ The coupling procedure for these variables is unmodified to earlier versions of the model (Goosse et al., 2010), while r~~. R~~ecent model improvements for the ice-climate coupling interface are described in Appendix A.

3.1 Pre-industrial reference model state

A pre-industrial climate state required as a reference for the anomaly forcing mode is generated by running the climate model with fixed present-day modelled ice sheet configuration to a steady state. Standard settings for orbital parameters and greenhouse gas forcing for this experiment are applied following the PMIP3 protocol (https://pmip3.lsce.ipsl.fr/). The present day ice sheet configurations for the GrIS and AIS are the result of prolonging the same stand-alone ice sheet experiments used to initialise the LIG ice sheet configuration described below towards the present day (Huybrechts and de Wolde, 1999; Huybrechts, 2002; Goelzer et al., 2016).

~~3.1~~3.2 Northern Hemisphere ice sheet forcing

At the onset of the LIG, large Northern Hemisphere (NH) ice sheets other than on Greenland were still present and melted away over the course of several millennia. To account for these ice sheet changes and their impact on climate and ocean evolution, a reconstruction of the penultimate deglaciation of the NH is necessary for our experiments starting in 135 kyr BP. Because there is very little geomorphological evidence for NH ice sheet constraints during

Termination II, a reconstruction of NH ice sheet evolution is made by remapping the retreat after the L~~l~~ast G~~g~~lacial M~~m~~aximum according to the global ice volume reconstruction (Lisiecki and Raymo, 2005) during the onset of the LIG. The same procedure was already used in earlier work to produce NH ice sheet boundary conditions for climate model simulations (Loutre et al., 2014; Goelzer et al., 2016~~5~~).

~~3.2~~3.3 Modelled sea-level change

The modelled sea-level evolution takes into account contributions from the prescribed NH ice sheets, the ~~Greenland and Antarctic ice sheets~~GrIS and AIS and the steric contribution due to density changes of the ocean water. The only component not explicitly modelled is the contribution of glaciers and small ice caps, which have been estimated to give a maximum contribution of 0.42 ± 0.11 m during the LIG (Masson-Delmotte et al., 2013) and may contain as much as 5-6 m sea-level equivalent~~SLE~~ during glacial times (CLIMAP, 1981; Clark et al., 2001).

The Antarctic contribution to global sea-level change is calculated taking into account corrections for ice replacing seawater, ~~and~~ ice being replaced by seawater *and* seawater being replaced by isostatic bedrock movement. These effects~~,~~ ~~both~~ are mainly of importance for the marine sectors of the WAIS. Note that these~~is~~ effects are~~is~~ not considered in the climate model, which operates with a fixed present-day land-sea mask. The additional correction for bedrock changes is responsible for a ~3 m lower sea-level contribution at 135 kyr BP compared to taking only changes in volume above floatation into account. This additional sea-level depression arises from depressed bedrock under the load of the ice in the marine sectors of the ice sheet.

For the GrIS~~Greenland ice sheet~~, the same corrections are applied, where the marine extent of ice grounded below sea level is parameterised. However, the corrections imply only a ~30 cm lower contrast to present day sea level due to ~~Greenland ice sheet~~GrIS expansion at 135 kyr BP and ~15 cm higher at 130 kyr BP compared to calculations based on the entire grounded ice volume. The change in sign arises from bedrock changes in delayed response to ice loading changes coming out of the penultimate glacial period.

The steric component of global sea level considers density changes due to local changes of temperature and salinity, but global salinity is restored as often done in ocean models to guarantee stability.

4 Experimental setup

4.1 Model forcing

All simulations are forced by time-dependent changes in greenhouse gas (GHG) concentrations and insolation running from 135 kyr BP until 115 kyr BP (Fig. 2~~Figure 2~~). The radiative forcing associated with the reconstructed GHG levels is below pre-industrial values for most of this period and hardly exceeds it at ~128 kyr BP (Fig. 2b). The changes in the distribution of insolation received by the Earth are ~~dynamically~~ computed from the changes in the orbital configuration (Berger, 1978) and represent the governing forcing during peak LIG conditions (Fig. 2a).

In order to account for coastline changes and induced grounding line changes, both ice sheet models are forced by changes in global sea-level stand (Fig. 2~~Figure 2~~c) using a recent sea-level reconstruction based on Red Sea data (Grant et al., 2012). The chronology of ~~the latter~~this data is thought to be superior compared to sea-level proxies based on ~~assumes ice volume to be independent of deep-sea temperatures, in contrast to directly using the~~ scaled benthic δ^{18}O records~~ as sea-level proxy~~ (Grant et al., 2012; Shakun et al., 2015). In this sea-level forcing approach, local changes due to geoidal eustasy are not taken into account, which would result in lower amplitude sea-level changes close to the ice sheets, but that would not be consistent with the stand-alone spin-up of the ice sheet models.

As mentioned earlier, the ice sheet models are forced with temperature anomalies relative to the pre-industrial reference climate. T~~As a measure t~~o ensure a realistic simulation of the GrIS~~Greenland ice sheet~~ evolution, the temperature anomaly forcing from the climate model over the GrIS~~Greenland ice sheet~~ needs to be rescaled. In absence of such scaling, the ice sheet almost completely melts away over the course of the LIG in disagreement with the ice core data, which suggests a large remaining ice sheet during the LIG (Dansgaard et al., 1982; NEEM community members, 2013). In the absence of firm constraints on the climate evolution over the ice sheet, the temperature scaling in the present study represents a pragmatic solution to produce a ~~n ice sheet~~GrIS evolution reasonably in line with ice core constraints on minimum ice sheet extent during the LIG. The scaling is only applied for the

GrIS, since we have not identified a physical process that would justify a similar procedure for to the AIS.

4.2 Reference simulation and sensitivity experiments

Our reference simulation is a fully coupled experiment with a~~A~~ uniform scaling of the atmospheric temperature anomaly over Greenland with a factor of R=0.4, which was chosen to give a good match to constraints on minimum extent of the GrIS during the LIG. Additional sensitivity experiments are listed in Table 1 and are described in the following.

~~was adopted in the reference~~T~~ experiment and is later compared to t~~wo sensitivity experiments with modified scaling (R=0.5, 0.3) are added to evaluate the impact on the results. The range of parameter R is chosen to retain an acceptable agreement of the minimum GrIS extent during the LIG with reconstructions. In practice, the high scaling factor is chosen to produce the smallest minimum ice sheet extent, which still has ice at the NEEM site. The low scaling factor was adopted to produce the smallest minimum ice sheet extent still covering Camp Century.

The three fully coupled experiments are complemented~~accompanied~~ by additional sensitivity experiments, in which the ice sheet models are forced~~ in stand-alone mode~~ with (modified) climate forcing produced by the fully coupled reference run~~s~~. These experiments serve to study ice sheet sensitivity in response to changes in the climate forcing and are also used to evaluate ice sheet-climate feedbacks ~~in comparison between~~by comparing the coupled and un-coupled system. The ice sheet ~~response~~ evolution in the ~~reference~~ forced~~stand-alone~~ reference experiment (ice sheet model run~~forced~~ offline with the recorded climate forcing of the coupled reference run) should~~is~~ by construction be identical to the response in the fully coupled run, and only serves as a control experiment. Two a~~A~~dditional forced experiments have been run with modified temperature scaling for the GrIS~~Greenland ice sheet~~ (R=0.5, 0.3), which can be directly compared to the respective fully coupled experiment.

For the AIS, an experiment~~s~~ with suppressed sub-shelf melting has~~ve~~ been performed to isolate the effect of ocean temperature changes on the ice volume evolution and sea-level contribution.

~~4.2~~4.3 Initialisation of the reference simulation

The goal of our initialisation technique is to prepare a coupled ice sheet-climate model state for the transient simulations starting at 135 kyr BP exhibiting a minimal coupling drift. Both ice sheet models are first integrated over the preceding glacial cycles in order to carry the long-term thermal and geometric history with them (Huybrechts and de Wolde, 1999; Huybrechts, 2002; Goelzer et al., 2016). The climate model is then initialized to a steady state with ice sheet boundary conditions, greenhouse gas forcing and orbital parameters for the time of coupling (135 kyr BP). When LOVECLIM is integrated forward in time in fully coupled mode, the climate component is already relaxed to the ice sheet boundary conditions. The mismatch between stand-alone ice sheet forcing and climate model forcing is incrementally adjusted in the period 135-130 kyr BP with a linear blend between the two to minimize the effect of changing boundary conditions for the ice sheet model. A small, unavoidable coupling drift of the ice sheet component arises from a switch of spatially constant to spatially variable temperature and precipitation anomalies at the time of coupling, but is uncritical to the results.

5 Results

The modelled LIG climate evolution and comparison with proxy reconstructions were presented in detail in two earlier publications (Loutre et al., 2014; Goelzer et al., 2016~~5~~) for the same climate model setup. Differences to the work by Goelzer et al. (2016~~5~~) arise from a different ice sheet evolution and from the incorporation of feedbacks between climate and ice sheets that are taken into account in our present, fully coupled approach.

5.1 Climate evolution

Global annual mean near-surface air temperature in the reference experiment (Fig. 3) shows a distinct increase until 129 kyr BP in response to orbital and greenhouse gas forcing (Fig. 2) and to an even larger extent in response to changes in ice sheet boundary conditions ~~(Figure 3)~~. The peak warming reaches 0.3 °C above the pre-industrial at 125.5 kyr BP. Thereafter, cooling sets in and continues at a much lower rate compared to the rate of warming before 129 kyr BP. The importance of ice sheet changes is illustrated by comparing the reference experiment with a climate simulation (Loutre et al., 2014) forced by insolation and GHG changes only (noIS) and with a one-way coupled climate model run (Goelzer et al., 2016~~5~~)

forced with prescribed NH, Antarctic and Greenland ice sheet changes (O~~o~~ne-way). The fully-coupled experiment exhibits a global mean temperature evolution during the LIG, which is very similar to One-way (Fig. 3). A~~The~~ much larger temperature contrast at the onset of the LIG in the reference experiment compared to noIS arises mainly from changes in surface albedo and melt water fluxes of the Northern Hemisphere ice sheets, which freshen the North Atlantic and lead to a strong reduction of the Atlantic meridional overturning circulation (Loutre et al., 2014). All three simulations show only small differences in the global mean temperature evolution after 127 kyr BP. The episode of relative cooling in the reference experiment with a local temperature minimum at 128 kyr BP is due to cooling of the Southern Ocean (SO) and sea-ice expansion in response to large Antarctic freshwater fluxes caused mainly by the retreat of the WAIS. This mechanism~~,~~ ~~which~~ was already described by Goelzer et al. (2016), but now occurs 2 kyr later ~~compared to~~in the ~~one-way~~fully coupled experiment, due to a modified timing of the AIS retreat. The effect of including ice-climate feedbacks by means of a two-way coupling is otherwise largely limited to the close proximity of the ice sheets as discussed in the following.

~~5.1~~5.2 Greenland ice sheet

The Greenland ice sheet evolution over the LIG period is largely controlled by changes in the surface mass balance ~~with predominant importance of~~dominated by -surface meltwater runoff ~~the ablation~~ (Fig. 4~~Figure 4~~c). Specifically,~~Marginal~~ summer surface melt water runoff from the margins is the dominant mass loss of the ~~ice sheet~~GrIS after 130 kyr BP, when the ice sheet has retreated largely on land. Due to increased air temperatures over Greenland, the mean accumulation rate (averaged over the ice covered area) is consistently above the present-day reference level after 128 kyr BP, but increases to at most 18% higher (Fig. 4~~Figure 4~~b). Conversely, the mean ~~ablation~~ runoff rate over Greenland shows an up to threefold increase compared to the present day with consistently higher-than present rates between 130.5 kyr to 120.5 kyr BP (Fig. 4~~Figure 4~~c). Temperature anomalies responsible for the increased ~~ablation~~ runoff are on average above zero between 129.5 kyr to 120.5 kyr BP and peak at 1.3 °C (after scaling) around 125 kyr BP (Fig. 4~~Figure 4~~a). The calving flux (Fig. 4~~Figure 4~~d) decreases as surface melting and runoff (Fig. 4~~Figure 4~~c) increase, removing some of the ice before it can reach the coast and also as the ice sheet retreats from the coast (cf. Fig. 5~~Figure 5~~), in line with decreasing area and volume (Fig. 4~~Figure 4~~f).~~(in line with decreasing area and volume, Figure 5) and as surface melting and runoff increase, removing~~

~~some of the ice before it can reach the coast.~~ In the second half of the experiment, runoff decreases with decreasing temperature anomalies and the calving flux increases again with increasing ice area and volume. The net mass balance of the ice sheet (Fig. 4e) reflects the compounded effect of all components with negative values before and positive values after the time of minimum volume.

Entering the warm period, the furthest retreat of the ice sheet occurs in the southwest and northwest (Fig. 5~~Figure 5~~), accompanied by an overall retreat from the coast. ~~Conversely~~At the same time, the ice sheet gains in surface elevation over the central dome due to increased accumulation. By 115 kyr BP, the ice sheet has regrown beyond its present day area almost everywhere and contact with the ocean is increasing. The GrIS volume change ~~translates into~~implies a sea-level contribution peak of 1.4 m at 123 kyr BP (Fig. 11a~~Figure 9~~). For the two sensitivity experiments (H~~h~~igh, L~~l~~ow) with modified scaling (R=0.5, 0.3), the contribution changes to 2.7~~8~~ m and 0.65 m, respectively, crucially controlled by the scaling factor (Table 2).

NEEM ice core data (NEEM community members, 2013) and radiostratigraphy of the entire ice sheet (MacGregor et al., 2015) indicate that the NEEM ice core site was ice covered through the entire Eemian as is the case for our reference experiment. Elevation changes from that ice core are however not very well constrained and even if they were, would leave~~s~~ room for a wide range of possible retreat patterns of the northern GrIS (e.g. Born and Nisancioglu~~Born et al.~~, 2012). The Camp Century ice core record contains some ice in the lowest part with a colder signature then ice dated as belonging to the Eemian period (Dansgaard et al., 1982). It is likely that this ice is from before the Eemian even in view of possible disturbance of the lower levels, which was shown to exist for the NEEM core site (NEEM community members, 2013). ~~Reconstruction of the age structure from radiostratigraphy (MacGregor et al., 2015) shows no ice at the Camp Century location before 115 kyr BP. However, it is possible that isochrones were disturbed and unreliable for interpretation in this region.~~ In view of this evidence, the north~~-~~western retreat of the ice sheet in our reference simulation may be too far inland, as a direct result of the largely unconstrained climatic forcing in this area. It was shown that a different climate forcing could produce ~~e.g.~~ a larger northern retreat still in line with the (limited) paleo evidence (Born and Nisancioglu~~Born et al.~~, 2012). Some more thinning and retreat in the south is also possible without violating constraints on minimal ice sheet extent from Dye-3 (Dansgaard et al., 1982). LIG ice cover of the Dye-3 site is not a necessity when taking into consideration that older ice found at the base of the core could have flowed in from a higher elevation.

A comparison of modelled temperatures in North-East Greenland (Fig. 6~~6~~) shows differences of up to 5 degrees between annual mean and summer temperatures in the reference experiment. Comparison with temperature reconstructions based on the NEEM ice core record indicates that the steep temperature increase marking the onset of the LIG occurs 2-3 kyr earlier in the model compared to the reconstructions. The amplitude of modelled summer temperatures attains levels of the central estimate, while annual mean temperatures fall in the lower uncertainty range of the reconstructions. Temperatures exceeding the central estimate are only reached in the One-way experiment, which exhibits a somewhat different retreat pattern of the GrIS due to the different climate forcing (Goelzer et al., 2016).

~~The climatic temperature anomaly over central Greenland in the coupled model shows a flat maximum around 127 kyr BP, similar to the global temperature evolution, but 2 kyr earlier compared to the NEEM reconstructions (NEEM community members, 2013). If assuming present-day configuration and spatially constant warming, ice mass loss from the GrIS could be expected to occur approximately as long as the temperature anomaly remains above zero, which is the case until ~ 122 kyr BP in the model and until ~ 119 kyr BP in the NEEM reconstruction. With a lower surface elevation, the time the ice sheet starts to gain mass again would be further delayed. Even with considerable uncertainty due to uncertain spatial pattern of the warming, which modifies this simple reasoning, we argue that the peak sea-level contribution from the GrIS has to occur late during the LIG. Based on the same argument, there is no evidence in the reconstructed NEEM temperature evolution suggesting a regrowth or substantial pause of melting of the Greenland ice sheet any time during the LIG.~~

~~The need for scaling the temperature forcing to produce a realistic Greenland ice sheet evolution equally applies when forcing our stand-alone ice sheet model with the temperature reconstructed from the NEEM ice core record (NEEM community members, 2013). It appears that practically any ice sheet model with (melt parameters tuned for the present day) would project a near-complete GrIS meltdown, if the amplitude and duration of warming suggested by the NEEM reconstructions would apply for the entire ice sheet. This problem would be further amplified if insolation changes were explicitly taken into account in the melt model (Robinson and Goelzer, 2014). We refer to this mismatch between reconstructed temperatures~~

~~and assumed minimum ice sheet extent as the "NEEM paradox". Several attempts to solve this paradox have been made by suggesting possible biases in the interpretation of the relationship between isotope ratio and temperature, which may not be assumed temporally and spatially constant (e.g. Merz et al., 2014; Sjolte et al., 2014; Steen-Larsen et al., 2014, Masson-Delmotte et al., 2015) and may be affected by changes in the precipitation regime (van De Berg et al., 2013). From the modelling point of view, the decisive question is over what spatial extent and when during the year the temperature reconstruction (and possible future reinterpretations) for the NEEM site should be assumed. A central Greenland warming of large magnitude could only be reconciled with the given geometric constraints if a (much) lower warming was present over the margins and during the summer, which is where and when the majority of the mass loss due to surface melting is taking place.~~

The strength of the ice-climate feedback on Greenland was examined by comparing additional experiments in which the coupling between ice sheet and climate is modified. Results from the fully coupled model ~~(Reference)~~ are compared to those from forced ice sheet runs ~~(SA)~~ that ~~, which~~ are driven with the climate forcing from the coupled reference model run (Table 2 and Fig. 7a). ~~In both cases the~~ The scaling of Greenland forcing temperature is set to a magnitude of 0.3 (Forced l~~l~~ow), 0.4 (Forced reference) and 0.5 (Forced h~~h~~igh), respectively. When the feedback between ice sheet changes and climate is included in the coupled experiments, the warming over the margins is considerably increased (reduced) for experiment H~~h~~igh (L~~l~~ow) compared to the respective forced~~stand-alone~~ experiments. Consequently, ~~sea-level contributions~~ice volume changes show a non-linear dependence on the temperature scaling for the fully coupled run, while they are near linear for the forced runs (Table 2~~Table 1~~ and Fig. 7~~Figure 6~~a~~, left~~). The dominant (positive) feedback mechanism arises from how changing albedo characteristics are taken into account for a melting ice sheet surface (Fig. 7b). The underlying surface type with different characteristic albedo values for tundra and ice sheet is determined by the relative amount of ice cover, which is modified when the area of the ice sheet is changing. On much shorter time scales, the~~The~~ albedo can change due to changes in snow depth and also due to changes of the snow cover fraction, which indicates how much surface area of a grid cell is covered with snow (Fig. 7~~Figure 6~~b~~, right~~). Both snow processes lead to lower albedo and increased temperatures in places where the ice sheet starts melting at the surface. The difference in warming between forced~~stand-alone~~ and fully-coupled experiments is ~~therefore~~ however located over the ice sheet margins and this does not have a considerable influence on the NH or global temperature response.

The snow albedo effects are near-instantaneous and their importance for the ice sheet response underline earlier findings that a basic albedo treatment is an essential aspect of a coupled ice–climate modelling system (e.g. Robinson and Goelzer, 2014). A ~~third, but~~ comparatively smaller effect and operating on much longer time scales arises from the retreating ice sheet margin being replaced by ~~lower albedo~~ tundra with a lower albedo (Fig. 7~~Figure 6~~b~~, right~~)~~, which operates on much longer time scales~~.

~~5.2~~5.3 Antarctic ice sheet

The annual mean air temperature anomaly over Antarctica (averaged over grounded ice) increases at the beginning of the experiment to reach a peak of up to 2°C at 125 kyr BP (Fig. 8~~Figure 7~~a), before cooling sets in and continues until 115 kyr BP. The warming before the peak ~~necessary to reach temperature anomalies of up to two degrees~~ is around a factor two faster than the cooling ~~trend~~ afterwards, with both transitions being near linear on the millennial time scale. The surface climate over the ~~Antarctic ice sheet~~AIS ~~surface climate~~ appears to be largely isolated from millennial time scale perturbations occurring in the Southern Ocean in response to changing freshwater fluxes in both hemispheres (Goelzer et al., 2016). While freshwater fluxes from the retreating ~~Antarctic ice sheet~~AIS itself lead to sea-ice expansion and surface cooling in the Southern Ocean, freshwater fluxes from the decay of the Northern Hemisphere ice sheets are communicated to the SH by the interhemispheric see-saw effect (Goelzer et al., 2016~~5~~). Pre-industrial surface temperature levels are first reached 128 kyr BP and after cooling again at 118 kyr BP. The accumulation rate (averaged over grounded ice) shows an initial increase in line with the higher temperatures until 130 kyr BP (Fig. 8b) but records a changing grounded ice sheet area further on, which mostly indicates retreat of the ice sheet from regions of higher accumulation. Relative to the pre-industrial, accumulation increases at most 20 % in annual values and up to 12 % for the long-term mean (grey and black lines in Fig. 8~~Figure 7~~b, respectively). As a consequence of the surface forcing, the AIS shows a small volume gain until 130.5 kyr BP (Fig. 8f) due to increase in precipitation before a large-scale retreat of the grounding line sets in. The average ~~ablation~~ runoff rate over grounded ice equally increases with increasing temperature (Fig. 8c) but remains of negligible importance (note difference of vertical scales between panel b and c in Fig. 8~~Figure 7~~) ~~.~~for the net mass balance (Fig. 8~~Figure 7~~e) of the ice sheet ~~(note difference of vertical scales between panel b and c in Figure 7).~~

Changes in the sub-shelf melt rate play an important role for the present mass balance of the AIS and are often discussed as a potential forcing for a WAIS retreat during the LIG (e.g. Duplessy et al., 2007; Holden et al., 2010) and during the last deglaciation (Golledge et al., 2014). The average sub-shelf melt rate diagnosed for the area of the present-day observed ice shelves in our reference simulation (Fig. 8d) ~~–~~increases to at most 20 % above the pre-industrial with a peak in line with the air temperature maximum (Fig. 8~~Figure 7~~a, d). However, ocean warming to above pre-industrial temperatures occurs already before 130 kyr BP (not shown), more than 2 kyr earlier compared to the air temperature signal. This is a consequence of the interhemispheric see-saw effect (Stocker, 1998), which explains SO warming and cooling in the North Atlantic as a consequence of reduced oceanic northward heat transport due to a weakening of the Atlantic meridional overturning circulation (Goelzer et al., 2016).

Ice sheet area and volume (Fig. 8f) decrease rapidly between 129 and 127 kyr BP, and indicate a gradual regrowth after 125 kyr BP, also visible in the net mass balance (Fig. 8e). Those changes arise mainly from a retreat and re-advance of the WAIS (Fig. 9~~Figure 8~~). In our model, the ice sheet retreat exhibits characteristics of an overshoot behaviour due to the interplay between ice sheet retreat and bedrock adjustment. The rebound of the bedrock, which is initially depressed under the glacial ice load, is delayed compared to the relatively rapid ice sheet retreat, giving rise to a grounding-line retreat well beyond the pre-industrial steady-state situation. These results are in line with earlier work with a stand-alone ice sheet model (Huybrechts, 2002), but also rely on a relatively large glacial-interglacial loading contrast in these particular models. The sea-level contribution above the present-day level from the ~~Antarctic ice sheet~~AIS peaks at 125 kyr BP at 4.4 m (Fig. 11b).

S~~Stand-alone s~~ensitivity experiments, in which specific forcing processes are suppressed, show that surface melting (not shown) and sub-shelf melting play a limited role for the AIS retreat in our experiments. The sea-level contribution peak in an experiment with suppressed sub-shelf melting (Fig. 11b) is about 40 cm lower compared to the reference experiment and remains around one meter lower between 123 kyr BP until the end of the experiment. The difference between the experiments at a given point in time arises from a lower overall sea-level contribution when sub-shelf melting is suppressed, but also from a difference in timing between both cases. The dominant forcing for the ~~Antarctic ice sheet~~AIS retreat in our model is a combination of rising global sea level and increasing surface temperature, which leads to increasing buoyancy and reduced ice shelf viscosity, respectively. The relative timing between sea-level forcing (Fig. 2c) and temperature forcing (Fig. 8a) is therefore of critical importance for the evolution of the ice sheet at the onset of the LIG.

The limited effect of surface melting and sub-shelf melting on the sea-level contribution is ultimately due to a limited magnitude of surface temperature and ocean temperature changes. The limited Antarctic and SO temperature response has already been highlighted in earlier studies with the same climate component (Loutre et al., 2014; Goelzer et al., 2016~~5~~) and is confirmed here with a fully-coupled model. The feedback mechanism suggested by Golledge et al. (2014) for Termination I, which draws additional heat for sub-shelf melting from freshwater-induced SO stratification and sea-ice expansion is also active in our experiment, but too short-lived and of too little amplitude to lead to substantially increased melt rates. Our limited AIS response to ~~environmental~~ climatic forcing is also in line with other modelling results for the LIG period (Pollard et al.~~and DeConto~~, 2015), albeit with a different forcing strategy, where substantial retreat of marine based sectors of the EAIS can only be achieved by including special treatment of calving fronts and shelf melting, which was not ~~attempted~~ included here.

As mentioned earlier, direct constraints of the ~~Antarctic ice sheet~~AIS configuration during the LIG are still lacking. Goelzer et al. (2016~~5~~) suggested that the timing of the main glacial-interglacial retreat of the AIS could be constrained by a freshwater induced oceanic cold event recorded in ocean sediment cores (Bianchi and Gersonde et al., 2002). The main retreat in their one-way coupled climate model run ~~model~~ happened ~129.5 kyr BP, a timing predating the time of retreat in the fully coupled model by ~2 kyr due to the difference in atmospheric and oceanic forcing. This lag is also visible in modelled temperature changes over the East Antarctic ice sheet (EAIS) that have been compared to temperature reconstructions for four ice core locations (Fig. 10~~9~~). One-way and Reference show a larger temperature contrast, better in line with the ice core data, compared to the experiment with a fixed ice sheet (noIS). However, the timing of warming was better matched in One-way with an earlier ice sheet retreat.

It is noteworthy in this context that the prescribed sea-level forcing imposes an important control for the timing of the Antarctic retreat and is a source of large uncertainty. We have only used the central estimate of the Grant et al. (2012) sea-level reconstruction, but propagated dating uncertainties could accommodate a shift of the forcing by up to 1 kyr either way. ~~Sensitivity~~ Former experiments (not shown) have indicated that the main retreat appears another 2 kyr later when a sea-level forcing based on a benthic $\delta^{18}O$ record (Lisiecki and Raymo, 2005) is used instead of the sea-level reconstruction of Grant et al. (2012).

~~5.3~~5.4 Thermal expansion of the ocean

The steric sea-level component due to ocean thermal expansion (Fig. 11~~Figure 9~~c) is largely following the global temperature evolution (Fig. 3), but is also strongly modified by changes in ice sheet freshwater input. Ocean expansion is ~~steep~~ rapid during peak input of freshwater and stagnant during episodes of decreasing freshwater input. This is because the net ocean heat uptake is large when freshwater input peaks, which happens in three main episodes in our experiment. Two episodes of freshwater input from the NH centred at 133.6 and 131.4 kyr BP are followed by an episode of combined input from the NH and the AIS centred at 128.2 kyr BP (not shown). The anomalous freshwater input leads to stratification of the surface ocean, sea-ice expansion and reduction of the air-sea heat exchange, effectively limiting the ocean heat loss to the atmosphere. This implies that global sea-level rise due to ice sheet melting is (weakly and temporarily) amplified by the freshwater impact on ocean thermal expansion. We simulate a peak sea-level contribution from thermal expansion of 0.35 m at 125.4 kyr BP, which forms part of a plateau of high contribution between 127.3 and 124.9 kyr BP (Fig. 11~~Figure 9~~c). The amplitude is ~~at the lower end, but well~~ within the range of ~~IPCC AR5~~current estimates of 0.4 ~~2~~± 0.3~~11~~ m (McKay et al., 2011; Masson-Delmotte et al., 2013).

~~5.4~~5.5 Global sea-level change

Combining contributions from GrIS, AIS and~~,~~ thermal expansion, global sea level peaks at ~5.3 m at 124.5 kyr BP (Fig. 12c) with a slow decrease thereafter as first the ~~Antarctic ice sheet~~AIS and 2 kyr later the ~~Greenland ice sheet~~GrIS start to regrow. For the ~~Antarctic ice sheet~~AIS the model indicates a clear asymmetry between relatively fast retreat and much slower regrowth (Fig. 12b).

Modelled GrIS and AIS sea-level contributions together with prescribed NH sea level are within the 67% confidence interval of probabilistic sea-level reconstructions (Kopp et al., 2009) for the period ~125-115 kyr BP (Fig. 12~~Figure 10~~). The last 20 m rise in sea-level contributions from the NH (including Greenland) is steeper and occurs 1~2 kyr earlier in our model compared to what the reconstructions suggest, which is consequently also the case for the rise in global sea level at the onset of the LIG. The Antarctic retreat in our model is more rapid compared to the reconstruction and does not show the regrowth~~hiatus~~ ~131-129 kyr BP suggested by the data from Kopp et al. (2009). The modelled ice sheet evolution in our reference run reproduces well the global average sea-level contribution 125-115 kyr BP based on the best estimate of Kopp et al. (2009) when taking into account the modelled steric contribution (0.35 m) and assuming a~~n additional~~ maximum possible contribution (0.42+-0.11 m) of glaciers and small ice caps (Masson-Delmotte et al., 2013). The multi-peak structure of global sea-level contributions during the LIG ~~-~~suggested by the median reconstructions (Kopp et al., 2009; 2013) is not reproduced with our model (Fig. 12c), mainly owing to the lack of such variation in the climate forcing and to the long response times of the ice sheets during regrowth to changing climatic boundary conditions.

6 Discussion

6.1 Global sea-level change

While the median projections in Kopp et al., (2009) visually suggest a double-peak structure in the global sea-level evolution during the LIG, our results show that the uncertainty range is wide enough to accommodate a global sea-level trajectory based on physical models without intermediate low stand. The simulated climate forcing in our case does not favour the presence of such variability, which admittedly could be due to missing processes or feedbacks in our modelling. Nevertheless, based on our own modelling results and the Kopp et al., (2009) reconstruction we are not convinced reproducing a double peak structure is a given necessity.

6.2 Greenland ice sheet evolution

The temperature anomaly over central Greenland in the coupled model shows a flat maximum around 127 kyr BP (Fig. 4a), similar to the global temperature evolution, but 2 kyr earlier compared to the NEEM reconstruction (NEEM community members, 2013). If assuming present-day configuration and spatially constant warming, ice mass loss from the GrIS could be expected to occur approximately as long as the temperature anomaly remains above zero, which is the case until ~ 122 kyr BP in the model and until ~ 119 kyr BP in the NEEM reconstruction. With a lower surface elevation, the time the ice sheet starts to gain mass again would be further delayed. Even with considerable uncertainty due to uncertain spatial pattern of the warming, which modifies this simple reasoning, we argue that the peak sea-level contribution from the GrIS has to occur late during the LIG. Based on the same argument, there is no evidence in the reconstructed NEEM temperature evolution suggesting a regrowth or substantial pause of melting of the GrIS any time during the LIG.

The need for scaling the temperature forcing to produce a realistic GrIS evolution would equally apply when our ice sheet model were forced directly with the temperature reconstructed from the NEEM ice core record (NEEM community members, 2013). It appears that practically any ice sheet model with (melt parameters tuned for the present day) would project a near-complete GrIS meltdown, if the amplitude and duration of warming suggested by the NEEM reconstructions would apply for the entire ice sheet. This problem would be further amplified if insolation changes were explicitly taken into account in the melt model (van de Berg et al., 2011; Robinson and Goelzer, 2014). We refer to this mismatch between reconstructed temperatures and assumed minimum ice sheet extent as the “NEEM paradox”. Several attempts to solve this paradox have been made by suggesting possible biases in the interpretation of the relationship between isotope ratio and temperature, which may not be assumed temporally and spatially constant (e.g. Merz et al., 2014; Sjolte et al., 2014; Steen-Larsen et al., 2014; Masson-Delmotte et al., 2015) or may be affected by changes in the precipitation regime (van de Berg et al., 2013) and sea ice conditions (Merz et al., 2016; Rasmus et al., 2016). From a modelling point of view, the decisive question is over what spatial extent and when during the year the temperature reconstruction (and possible future reinterpretations) for the NEEM site should be assumed. A central Greenland warming of large magnitude could only be reconciled with the given geometric constraints if a (much) lower warming was present over the margins and during the summer, which is where and when the majority of the mass loss due to surface melting is taking place.

6.3 Antarctic ice sheet evolution

The main forcing for WAIS retreat during Termination II and the LIG was found to be global sea-level rise, and to a lesser extent surface warming causing a gradual thinning of the ice shelves as the ice softened. These processes also played during Termination I and into the Holocene in simulations with the same ice sheet model (Huybrechts, 2002), but did not produce an overshoot. That is mainly because the speed of sea-level rise was slower and the sea-level itself did not overshoot the Holocene level. Of importance to generate overshoot ~~behavior~~ behaviour is the speed of sea-level rise relative to the speed of bedrock rebound as both control grounding-line migration because of hydrostatic equilibrium. If the sea-level rise is faster than the bedrock uplift, grounding line retreat will be enhanced, as was the case during Termination II in our model experiments. If on the contrary, the bedrock rebound after ice unloading is faster than the sea-level rise, this will tend to dampen grounding-line retreat, as shown in the sensitivity experiments discussed in Huybrechts (2002).

Ice shelf viscosity changes also played a role during Termination II and the LIG, but were not found to be the dominant forcing. The response time of viscosity changes in the ice shelves is governed by vertical heat transport, having a typical characteristic time scale of 500 years with respect to surface temperature (Huybrechts and de Wolde, 1999). The mechanism can only be effective over longer time scales and for a limited warming such as occurred during the LIG as otherwise the ice shelves would largely disintegrate from both surface and basal melting. In future warming scenarios, the effect of shelf viscosity changes is therefore usually too slow compared to the anticipated direct effect of increased surface and basal melting rates. For instance, in the future warming scenarios performed with LOVECLIM under 4xCO_2 conditions (Huybrechts et al., 2011), shelf melt rates increased 5-fold, and the ice shelves were largely gone before they had a chance to warm substantially. The implication is that analogies between these different time periods should be reserved on account of different processes playing at different time scales.

6.4 Comparison with other work

An earlier attempt to model the coupled climate-ice sheet evolution for the Greenland ice sheet over the LIG period (Helsen et al., 2013) applied an asynchronous coupling strategy to cope with the computational challenge of such long simulations. While it can be assumed that their high-resolution regional climate model provides a more accurate climate forcing compared to our approach, we still lack substantial climate and ice sheet reconstructions for the LIG period to effectively validate model simulations. This applies to the simulated climate as well as to the resulting ice sheet geometries, limiting attempts to constrain the GrIS sea-level contribution to arrive at relatively large and overlapping uncertainty ranges (e.g. Robinson et al., 2011; Stone et al., 2013; Helsen et al., 2013; Langebroek and Nisancioglu, 2016). Incidentally, o~~O~~ur range of modelled GrIS sea-level contribution is ~~incidentally~~ in very close agreement with recent results from a large ensemble study of the LIG sea-level contribution constrained against present-day simulations and elevation changes at the NEEM ice core site (Calov et al., 2015). Despite a possible degree of coincidence in this partic~~lu~~ular case, the overlap between results reached by largely different methods is indicative of the lack of better constraining data needed to arrive at much narrower uncertainty ranges.

6.5 Model limitations

Simulating the fully-coupled ice sheet-climate system for the entire duration of the LIG as presented here is an important step forward for a better understanding of the Earth system during this period. However, our attempt deserves a critical discussion of the limitations of the model setup.

A so far unavoidable side effect to running a fully coupled model for several thousands of years is the limited horizontal resolution of the atmospheric model. The katabatic wind effect discussed by Merz et al. (2014) and other small-scale circulation patterns are therefore likely underrepresented. A quantification of how much the strength of ice sheet-climate feedbacks depends on spatial resolution of the climate model would be an interesting study, but is not something we could add to with our model set-up.

The applied PDD scheme has been extensively ~~validated~~validated with results of more complex Regional Climate Models for simulations of the recent past (e.g. Vernon et al., 2013), but ~~but~~ several studies point to limitations of this type of melt model when applied for periods in the past with a different orbital configuration (e.g. van de Berg et. al., 2011; Robinson and Goelzer, 2014). Their results indicate that the stronger northern summer insolation during the LIG should result in additional surface melt on the Greenland ice sheet compared to simulations based on temperature changes alone. We note that this suggests an underestimation of LIG melt with the PDD model and increased melt if it was corrected for. Thus, including an additional melt contribution due to insolation would further increase the contrast of the NEEM paradox in our simulation. Our ~~modeling~~ modelling therefore provides no arguments to support the contention that the limited LIG warming implied over Greenland would be indicative of an overly sensitive ice sheet and mass balance model.

~~T~~Instead, the applied scaling of the temperature anomaly forcing for the GrIS is a necessity to keep the ice sheet from losing too much mass during the warm period and to maintain ice sheet retreat to within limits of reconstructions. Clearly, this implies a limited predictive capability of our model, which is now forced to comply with the given constraints on minimum ice extent during the LIG. However, the Antarctic simulation would not be strongly affected by changes in the melt model due to the limited role of surface melting for the evolution of the AIS during the LIG.

The sea-saw effect evoked by NH freshwater forcing leads to millennial time scale temperature variations in the SO, but the surface climate over the AIS is hardly affected in our simulations. Despite some improvement when ice sheet changes are included, the limited Antarctic temperature response appears to be a general feature of the LOVECLIM model (e.g. Menviel et al., 2015), which fails to reproduce a several degree warming during the LIG reconstructed at deep ice core locations. We suspect that the limited resolution of the atmospheric model contributes to this shortcoming but we have not been able to quantify that.

6.6 Possible improvements

Uncertainty in the age model of the Grant et al. (2012) sea-level reconstruction could in principle be used to force the AIS to an earlier retreat, better in line with the Kopp et al. (2009) reconstructions. We have not attempted that, since other uncertainties, in particular in the climate forcing are large and do not warrant to attempt a precise chronology. Earlier experiments (not shown) indicate however that using a benthic δ^{18}O-stack (Lisiecki and Raymo, 2005) would lead to an even later retreat of the AIS and thus increase the mismatch with the Kopp et al. (2009) reconstruction.

~~6~~7 Conclusion

We have presented the first~~a~~ coupled transient simulation of the entire LIG period with interactive Greenland and Antarctic ice sheet components. In our results, both ice sheets contribute to the sea-level high stand during the Last Interglacial, but are subject to different forcing and response mechanisms. While the GrIS is mainly controlled by changes in surface melt water runoff, the ~~Antarctic ice sheet~~AIS is only weakly affected by surface and sub-shelf melting. Instead, grounding line retreat of the AIS is forced by changes in sea level stand and to a lesser extent surface warming, which lowers the ice shelf viscosity. ~~Limited by the existing ice core constraints on minimal ice sheet extent, T~~the peak ~~Greenland ice sheet~~GrIS contribution in our reference experiment is 1.4 m. However, this result is strongly controlled by the need to scale the climate forcing to match existing ice core constraints on minimal ice sheet extent. This shortcoming in our modelling reflects the NEEM paradox, that strong warming over the ice sheet coincides with limited mass loss from the GrIS, indicative of a fundamental missing link in our understanding of the LIG ice sheet and climate evolution. ~~, while t~~The Antarctic contribution is 4.4 m predominantly sourced from WAIS retreat. The modelled steric contribution is 0.35 m, in line with other modelling studies. Taken together, the modelled global sea-level evolution is consistent with reconstructions of the sea-level high stand during the LIG, but no evidence is found for sea-level variations on a millennial to multi-millennial time scale that could explain a multi-peak time evolution. ~~Ice-climate feedbacks and in particular T~~The treatment of albedo changes at the atmosphere-ice sheet interface play an important role for the ~~Greenland ice sheet~~GrIS and constitute a critical element when accounting for ice sheet-climate feedbacks in our fully-coupled approach. Large uncertainties in the projected sea-level changes remain due to a lack of comprehensive knowledge about the climate forcing at the time and a lack of constraints on LIG ice sheet extent, which are limited for Greenland and virtually absent for Antarctica.

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Appendix A: Ice-climate coupling improvements

Compared to earlier versions of the model (Goosse et al., 2010), recent model improvements for the coupling interface between climate and ice sheets have been included for the present study. Ocean temperatures surrounding the ~~Antarctic ice sheet~~AIS are now used directly to parameterise spatially explicit sub-ice-shelf melt rates, defining the flux boundary condition at the lower surface of the ~~Antarctic ice sheet~~AIS in contact with the ocean. The sub-shelf basal melt rate M_{shelf} is parameterised as a function of local mid-depth (485-700 m) ocean-water temperature T_{oc} above the freezing point T_f (Beckmann and Goosse, 2003):

$$M_{shelf} = \rho_w c_p \gamma_T F_{melt} (T_{oc} - T_f) / L\rho_i,$$

where ρ_i=910 kg m^{-3} and ρ_w=1028 kg m^{-3} are ice and seawater densities, c_p=3974 J kg^{-1} °C^{-1} is the specific heat capacity of ocean water, γ_T= 10^{-4} is the thermal exchange velocity and L=3.35 x 10^{5} J kg^{-1} is the latent heat of fusion. The local freezing point is given (Beckmann and Goosse, 2003) as

$$T_f = 0.0939 - 0.057 \cdot S_0 + 7.64 \times 10^{-4} z_b,$$

with a mean value of ocean salinity S_0=35 psu and the bottom of the ice shelf below sea level z_b. A distinction is made between protected ice shelves (Ross and Ronne-Filchner) with a melt factor of F_{melt} = 1.6x10^{-3}m s^{-1} and all other ice shelves with a melt factor of F_{melt} = 7.4x10^{-3}m s^{-1}. The parameters are chosen to reproduce observed average melt rates (Depoorter et al., 2013) under the Ross, Ronne-Filchner and Amery ice shelves for the pre-industrial LOVECLIM ocean temperature and Bedmap2 (Fretwell et al., 2013) shelf geometry. For ice shelves located inland from the fixed land-sea mask of the ocean model, mid-depth ocean temperature from the nearest deep-ocean grid point in the same embayment is used for the parameterisation.

In addition, surface melting of the Antarctic ice shelves has been taken into account, compared to earlier model versions where all surface meltwater was assumed to refreeze at the end of summer. The surface mass balance of ice sheet and ice shelf are now treated consistently with the same positive-degree-day model including capillary water and refreezing terms. The same melting schemes for basal and surface melt have been used for the ~~Antarctic~~

~~ice sheet~~AIS model version that participated in the PlioMIP intercomparison exercise of de Boer et al. (2015).

The atmospheric interface for the ~~Greenland ice sheet~~ GrIS was redesigned to enable ice sheet regrowth from a (semi-) deglaciated state given favourable conditions. This is accomplished by calculating surface temperatures independently for different surface types (ocean, ice sheet, tundra), which most importantly prevents~~ing~~ tundra warming to affect~~ing~~ proximal ice sheet margins~~ by calculating surface temperatures independently for different surface types (ocean, ice sheet, tundra)~~. At the same time, the full range of atmospheric forcing is taken into account by allowing the ice sheet forcing temperature to exceed the melting point at the surface. This provides an in principle unbounded temperature anomaly forcing for increasing atmospheric heat content for the positive-degree-day melt scheme.

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10 Tables

Table 1~~1~~. Overview of all discussed model experiments. The second column gives the scale factor R for temperature anomalies over the Greenland ice sheet.

Name	**R**	**Description**
Reference	0.4	Fully coupled reference simulation
High	0.5	Fully coupled simulation
Low	0.3	Fully coupled simulation
Forced reference	0.4	Forced with climate output from Reference
Forced high	0.5	Forced with climate output from Reference
Forced low	0.3	Forced with climate output from Reference
No sub-shelf melting	0.4	Suppressed Antarctic sub-shelf melting

~~**8**~~

Table 2. Peak sea-level contribution in sea-level equivalent (SLE) and timing from the Greenland ice sheet~~s~~ above present-day levels for three different parameter choices.

	Fully coupled experiments		Forced~~Stand-alone~~ repeat experiments	
Name~~EXP~~	SLE (m)	time of peak (kyr BP)	SLE (m)	time of peak (kyr BP)
High	+2.72~~7~~	122.8~~5~~	+2.01~~2~~	123.6~~3~~
Reference	+1.42	123.3~~0~~	+1.42	123.3~~0~~
Low	+0.65~~2~~	124~~3~~.0~~8~~	+0.81~~3~~	123.7~~3~~

~~9~~11 Figures

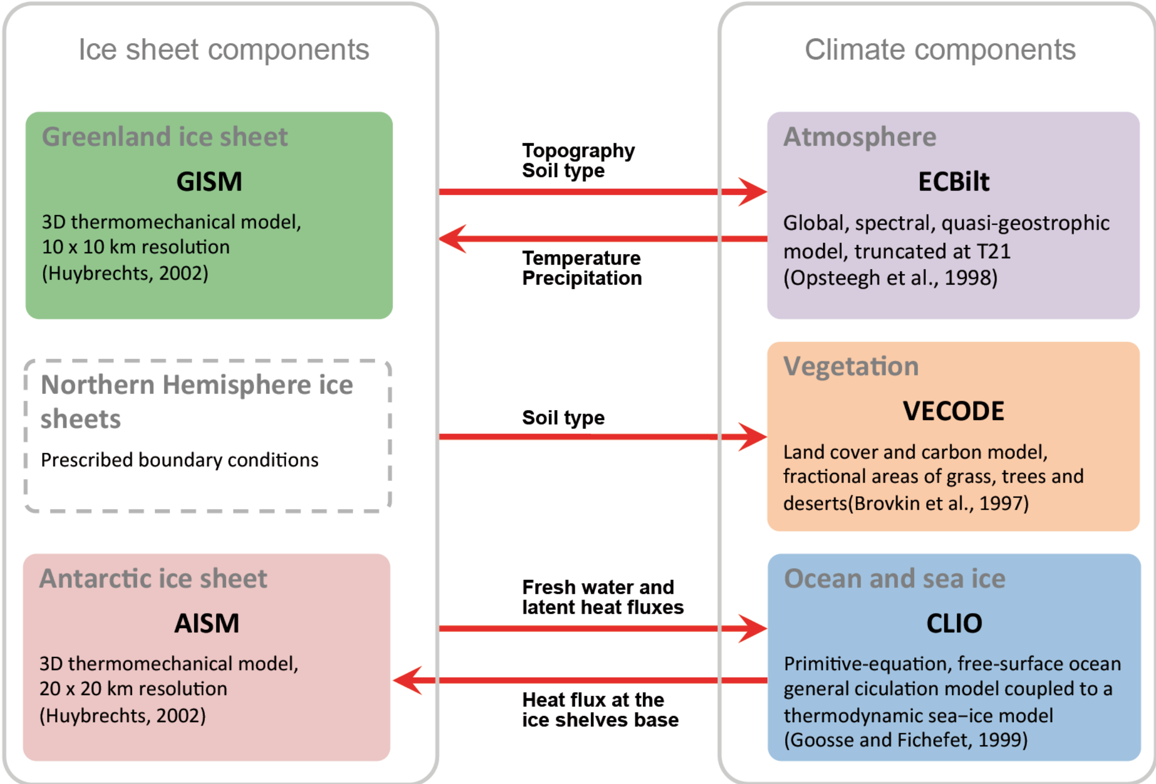


Fig.~~ure~~ 1~~1~~. LOVECLIM model setup for the present study including dynamic components for the Greenland and Antarctic ice sheets and prescribed Northern Hemisphere ice sheet boundary conditions.

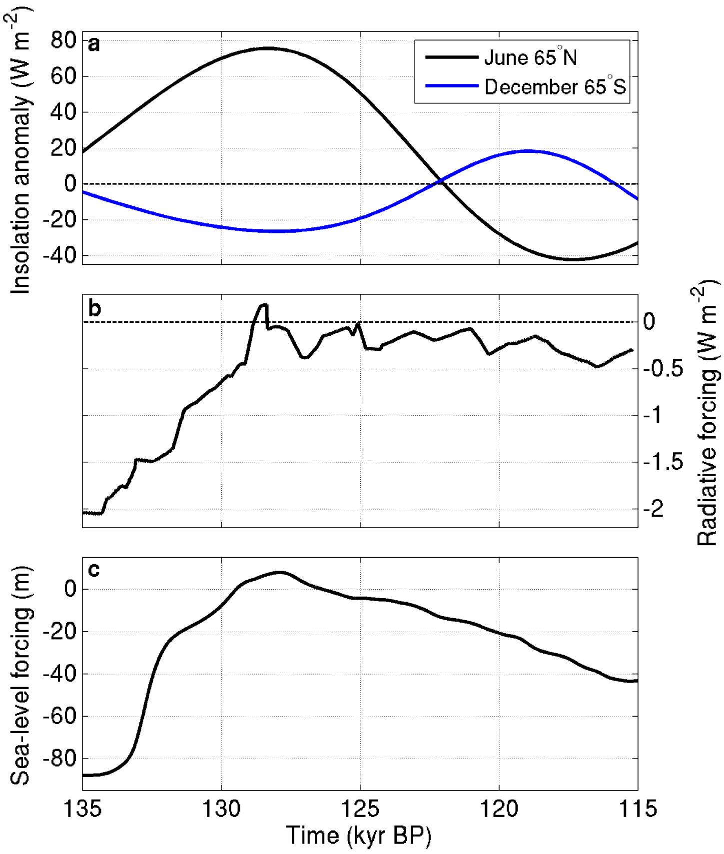


Fig.~~ure~~ 2~~2~~.~~:~~ Prescribed model forcing. A~~Top: a~~verage monthly insolation anomaly (a) at 65° North in June (black) and 65° South in December (blue) to illustrate the spatially and temporally resolved forcing (Berger, 1978), ~~. ~~c~~Middle: c~~ombined radiative forcing anomaly of prescribed greenhouse gas concentrations relative to the present day (b) and~~.~~ ~~Bottom:~~ sea-level forcing for the ice sheet components (c) derived from a Red Sea sea-level record (Grant et al. 2012).

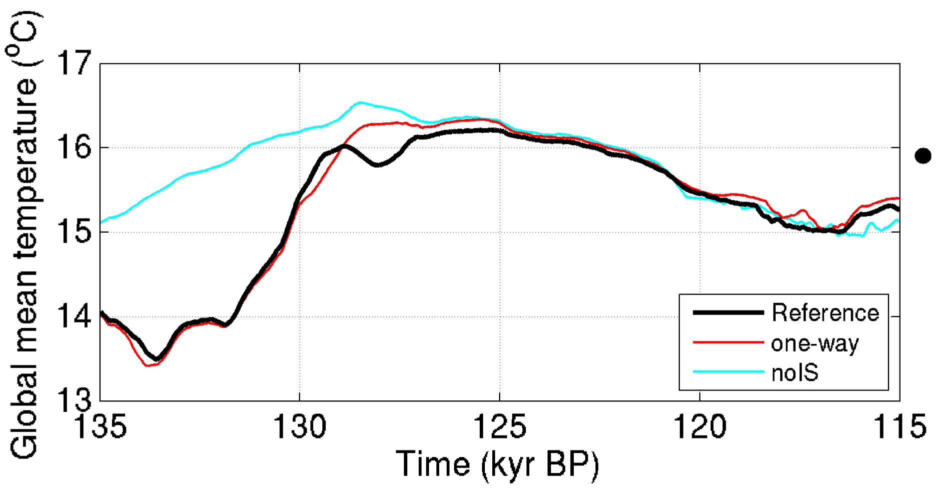


Fig.~~ure~~ 3~~3~~.~~:~~ Global annual mean near-surface air temperature evolution of the reference run (black) compared to experiments with prescribed Greenland and Antarctic ice sheet evolution from stand-alone experiments (O~~o~~ne-way, red) and no ice sheet changes at all (noIS, light blue). The filled circle on the right axis indicates the temperature for a pre-industrial control experiment of the reference model with present day ice sheet configuration.

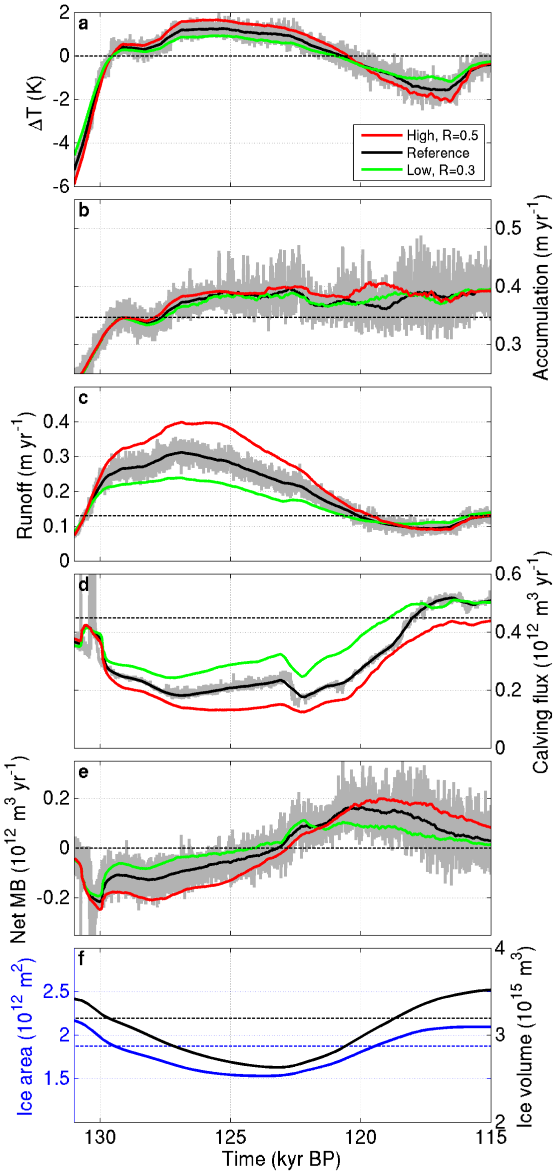


Fig.~~ure~~ 44. Greenland ice sheet forcing characteristics for the reference run (black) and with higher (red) and lower (green) temperature scaling. C~~C~~limatic temperature anomaly relative to pre-industrial (a). ~~(a) ,~~ A~~a~~ccumulation rate (b) and runoff rate (c) ~~are~~ given as ice sheet wide spatial averages over grounded ice. Calving flux (d), net mass balance (e) and other mass balance terms (b, c) ~~are~~ given in water equivalent. ~~(e)~~ Ice area (blue) and ice volume (black) for the reference run (f). All lines are smoothed with a 400 years running mean except for the grey lines giving the full annual time resolution for the reference run. Horizontal dashed lines give the pre-industrial reference values, except for panel e, where it is the zero line.

1220 |

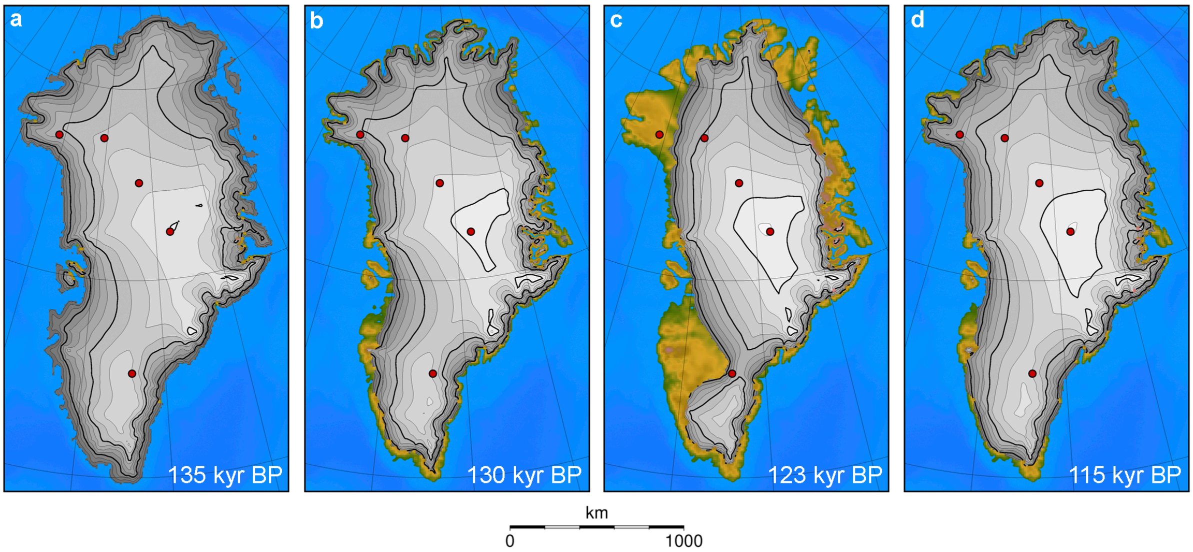


Fig.~~ure~~ ~~5~~5. Greenland ice sheet geometry at 135 kyr BP (a), 130 kyr BP (~~left~~b), for the minimum ice sheet volume at 123 kyr BP with a sea-level~~SL~~ contribution of 1.4 m (~~middle~~c) and at the end of the reference experiment at 115 kyr BP (~~right~~d). The red dots indicate the deep ice core locations (from south to northwest: Dye-3, GRIP, NGRIP, NEEM, Camp Century).

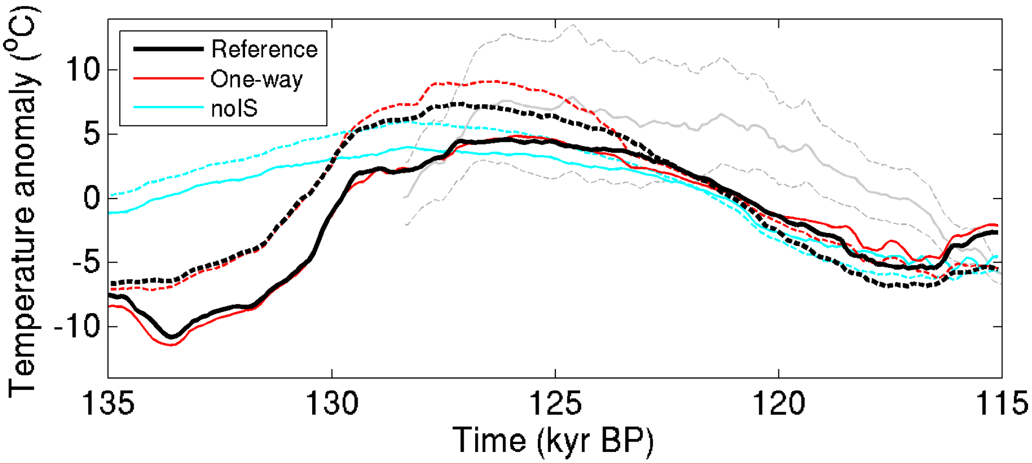


Fig. 6~~6~~. Comparison of modelled North-East Greenland annual mean (solid) and summer (June-July-August, dashed) surface temperature evolution (72° - 83° N and 306°33’ - 317° 48’ E) with reconstructed temperature changes (grey) at deep ice core site NEEM (77°27’ N, 308°56’ E). The solid grey line is the central estimate and grey dashed lines give the estimated error range for NEEM.

a **b**

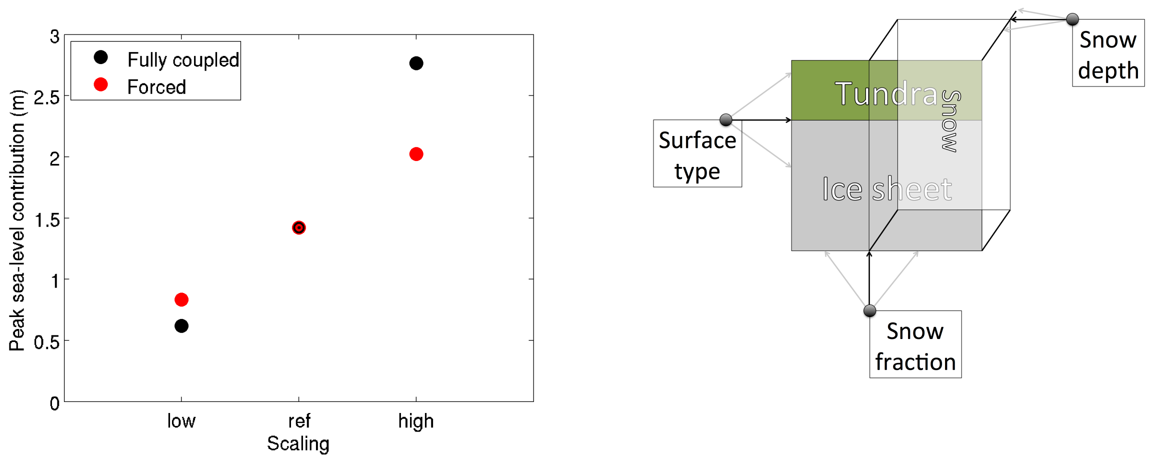


Fig.~~ure~~ 7~~6~~. ~~(a)~~ Scaling of sea-level contribution from the Greenland ice sheet as a function of temperature changes for the full model (black) and forced model (red) in comparison (a). ~~(b)~~ Schematic of the albedo parameterisation in the land model for (partially) ice-covered areas (b), which is a function of the underlying surface type, snow fraction and snow depth. See main text for details

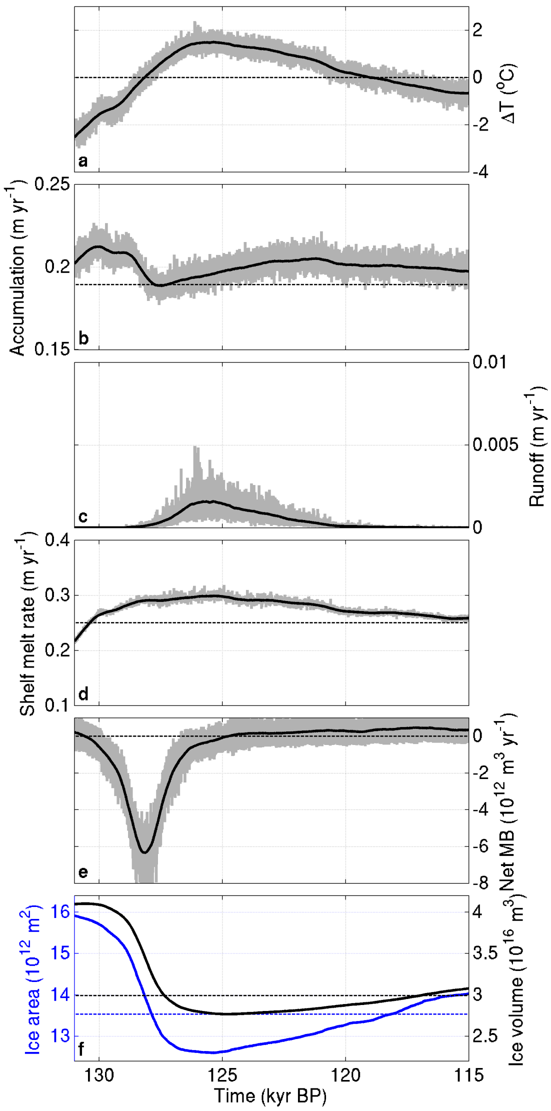
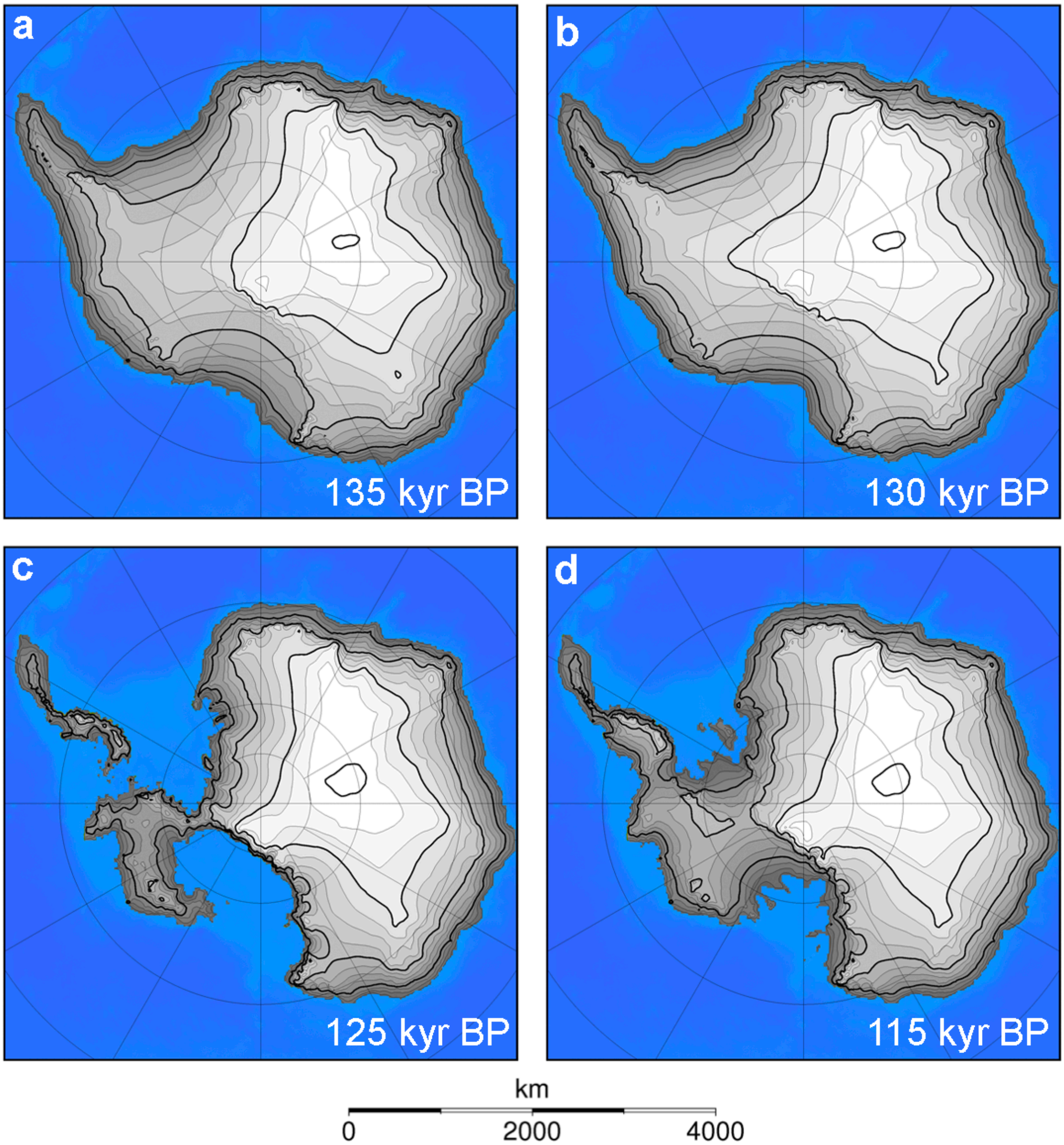


Fig.~~ure~~ 8~~7~~. Antarctic ice sheet forcing and characteristics. Temperature anomaly relative to pre-industrial (a), average ice sheet wide accumulation rate (b), average ice sheet wide runoff rate (c), average sub-shelf melt rate diagnosed for the area of the present-day observed ice shelves (d) and net mass balance of the grounded ice sheet (e). Mass balance terms (b-e) are given in water equivalent. (f) ~~. (e)~~ Grounded ice sheet area (blue) and volume (black). Grey lines give full annual time resolution, while black lines (and blue in f~~e~~) are smoothed with a 400 years running mean. Horizontal dashed lines give the pre-industrial reference values, except for panel e, where it is the zero line.



Fig~~ure.~~ 9~~8~~. Antarctic grounded ice sheet geometry at 135 kyr BP (a), ~~at~~ 130 kyr BP (b~~a~~), for the minimum ice sheet volume at 125 kyr BP with a sea-level~~SL~~ contribution of 4.4 m (c~~b~~) and at the end of the reference experiment at 115 kyr BP (d~~e~~).

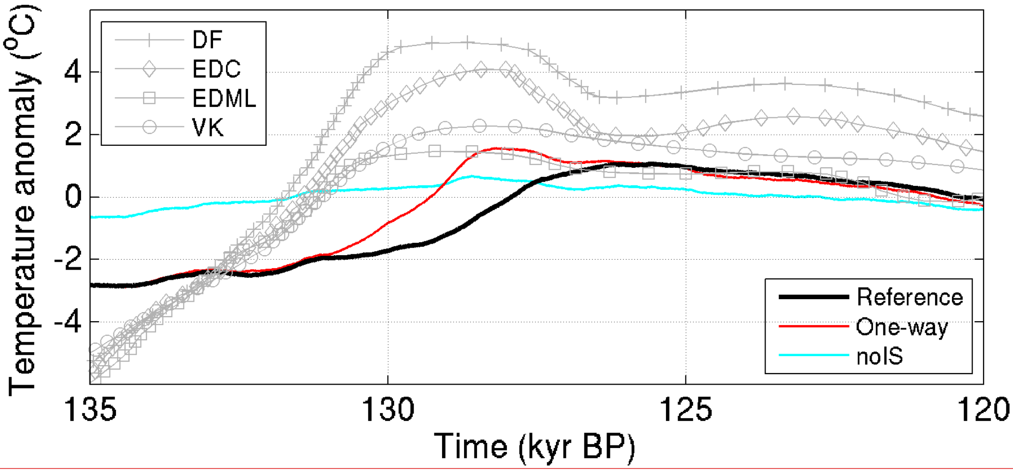


Fig. 10~~10~~. Comparison of modelled East Antarctic temperature evolution with reconstructed temperature changes at deep ice core sites. Modelled temperature anomalies are averaged over a region 72° - 90° S and 0° - 150° E. Ice core temperature reconstructions for the sites EPICA Dronning Maud Land (EDML, 75°00′ S, 00°04′ E), Dome Fuji (DF, 77°19′ S, 39°40′ E), Vostok (VK, 78°28′ S, 106°48′ E) and EPICA Dome C (EDC, 75°06′ S, 123°21′ E) are from Masson-Delmotte et al. (2011).

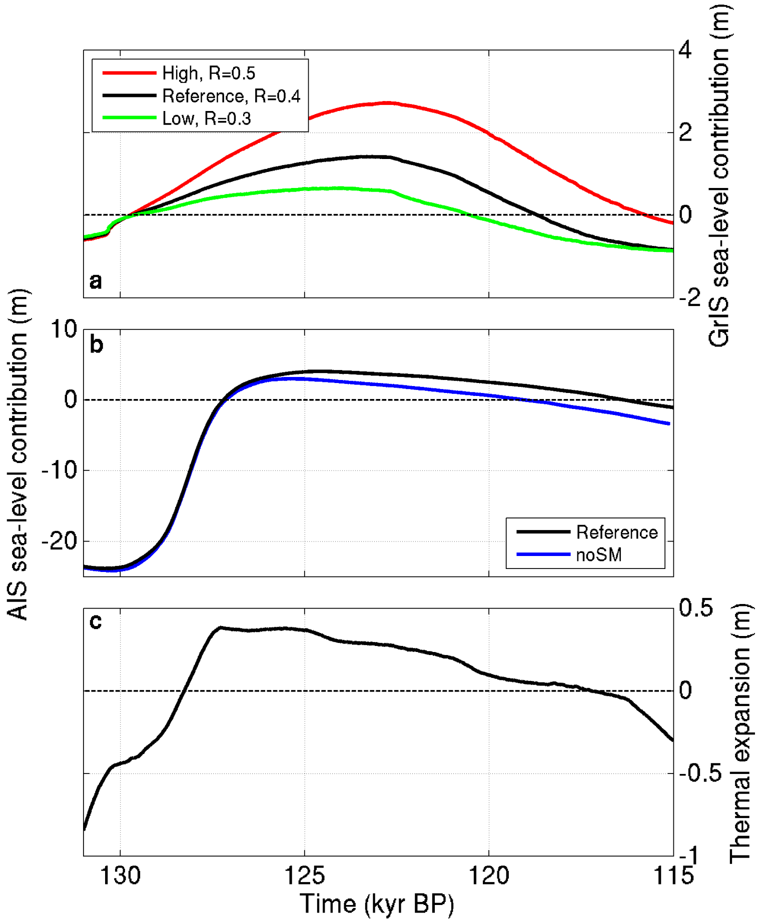


Fig.~~ure~~ 11~~9~~. ~~(a)~~ Sea-level contribution from the Greenland ice sheet for the reference run (black) and two sensitivity experiments with higher (red) and lower (green) temperature scaling (a). ~~(b)~~ Sea-level contribution from the Antarctic ice sheet (b) from the reference run (black) and from a sensitivity experiment without sub-shelf melting (blue). ~~(c)~~ Sea-level contribution from oceanic thermal expansion from the reference run (c).

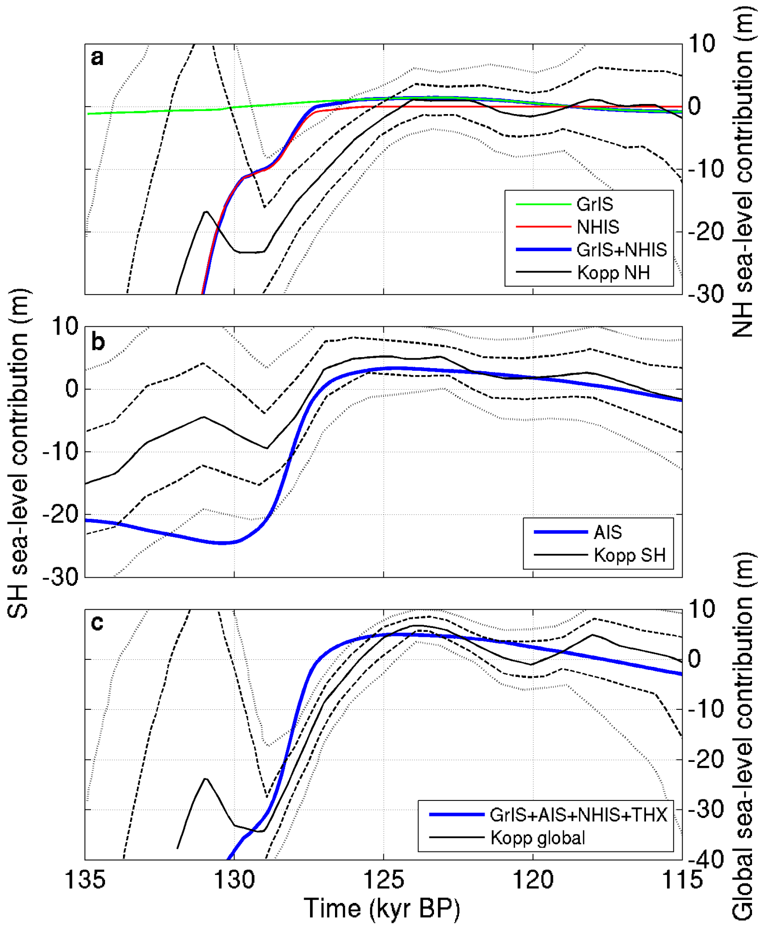


Fig.~~ure~~ 12~~10~~. Modelled sea-level contributions from this study (colour lines) compared to probabilistic sea-level reconstructions (black lines) from Kopp et al. (2009) for the NH (a) the SH (b) and global (c). For the reconstructions, solid lines correspond to the median projection, dashed lines to the 16th and 84th percentiles, and dotted lines to the 2.5th and 97.5th percentiles.