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Climate of the Past Discussions

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 changes 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 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 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). Due to polar amplification, high latitude surface temperatures, when averaged over several thousand years, were at least 2°C larger than present (Masson-Delmotte et al., 2013) and were up to 5°C 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

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Published: 18 January 2016

Climate of the Past Discussions

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 and Antarctic ice sheets.

Because thus far direct evidence for an Antarctic ice sheet 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 (GlIC). This illustrates that the attribution problem is so far largely underdetermined. It appears that the lower bound of 5.5 m (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), GlIC (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), 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 contribution, supposedly from marine-based sectors in the Wilkes and Aurora basins (Pollard and DeConto, 2015). 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 evolution is somewhat better constrained 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 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) 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 Berg et al., 2013; Merz et al., 2014; Sjolte et al., 2014; Steen-Larsen et al., 2014, Masson-Delmotte et al., 2015). 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 et al., 2012).

Modelling studies of the 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 et al., 2012; Stone 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 during the LIG are rare due to the aforementioned lack of climate and geomorphological constraints for that period. However, results have been presented in studies with 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).

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 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 high resolution ice sheet models of the Greenland and Antarctic ice sheets fully coupled to 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. 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 System Model of Intermediate Complexity (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 (Figure 1). The model has been utilised in a large number of coupled climate-ice sheet studies (e.g. Driesschaert et al.,

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Manuscript under review for journal Clim. Past
Published: 18 January 2016

2007; Swingedouw et al., 2008; Goelzer et al., 2011; 2012a). 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. (2015). 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 and Antarctic ice sheets 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).

Because of the relatively coarse resolution of the atmosphere in LOVECLIM (T21), the high-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. The ice sheet models in turn provide the climate model with changing topography, ice sheet extent (albedo) and spatially and temporally variable freshwater fluxes, unmodified to earlier versions of the model (Goosse et al., 2010). Recent model improvements for the ice-climate coupling interface are described in Appendix A.

3.1 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 last glacial maximum 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., 2015).

3.2 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 and the steric contribution due to density changes of the ocean water. The only component not explicitly modelled is the contribution of

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Manuscript under review for journal Clim. Past
Published: 18 January 2016

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 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 and being replaced by seawater *and* seawater being replaced by isostatic bedrock movement, both mainly of importance for the marine sectors of the WAIS. Note that this effect 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 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 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.

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 (Figure 2). The radiative forcing associated with the reconstructed GHG levels is below preindustrial values for most of this period and hardly exceeds it at ~128 kyr BP. 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.

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 (Figure 2c) using a recent sea-level reconstruction based on Red Sea data (Grant et al., 2012). The chronology of the latter assumes ice volume to be independent of deep-sea temperatures, in contrast to directly using the scaled benthic $\delta^{18}O$ record as sea-level proxy (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 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. As a measure to ensure a realistic simulation of the Greenland ice sheet evolution, the temperature anomaly forcing from the climate model over the 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 climate evolution over the ice sheet, the temperature scaling in the present study represents a pragmatic solution to produce an ice sheet evolution reasonably in line with ice core constraints on minimum ice sheet extent during the LIG. A uniform scaling of the atmospheric temperature anomaly with a factor of R=0.4 was adopted in the reference experiment and is later compared to two sensitivity experiments with modified scaling (R=0.5, 0.3).

The fully coupled experiments are 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 runs. 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 the coupled and un-coupled system. The ice sheet response in the reference stand-alone experiment (forced offline with the recorded climate forcing of the coupled reference run) is by construction identical to the response in the fully coupled run. Additional experiments have been run with modified temperature scaling for the Greenland ice sheet (R=0.5, 0.3), which can be compared to the respective fully coupled experiment. For the AIS, experiments with suppressed shelf melting have been performed to isolate the effect of ocean temperature changes on the ice volume evolution and sea-level contribution.

4.2 Initialisation

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. 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 reconstructions were presented in detail in two earlier publications (Loutre et al., 2014; Goelzer et al., 2015) for the same climate model setup. Differences to the work by Goelzer et al. (2015) arise from a different ice sheet evolution and feedbacks between climate and ice sheets that are taken into account in our present, fully coupled approach.

Global annual mean near-surface air temperature in the reference experiment shows a distinct increase until 129 kyr BP in response to orbital and greenhouse gas forcing 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., 2015) forced with prescribed NH, Antarctic and Greenland ice sheet changes (one-way). The much larger temperature contrast at the onset of the LIG compared to noIS arises from changes in surface albedo and melt water fluxes of the Northern Hemisphere ice sheets, which freshen the North Atlantic

Clim. Past Discuss., doi:10.5194/cp-2015-175, 2016
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Published: 18 January 2016

and lead to a strong reduction of the Atlantic meridional overturning circulation. 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, which occurs 2 kyr later compared to the one-way experiment.

5.1 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 the ablation (Figure 4). Marginal summer surface melt water runoff is the dominant mass loss of the ice sheet after 130 kyr BP, when the ice sheet has retreated largely on land. Due to increased 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. Conversely, the mean ablation 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. Temperature anomalies responsible for the increased ablation 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. The calving flux decreases as the ice sheet retreats from the coast (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.

Entering the warm period, the furthest retreat of the ice sheet occurs in the southwest and northwest (Figure 5), accompanied by an overall retreat from the coast. Conversely, 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 a sea-level contribution peak of 1.4 m at 123 kyr BP (Figure 9). For the two sensitivity experiments (high, low) with modified scaling (R=0.5, 0.3), the contribution changes to 2.8 m and 0.6 m, respectively.

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

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Manuscript under review for journal Clim. Past
Published: 18 January 2016

that ice core are however not well constrained and leaves room for a wide range of possible retreat patterns of the northern GrIS (e.g. 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, a direct result of the largely unconstrained climatic forcing. 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 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.

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

Clim. Past Discuss., doi:10.5194/cp-2015-175, 2016
Manuscript under review for journal Clim. Past
Published: 18 January 2016

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), which are driven with the climate forcing from the coupled reference model run. In both cases the scaling of Greenland forcing temperature is set to a magnitude of 0.3 (low), 0.4 (ref) and 0.5 (high), 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 high (low) compared to the stand-alone experiments. Consequently, sea-level contributions show a non-linear dependence on the temperature scaling for the fully coupled run, while they are near linear for the forced runs (Figure 6, left). The dominant feedback mechanism arises from how changing albedo characteristics are taken into account for a melting ice sheet surface. 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 6, right). Both lead to lower albedo and increased temperatures in places where the ice sheet starts melting at the surface. The difference in warming between stand-alone and fully-coupled experiments is therefore located over the ice sheet margins and does not have a considerable influence on the NH or global temperature response. The 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 arises from the retreating ice sheet margin being replaced by lower albedo tundra (Figure 6, right), which operates on much longer time scales.

5.2 Antarctic ice sheet

The annual mean air temperature anomaly over Antarctica (averaged over grounded ice) increases at the beginning of the experiment to a peak at 125 kyr BP (Figure 7), before cooling sets in and continues until 115 kyr BP. The warming 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 Antarctic ice sheet 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. While freshwater fluxes from the retreating Antarctic ice sheet 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., 2015). 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 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 Figure 7, respectively). As a consequence of the surface forcing, the AIS shows a small volume gain until 130.5 kyr BP due to increase in precipitation before a large-scale retreat of the grounding line sets in. The average ablation rate over grounded ice equally increases with increasing temperature but remains of negligible importance for the mass balance 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

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Climate of the Past Discussions Open Access EGU

shelves in our reference simulation increases to at most 20 % above the pre-industrial with a peak in line with the air temperature maximum. However, ocean warming to above pre-industrial temperatures occurs already before 130 kyr BP, 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 weakening of the Atlantic meridional overturning circulation.

Ice sheet area and volume decrease rapidly between 129 and 127 kyr BP, and indicate a gradual regrowth after 125 kyr BP. Those changes arise mainly from a retreat and re-advance of the WAIS (Figure 8). In our model, the 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 peaks at 125 kyr BP at 4.4 m.

Stand-alone sensitivity experiments, in which specific forcing processes are suppressed, show that surface melting and sub-shelf melting play a limited role for the AIS retreat in our experiments. The sea-level contribution peak in an experiment with supressed sub-shelf melting 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 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 and temperature forcing 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., 2015) 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 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 forcing is also in line with other modelling results for the LIG period (Pollard 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 here.

As mentioned earlier, direct constraints of the Antarctic ice sheet configuration during the LIG are still lacking. Goelzer et al. (2015) 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 model happened ~129.5 kyr BP, a timing predating the time of retreat in the coupled model by ~2 kyr due to the difference in atmospheric and oceanic forcing. It is noteworthy in this context that the prescribed sea-level forcing imposes an important control for the timing of the Antarctic retreat. Sensitivity experiments indicate 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 Thermal expansion of the ocean

The steric sea-level component due to ocean thermal expansion (Figure 9c) is largely following the global temperature evolution, but is also strongly modified by changes in ice sheet freshwater input. Ocean expansion is steep 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,

Clim. Past Discuss., doi:10.5194/cp-2015-175, 2016
Manuscript under review for journal Clim. Past
Published: 18 January 2016

which forms part of a plateau of high contribution between 127.3 and 124.9 kyr BP (Figure 9c). The amplitude is at the lower end, but well within the range of IPCC AR5 estimates of 0.42± 0.11 m (Masson-Delmotte et al., 2013).

5.4 Global sea-level change

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

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 (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 hiatus ~131-129 kyr BP suggested by the data. 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 an additional 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 reconstructions (Kopp et al., 2009; 2013) is not reproduced with our model, mainly owing to the long response times of the ice sheets during regrowth to changing climatic boundary conditions.

6 Conclusion

We have presented 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 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 surface warming, which lowers the shelf viscosity. Limited by the existing ice core constraints on minimal ice sheet extent, the peak Greenland ice sheet contribution in our reference experiment is 1.4 m, while 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 the treatment of albedo changes at the atmosphere-ice sheet interface play an important role for the Greenland ice sheet. 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 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 in contact with the ocean. The sub-shelf basal melt

Clim. Past Discuss., doi:10.5194/cp-2015-175, 2016
Manuscript under review for journal Clim. Past
Published: 18 January 2016

Climate of the Past Discussions

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

The atmospheric interface for the Greenland ice sheet was redesigned to enable ice sheet regrowth from a (semi-) deglaciated state given favourable conditions. This is accomplished by preventing tundra warming affecting 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

Clim. Past Discuss., doi:10.5194/cp-2015-175, 2016
Manuscript under review for journal Clim. Past
Published: 18 January 2016

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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Climate of the Past
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Published: 18 January 2016

9 Tables

Table 1 Peak sea-level contribution and timing from the Greenland ice sheets above present-day levels for three different parameter choices.

	Fully coupled experiments		Stand-alone repeat experiments	
EXP	SLE (m)	time of peak	SLE (m)	time of peak
high	2.77	-122.5	2.02	-123.3
reference	1.42	-123.0	1.42	-123.0
low	0.62	-123.8	0.83	-123.3

Clim. Past Discuss., doi:10.5194/cp-2015-175, 2016
Manuscript under review for journal Clim. Past
Published: 18 January 2016

Climate of the Past Discussions
Open Access

10 Figures

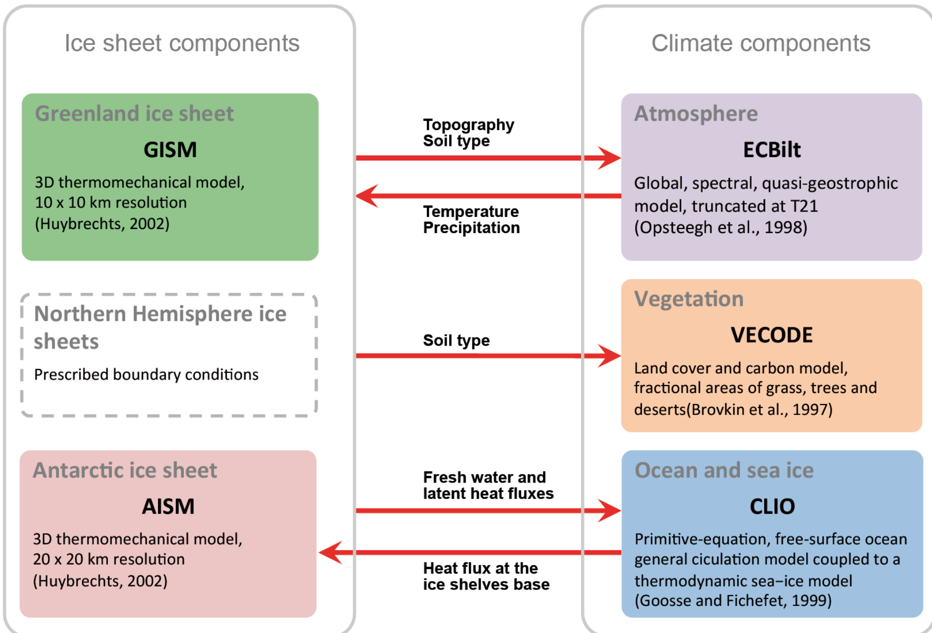

Figure 1 LOVECLIM model setup for the present study including dynamic components for the Greenland and Antarctic ice sheets and prescribed Northern Hemisphere ice sheet boundary conditions.

Clim. Past Discuss., doi:10.5194/cp-2015-175, 2016
Manuscript under review for journal Clim. Past
Published: 18 January 2016

Climate of the Past Discussions
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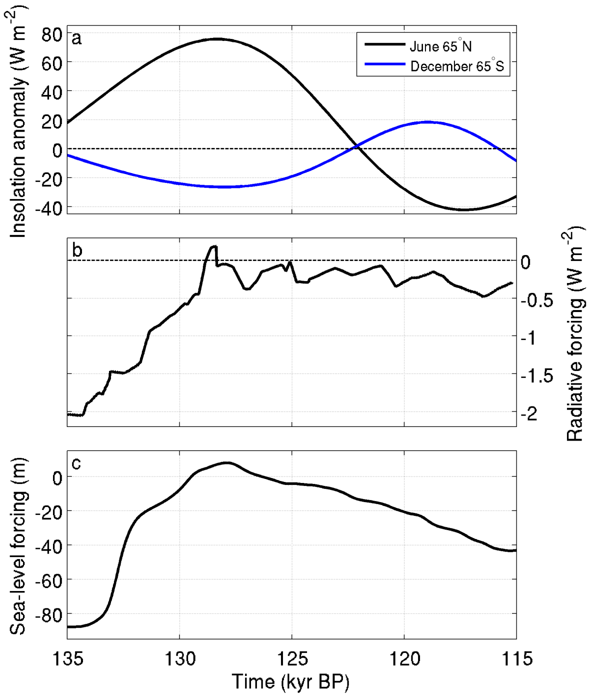

Figure 2: Prescribed model forcing. Top: average monthly insolation anomaly at 65° North in June (black) and 65° South in December (blue). Middle: combined radiative forcing anomaly of prescribed greenhouse gas concentrations relative to the present day. Bottom: sea-level forcing for the ice sheet components derived from a Red Sea sea-level record (Grant et al. 2012).

Clim. Past Discuss., doi:10.5194/cp-2015-175, 2016
Manuscript under review for journal Clim. Past
Published: 18 January 2016

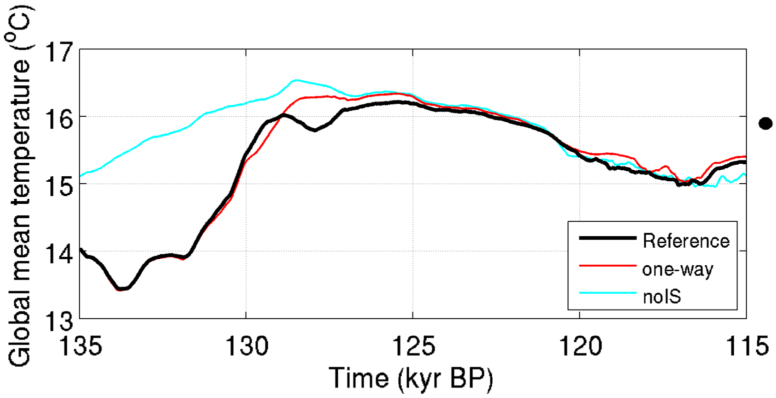

Figure 3: Global annual mean near-surface air temperature evolution of the reference run (black) compared to experiments with prescribed Greenland and Antarctic ice sheet evolution from stand-alone experiments (one-way, red) and no ice sheet changes at all (noIS, light blue). The filled circle on the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

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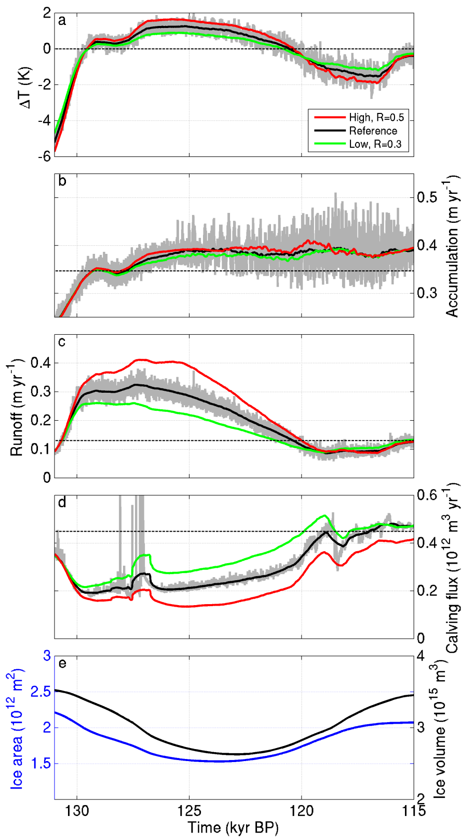

730 **Figure 4 Greenland ice sheet forcing characteristics for the reference run (black) and with higher (red)**
731 **and lower (green) temperature scaling. Climatic temperature anomaly relative to pre-industrial (a),**
732 **accumulation rate (b) and runoff rate (c) are given as ice sheet wide spatial averages over grounded ice.**
733 **Calving flux (d) and other mass balance terms (b, c) are given in water equivalent. (e) Ice area (blue) and**
734 **ice volume (black) for the reference run. All lines are smoothed with a 400 years running mean except for**
735 **the grey lines giving the full annual time resolution for the reference run.**

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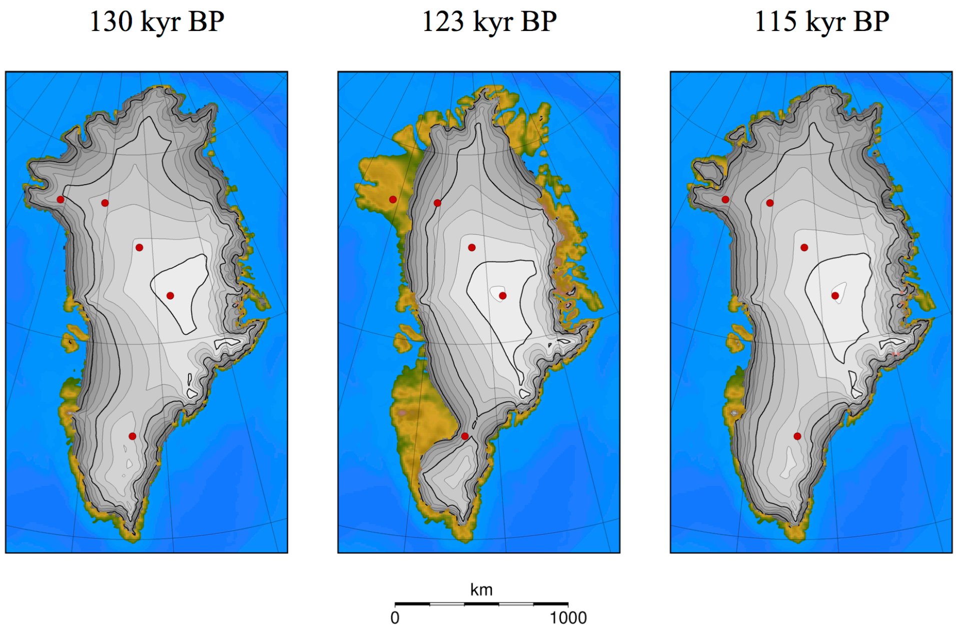

Figure 5 Greenland ice sheet geometry at 130 kyr BP (left), for the minimum ice sheet volume at 123 kyr BP with a SL contribution of 1.4 m (middle) and at the end of the reference experiment at 115 kyr BP (right). The red dots indicate the deep ice core locations (from south to northwest: Dye-3, GRIP,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

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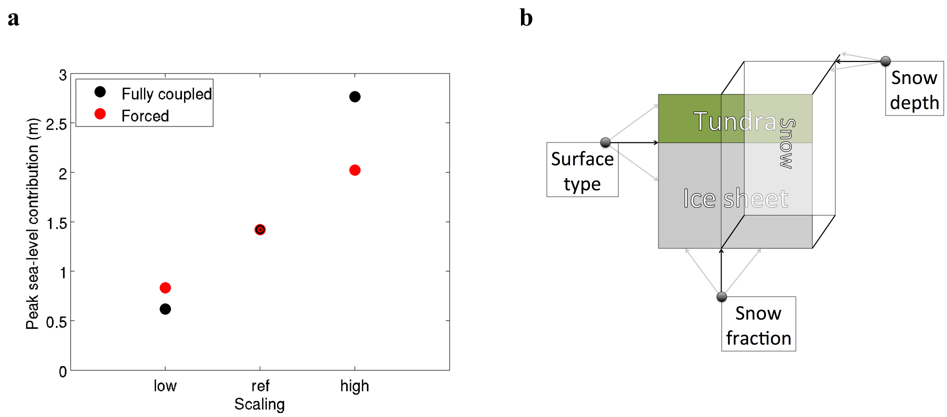

745 **Figure 6 (a) Scaling of sea-level contribution from the Greenland ice sheet as a function of temperature**
746 **changes for the full model (black) and forced model (red) in comparison. (b) Schematic of the albedo**
747 **parameterisation in the land model for (partially) ice-covered areas.**

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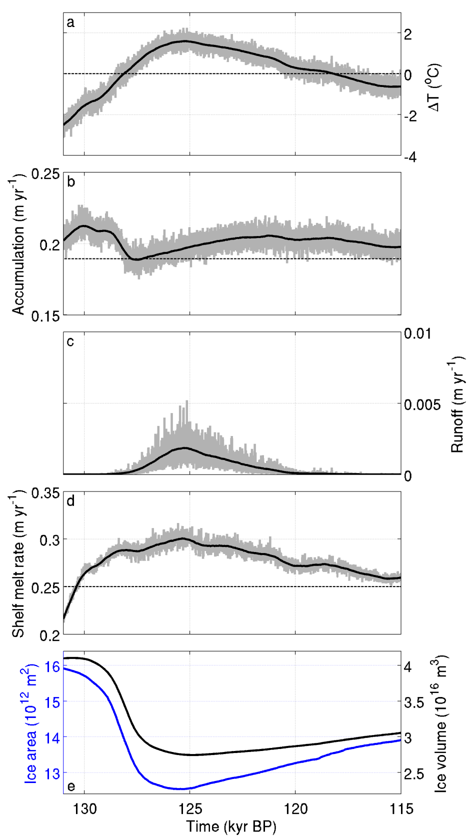

751 **Figure 7 Antarctic ice sheet forcing and characteristics. Temperature anomaly relative to pre-industrial**
752 **(a), average ice sheet wide accumulation rate (b), average ice sheet wide runoff rate (c), average shelf melt**
753 **rate diagnosed for the area of the present-day observed ice shelves (d). (e) Grounded ice sheet area (blue)**
754 **and volume (black). Grey lines give full annual time resolution, while black lines (and blue in e) are**
755 **smoothed with a 400 years running mean.**

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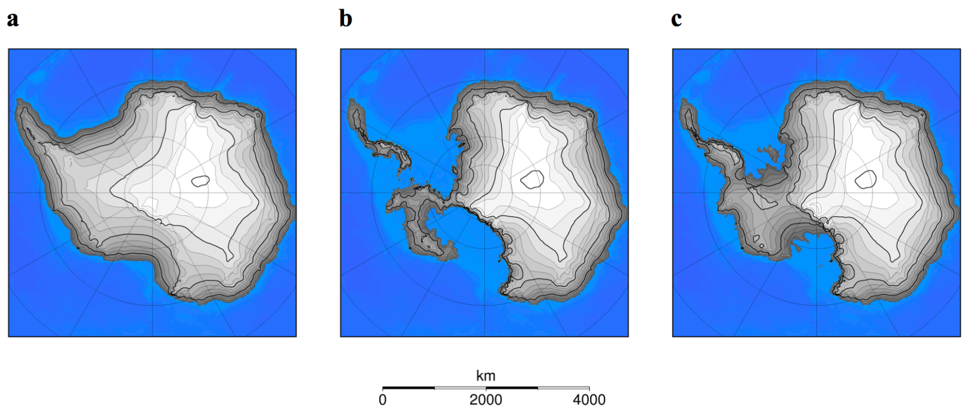

Figure 8 Antarctic grounded ice sheet geometry at 130 kyr BP (a), for the minimum ice sheet volume at 125 kyr BP with a SL contribution of 4.4 m (b) and at the end of the reference experiment at 115 kyr BP (c).

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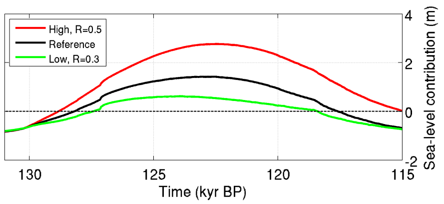
a



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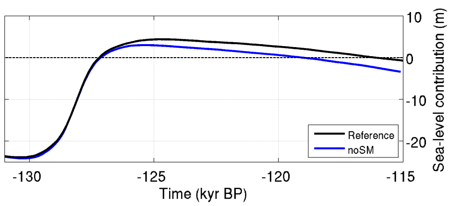

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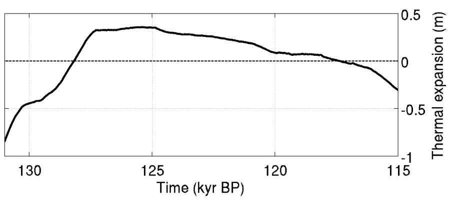

Figure 9 (a) Sea-level contribution from the Greenland ice sheet for the reference run (black) and two sensitivity experiments with higher (red) and lower (green) temperature scaling. (b) Sea-level contribution from the Antarctic ice sheet from the reference run (black) and from a sensitivity experiment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

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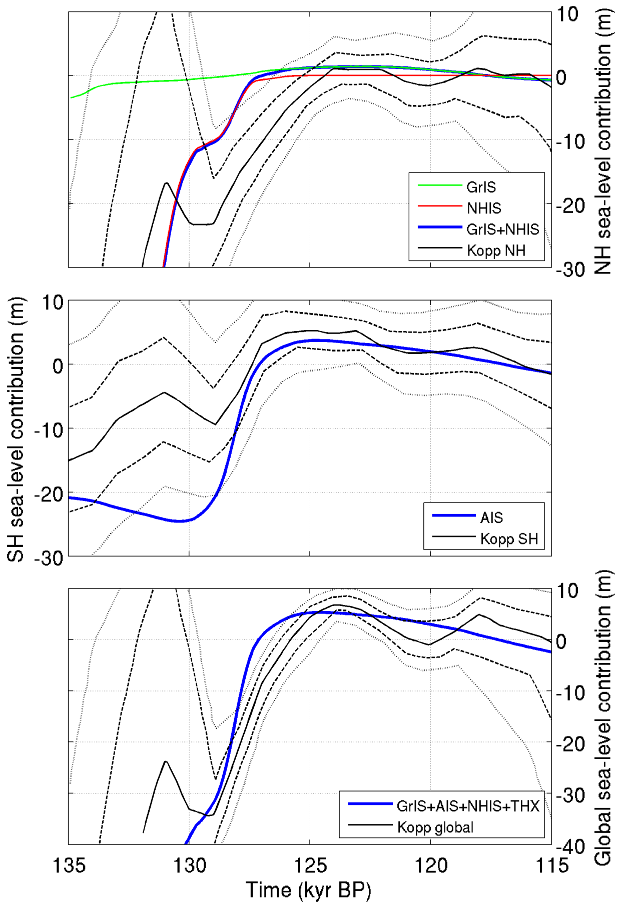

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772 **Figure 10 Modelled sea-level contributions from this study (colour lines) compared to probabilistic sea-**
773 **level reconstructions (black lines) from Kopp et al. (2009).**

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