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Climate of the Past Discussions

Interactive comment on "Greenland warming during the last interglacial: the relative importance of insolation and oceanic changes" *by* Rasmus A. Pedersen et al.

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Authors' response to reviewer comments on "Greenland warming during the last interglacial: the relative importance of insolation and oceanic changes" by Rasmus A. Pedersen et al.

We would like to thank the reviewers for the constructive comments. The authors' response to each comment is inserted below in *blue italics.*

Page and line numbers below mark the locations in the attached marked-up manuscript.

Anonymous Referee # 2 Received and published: 24 June 2016

This manuscript evaluates the role of insulation and sea surface temperature changes on the Greenland temperature during the Eemian. This work is interesting and valuable as it could offer insights into (i) the drivers of sea level changes during that period, (ii) the drivers of climate change and (iii) the reasons for the discrepancy between modelled and reconstructed Greenland temperature. The work carried out is sound and well described (apart from a few minor clarifications that need to be made), but the implications of the results are not sufficiently well presented and some of the analysis needs to go a bit further. This paper could have a lot more impact with a little bit of adjustment to the manuscript and a little bit more analysis of the result. I therefore suggest the manuscript to be accepted after some corrections and clarification. These would be a bit more than minor revisions, but i don't anticipate they would require too much work.

Overall the manuscript does a good job at describing the changes associated with SST and insulation forcings, but does discuss the reasons of these changes. In particular, I would like to see some explanation of the role of insulation on precipitation seasonality.

We have added more details to the discussion of the snowfall changes.

Page 7, Line 20

"During summer, iL+oP illustrates that the insolation contributes to the snowfall increase over the interior ice sheet. The fall pattern in iL+oL on the other hand indicates non-linear behavior, in that iL+oL does not resemble the sum of the two hybrid experiments: the increase on the eastern GrIS is only seen in iL+oL (as illustrated by difference in the bottom row of Fig. 4). Note, however, that Fig. 4 displays the relative change in snowfall, and the elevated northeastern region is very dry. The absolute snowfall anomaly (not shown) decreases rapidly towards the interior ice sheet, and the peak in the relative anomalies corresponds to a modest absolute increase (less than 0.2 mm/day). The non-linear behavior appears to be related to atmospheric circulation changes. The seasonal mean 10 m wind in iL+oL (not shown) has strengthened

southward flow along the northeast coast compared to the control climate and the hybrid experiments, which could contribute to increased orographic precipitation in the region; despite being mainly along to coast. The modest absolute precipitation increase in this region could, however, be related to very few storm events, that would not be evident from the seasonal mean circulation anomalies. "

There is some mention of 'non-linearity' effect, but this is very much glanced over. It needs more description of what that means, how strong the non-linearity is and what causes it.

We have added new plots to Figure 3-6 illustrating the difference iL+oL – (iL+oP + iP+oL). These have been used for more elaborate discussion of 'non-linearities' throughout the manuscript. Three examples are highlighted here:

Page 7, Line 3

"The largest difference is found in JJA near the Disko Bay on the central west coast, where the iL+oL warming is stronger than the sum of the hybrid experiments. As previously described, this region exhibits an albedo decrease due to loss of snow cover. The combination of snow melt driven by oceanic warming and the positive insolation anomaly in iL+oL gives rise to a strengthened albedo feedback that causes the apparent non-linearity. The insolation anomaly alone (in iL+oP) only causes a modest loss of snow cover, and the impact of the surface albedo feedback is therefore limited. "

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"The fall pattern in iL+oL on the other hand indicates non-linear behavior, in that iL+oL does not resemble the sum of the two hybrid experiments: the increase on the eastern GrIS is only seen in iL+oL (as illustrated by difference in the bottom row of Fig. 4). Note, however, that Fig. 4 displays the relative change in snowfall, and the elevated northeastern region is very dry. The absolute snowfall anomaly (not shown) decreases rapidly towards the interior ice sheet, and the peak in the relative anomalies

corresponds to a modest absolute increase (less than 0.2 mm/day). The non-linear behavior appears to be related to atmospheric circulation changes. The seasonal mean 10 m wind in iL+oL (not shown) has strengthened southward flow along the northeast coast compared to the control climate and the hybrid experiments, which could contribute to increased orographic precipitation in the region; despite being mainly along to coast. The modest absolute precipitation increase in this region could, however, be related to very few storm events, that would not be evident from the seasonal mean circulation anomalies. "

Page 8, Line 11

"The difference between iL+oL and the sum of the hybrid experiments illustrate similar magnitude, but opposite differences for T_{ann} and T_{pw}. The non-linear behavior here, in temperature as well as precipitation, is related to the varying response of the atmospheric circulation. The steep slopes of the ice sheet combined with katabatic winds and the anti-cyclonic circulation around the ice sheet margins generally limits the heat advection towards the interior ice sheet (Noël et al., 2014; Merz et al., 2016). Hence, potential precipitation and temperature changes on the interior ice sheet are largely dependent on changes in the circulation, which is not responding linearly to the combined insolation and oceanic forcings. The largest deviation is, however, found on the central west coast, where loss of snow cover and a strengthened albedo feedback explain the non-linearity (as described in relation to Fig. 3). "

In the discussion and introduction, clarify that part of the SST changes are caused by insulation and that this study focuses on the direct effect of insulation vs ocean temperature changes.

We have rewritten part of the introduction to clarify this.

Page 3, Line 14

"Using a series of general circulation model (GCM) experiments, we assess the Green-

land climate during the Eemian. We investigate how the simulated changes could affect the GrIS surface mass balance and the ice core record, and compare the reconstructed and simulated temperatures. While the insolation change is the only forcing in our experiments, we further compare the direct impact of the insolation change and the indirect effect of retreating sea ice and increasing sea surface temperatures (SSTs). The direct and indirect impacts are separated using two hybrid experiments: one forced by Eemian insolation and fixed pre-industrial sea surface conditions (direct impact, "insolation-only") and one with pre-industrial insolation and Eemian sea surface conditions (indirect impact, "ocean-only"). The temperature change during the Eemian resembles that of future climate scenarios (e.g. Clark and Huybers, 2009), and our comparison could reveal whether the Eemian is an appropriate analogue for future climate change in Greenland; i.e. whether insolation or the ambient oceanic warming dominates the total response."

Also, there should be a discussion of how well the model simulates modern Greenland temperature and how that would impact interpretation of the results. For example, some GCMs have difficulties simulating Arctic cloud processes. Could that affect the sensitivity of the model to changes in insulation/SSTs ?

A comment on model performance has been added to the Methods section.

Page 4, Line 10

"Compared to the widely used version 2.3, which was included in the latest IPCC assessment report (Flato et al., 2013), the new EC-Earth version includes updated versions of both the atmosphere and ocean models. Comparison of a present-day simulation to gridded observational data reveals an improved overall performance in version 3.1 compared to the previous version with a few remaining biases (cf. Davini et al., 2014). Relevant for this study, the comparison reveals a cold bias over most of Greenland and a too extensive Arctic sea ice cover."

The conclusions of the manuscript are a bit underwhelming. The start of the manuscript suggests that this study could shed light on the reasons for model-data discrepancy regarding Greenland Eemian temperature. The paper concludes that changes in ice sheet topography are to be blamed, but that is precisely a factor that the paper was not including. Is there nothing to be learned about the model's sensitivity to insulation and SST changes ?

The conclusion has been rewritten.

Page 10, Line 17

"Our experiments suggest that Greenland experienced higher temperatures and increased snowfall throughout the year during the Eemian. The hybrid simulations, which compare the direct impact of the insolation change to the indirect impact of changed sea surface conditions, illustrate that the largest contribution to both the warming and snowfall increase is due to oceanic changes. The ocean-only experiment exhibits increased temperatures and snowfall throughout the year, and provides a memory effect that prolongs the impact of the summertime insolation increase. The warming is widespread and even reaches the interior, elevated part of the ice sheet (including the NEEM ice core site). The direct impact of the insolation favors increased temperature and snowfall during summer, but colder and drier conditions during fall and winter.

Analysis of the simulations from an ice core perspective changes the apparent relative importance of insolation and sea surface changes. At the NEEM deposition site, the insolation changes favor changes in the precipitation seasonality that increase the summer weight in the precipitation-weighted temperature. Consequently, the isolated impacts of insolation and the associated oceanic changes on the precipitation-weighted temperature are comparable, despite the fact that the oceanic changes cause about 2 K higher annual mean warming. With the precipitation seasonality taken into account, our simulations, in line with previous model studies (Braconnot et al., 2012; Lunt et al., 2013; Masson-Delmotte et al., 2013; Otto-Bliesner et al., 2013), underestimate the warming compared to the NEEM ice core reconstructions.

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The model–data discrepancy can in part be explained by the experiment design and the model performance. Incorporation of ice sheet elevation changes would increase the near-surface temperature following the atmospheric lapse rate, and local circulation might furthermore be affected by altered ice sheet topography. Merz et al. (2014a) estimate that an increased slope of the ice sheet could contribute up to 3.1 K annual mean warming locally at the NEEM location. Additionally, changed precipitation patterns could affect the precipitation-weighted temperature reflected in the ice core record (Merz et al., 2014b).

Sea ice changes can affect both warming, circulation, and precipitation near GrIS depending on both the magnitude and the location of sea ice loss (Merz et al., 2016; Pedersen et al., 2016a). EC-Earth simulates an extensive sea ice cover under present and pre-industrial conditions, suggesting that the Eemian could be similarly overestimated. Despite the substantial Arctic warming, our simulations suggest that the Eemian Arctic sea ice extent was slightly larger than the present (e.g. in the Baffin Bay); further sea ice reduction, especially in the vicinity of Greenland, could further increase GrIS warming (Pedersen et al., 2016a). Based on precipitation-weighted temperature estimates, our hybrid simulations indicate that the combined effect of sea ice loss and SST increase is responsible for 0.8–1.5 K warming recorded at the NEEM deposition site (annual mean temperatures indicate a warming impact of 1.9–2.5 K). Merz et al. (2016) illustrate how further sea ice reduction could accelerate Greenland warming, and estimate that uncertainty in the sea ice cover can account for 1.6 K annual mean warming at the NEEM site.

The combined impact of the simulated warming and snowfall increase could favor substantial ice sheet changes. SMB calculations revealed that while the oceanic changes favor increased accumulation over the southeastern GrIS, the changed insolation causes increased melting along the coastal parts of the ice sheet. The hybrid experiments indicate that the insolation is the dominant factor behind the expected reduction of the GrIS. This reiterates the finding of van de Berg et al. (2011), that direct *use of the relation between temperature and mass loss in the Eemian is likely to overestimate future greenhouse gas-driven melting. The SMB changes are consistent with previous ice sheet reconstructions (e.g. Born and Nisancioglu, 2012; Quiquet et al., 2013; Stone et al., 2013) suggesting ice sheet retreat in the southwest and northern coastal GrIS. "*

Finally the mass balance calculations are really interesting and valuable, but the results are a bit lost in the manuscript which is a real shame.

We have elaborated on the SMB discussion through the manuscript. Examples from the abstract, the introduction and the conclusion:

Page 1, Line 12

"Surface mass balance calculations with an energy balance model further indicate that the combination of temperature and precipitation anomalies leads to potential mass loss in the north and southwestern parts of the ice sheet. The oceanic conditions favor increased accumulation in the southeast, while the insolation appears to be the dominant cause of the expected ice sheet reduction. Consequently, the Eemian is not a suitable analogue for future ice sheet changes. "

Page 3, Line 24

"In the assessment of the Greenland climate, we also aim to investigate how the simulated Eemian climate could impact the ice sheet. The ice sheet response is a combined result of dynamics (ice flow) and surface mass balance changes (melt and accumulation). Here, we employ a detailed surface scheme to assess the surface mass balance. Again, the assessment of the relative importance of the insolation and sea surface warming will indicate whether Eemian ice sheet reconstructions are useful analogues for future ice sheet changes."

Page 11, Line 26

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substantial ice sheet changes. SMB calculations revealed that while the oceanic changes favor increased accumulation over the southeastern GrIS, the changed insolation causes increased melting along the coastal parts of the ice sheet. The hybrid experiments indicate that the insolation is the dominant factor behind the expected reduction of the GrIS. This reiterates the finding of van de Berg et al. (2011), that direct use of the relation between temperature and mass loss in the Eemian is likely to overestimate future greenhouse gas-driven melting. The SMB changes are consistent with previous ice sheet reconstructions (e.g. Born and Nisancioglu, 2012; Quiquet et al., 2013; Stone et al., 2013) suggesting ice sheet retreat in the southwest and northern coastal GrIS. "

Other minor comments:

- Line 20: "While the ice core air content only suggests limited elevation changes at the NEEM site (45 $\pm$ 350 m higher than present ice sheet elevation), the NEEM ice core temperature reconstruction has been corrected using the surface elevation change estimate from the ice core air content (NEEM community members, 2013)." A lot of repetition in this sentence which I find a bit difficult to understand, so I suggest modifying it.

The sentence has been rewritten.

Page 2, Line 24

"The NEEM ice core temperature reconstruction has been corrected for this effect using the ice core air content which suggests an elevation increase of 45$\pm$350 m relative to the present ice sheet elevation (NEEM community members, 2013)."

- Section 2.3 page 2, line 20. Reference for the SST and sea ice boundary conditions. Is this from Pedersen et al. (2016b)?

Correct; this has been clarified.

Page 5, Line 5

“We have designed four experiments to investigate how the last interglacial insolation changes impacted the climatic conditions on Greenland (cf. Table 1). An experiment with Eemian (125 ka) conditions (“iL+oL”, full Eemian experiment) is compared to a pre-industrial control climate state (“iP+oP”). The simulations are forced with GHGs and insolation from the respective periods along with prescribed sea surface temperatures (SST) and sea ice concentration (SIC) obtained from fully coupled model experiments with identical GHGs and insolation (the coupled simulations are described in Pedersen et al., 2016b).”

- Section 2.3 line 27: clarify, what the impact of insolation on SST changes is based on? is this again from Pedersen et al. (2016b) ?

The sentence has been rewritten.

Page 5, Line 23

“In the coupled simulations from Pedersen et al. (2016b), the induced insolation forcing leads to sea ice retreat and increasing SSTs across high northern latitudes. Figure 2 depicts sea ice concentration and SST anomalies in the coupled simulations from Pedersen et al. (2016b), indicating the differences between the sea surface boundary conditions employed here. The sea ice reduction is primarily manifested as a northward retreat of the ice edge; the sea ice concentration in the central Arctic is largely unchanged. The strongest warming is found in the North Atlantic following the northward retreat of the sea ice edge and a strengthening of the Atlantic meridional overturning circulation (AMOC). The AMOC increase is related to a regional increase of the surface salinity and increased wintertime convection, which is in part related to biases in the pre-industrial control climate (see detailed description in Pedersen et al., 2016b).”

- Page 5, line 29: “The simulated responses reveal that the ice sheet topography is important for the precipitation changes: Figure 4 reveals several examples of contrasting snowfall changes on the east and western side of the ice divide.” I understand what is meant here, but I would suggest clarifying this statement as the readers may confuse

(i) the control that topography has on the pattern of climate change observed, with (ii) the effect of topographical changes not included here.

This has been rewritten.

Page 7, Line 9

"Figure 4 reveals several examples of contrasting snowfall changes on the east and western side of the ice divide, illustrating the barrier effect of the ice sheet (e.g. Ohmura and Reeh, 1991). This pattern suggests that inclusion of ice sheet topography changes could impact the precipitation patterns; as illustrated by Merz et al. (2014b)."

- Figure 6 add label for "effect of SST" "effect of insolation" above the subplots to help the reader understand the results.

Explanatory labels have been added to all plots: "full", "insolation", and "ocean".

- Page 6, line 31. This paragraph needs more discussion. The second sentence is not enough to justify the non-linearity. I suggest formalising slightly more the factor decomposition to calculate the interaction between ocean and insulation forcings (see Stein and Alpert) or at least state that adding the two effects does not give the full temperature change. Also, add a discussion of the reasons for this. Why is this non-linearity different for precipitation-weighted and absolute temperature difference? Can you explain the processes that lead to the non-linearity ?

Stein, U., Alpert, P., 1993. Factor Separation in Numerical Simulations. Journal of the Atmospheric Sciences 50, 2107–2115.

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Please also note the supplement to this comment:
http://www.clim-past-discuss.net/cp-2016-48/cp-2016-48-AC2-supplement.pdf

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