Response to comments by anonymous referee #1 (referee comments in bold font)

The authors once again thank the referee for the review that will result in significant improvements of this manuscript. We have carefully considered all comments and addressed them accordingly in the manuscript. Responses to the individual comments are given below.

General information. Most of the figures have been revised to enhance the continents, latitude and longitude lines with labels and also the contours of the ice sheets. We have also added panels of the present day (reanalysis) to validate the models capability in simulating the interglacial climate.

To aid the reader and support the conclusions we draw in the manuscript an extensive "supplementary material" is provided where we show the evolution of the eddy geopotential field in both summer (JJA) and winter (DJF) for all simulated cases using both interglacial and LGM ocean heat flux convergence. We also show the evolution of the sea-ice margin and upper tropospheric zonal winds over the glacial cycle using the different ocean parameterisations as well as difference plots for the summer surface temperature between the fully forced and sensitivity simulations.

This paper presents modelling results to examine how the paleo ice sheets at different key periods of the last glacial cycle (MIS5b, MIS4 and LGM) may have impacted the the atmospheric circulation through both thermal and topographic forcings, and how the perturbations induced by ice sheets may have influenced the evolution of ice sheets themselves. The simulations are performed using the atmospheric CAM3 model and the ice-sheet reconstructions by Kleman et al (2013) used as boundary conditions. The results presented in this manuscript suggest that the large-scale atmospheric winter circulation rather resemble that of the interglacial period during MIS 5B and MIS 4 with a southwest-northeast tilt

of the North Atlantic jet stream. This is attributed to the weak interaction between the mean flow and the ice sheets. At the opposite, at the LGM, a zonalisation of the jet is observed in response to the large North American ice sheet. A second interesting results concerns the presence of warm temperatures anomalies over Alaska and Siberia due to a strong anticyclonic circulation resulting from the ice sheet topographic forcing that prevents perennial snow cover from occurring in these areas The paper offers an interesting contribution to the understanding of the links between ice sheets and past atmospheric circulation during the last glacial cycle. It is clearly organized and very well-written. Therefore, the paper deserves being published in Climate of the Past provided that a few minor revisions, suggested below, are addressed.

Specific comments:

Page 1384 (Introduction): The authors explain that the atmospheric circulation during the long build-up phase of the Northern hemisphere ice sheets has received little attention. Although they are right, they should mention a recent study by Beghin et al. (2014) in Climate of the Past that investigated the relationships between atmospheric circulation and development of ice sheets throughout the last glacial cycle.

Response:
We have added a few references (including the above mentioned study) in the introduction:

"Another key issue is the extent to which atmospheric perturbations induced by pre-LGM ice sheets helped shape the evolution of the ice sheets themselves (Beghin et al., 2014). //...// Remote interactions between widely separated ice sheets mediated by stationary Rossby waves have received less attention (Lindeman and Oerlemans, 1987; Kageyama and Valdes, 2000; Beghin et al., 2014), though there have been suggestions that the North American ice sheets excited a stationary wave train acting to warm north-western Europe, suppressing ice growth there and potentially explaining why the Eurasian Ice Sheet was considerably smaller than the Laurentide in the latter stages of the glaciation (Roe and Lindzen, 2001)."

Zonalisation of the jet at the LGM: The authors should more thoroughly discuss the extent to which the zonalisation of the jet at the

LGM is model-dependent. To my knowledge, most of the models included in the PMI3 database do not produce this zonalisation, except the GISS model (in which the ice-sheet boundary condition are given by the ICE-5G reconstruction; see also Ullman et al., 2014, Climate of the Past)

Response:
We thank the reviewer for providing this highly relevant reference. The following statement about the model dependence has been included in the introduction;

"Though there are appreciable model-to-model (Braconnot et al., 2007; Li and Battisti, 2008; Otto-Bliesner et al., 2009; Kageyama et al., 2013a) and model-data discrepancies (Kageyama et al., 2006; Otto-Bliesner et al., 2009; Kageyama et al., 2013b), these studies generally depict an LGM climate substantially different from present. This is especially true in the Atlantic sector, which exhibits pronounced cooling of the northern North Atlantic Ocean, southward displacement of the sea-ice margin and southward-shifted, and, in some studies, a nearly zonally-oriented atmospheric jet stream and storm track (e.g. Li and Battisti, 2008; Kageyama et al., 2013a; Ullman et al., 2014). A recent study by Ullman et al. (2014) attributed the massive mechanical forcing of the Laurentide Ice Sheet (in particular the ICE-5G reconstruction used in PMIP2, Peltier, 2004) as a key factor for the zonalisation of the jet. Similarly, in a model-based decomposition of various factors involved in creating the LGM climate, Pausata et al. (2011) ascribed the largest circulation change in the Atlantic region to the mechanical forcing of the Laurentide, rather than to increased albedo or reduced CO_2."

Page 1390 and table 3: Could the authors give explanations of the reason why the equator-to-pole gradient is slightly smaller at LGM than at MIS4?

Response:
The reason for the slightly larger meridional temperature gradient at MIS 4 than at the LGM is because of variations in the insolation due the orbital parameters. It turns out that the high latitude insolation (in the northern hemisphere) is greater in spring (MAM) but generally smaller over the latter half of the year (JASO) at MIS 4 compared to the LGM, see Fig. 1 (in this document). The insolation is of course effectively zero at high latitudes in the winter season in both cases. The tropics, on the other hand, receive slightly more insolation integrated over the year, which acts to further strengthen

the meridional temperature difference. (Note that the total annual insolation integrated over the planetary surface is the same in both cases. It is merely the spatial and temporal distribution that changes with the orbital parameters.)

Table 3 in the manuscript shows that the meridional temperature gradient is strengthened even more when we introduce the ice sheet to the system. This follows nicely from the previous argument as the ice sheets high albedo reflects much of the incoming solar radiation in areas where the sensitivity simulations (the set of simulations without ice sheets but appropriate greenhouse gases and insolation) only have seasonal snow cover. A higher surface albedo effectively means lower temperatures at high latitudes and thus a greater meridional temperature gradient.

We have added the following paragraph in the text to explain this result:

"The somewhat larger meridional temperature gradient in MIS 4 compared to the LGM is related to the difference in Earth's orbital parameters at the nominal time of the simulations. The northern hemisphere high latitudes in MIS 4 receive more insolation in spring compared to the LGM but the summer and fall insolation is less (not shown), thus rendering the Arctic generally colder over a large part of the year. When introducing the ice sheets this effect is intensified as their high albedo helps to cool regions with a seasonal snow cover in the sensitivity simulations. The annual insolation in the tropics is also slightly higher in MIS 4 compared to the LGM, which acts to further strengthen the meridional temperature gradient."

Page 1391 Would it be possible to better assess the relationship between the location of sea-ice margin and and wind direction? A possible way would be to perform atmospheric simulations forced by different reconstructions of sea-ice cover.

Response:
We have performed this sensitivity study by conducting simulations using alternative choices of OHT prescription which yield very different sea-ice cover in the North Atlantic. We find that the sea-ice margin is not of principal importance for the orientation of the Atlantic jet, although it may help to expand the zonalised part of the jet axis at the LGM. Supplementary figure S5 shows the evolution of the winter (DJF) sea-ice cover and the 300 hPa zonal wind over the glacial cycle using both the interglacial and LGM ocean parameterisations (OHT).

The characteristic interglacial southwest-northeast tilt of the jet remains in the MIS 5b and MIS 4 simulations (regardless of OHT), while the sea-ice cover expands significantly and also directly below the jet axis primarily in the western ocean basin. At the LGM the eastern Atlantic remains largely ice free when using the interglacial OHT but the jet axis has a conspicuous zonal orientation in this region. The spatial extension of the zonalisation is however less than what is obtained with the LGM OHT where the sea-ice margin is farther equatorward. This implies that the sea-ice is not of chief importance for the orientation of the jet in general, but it may help to zonalise a larger segment of the jet at the LGM.

We have added a note about this in the text and also a reference to the supplementary material.

Page 1391 Lines 1-2 : The authors refer to a "pattern familiar from present-day observations". Could the authors add an additional figure showing both model results for the present-day period as well as the present-day observations for eddy heights?

Response:
This is a very relevant comment. We have included a panel showing the present day (ERA-Interim reanalysis) eddy height, precipitation and zonal wind speed in Figures 3-6.

Page 1391 Line 8: I am not really sure to understand this sentence? What is also "imparted by the Atlantic storm track"? Is it the southwest-northeast tilt? If so, could the authors explain why?

Response:
Yes, we are talking about the tilt. The word "imparted" suggests a one-way control of the storm track by the jet, which is in fact not strictly true, so we have replaced this word by the more neutral statement "[tilt] also seen in the storm track". The reason for the tilt of the Atlantic stormtrack is a topic of ongoing research and the explanation involves feedback mechanisms between topographic waves excited (primarily) by the Rockies, the SST field in the Atlantic and eddy fluxes by baroclinic waves from low-latitudes. We have provided a number of relevant references that discuss these mechanisms.

The general notion is that the Atlantic cyclones tend to be guided by the jetstream and thereby giving the stormtrack a similar tilt as the mean flow. The problem is that the jetstream exists largely as a consequence of the cyclones which makes the chain of feedback effects opaque and hard to unravel in its full depth.

Page 1392: Lines 5-6: I am not really convinced that changes in precipitation from MIS4 to LGM are larger than the changes from MIS5b to MIS4. Unless a proper justification is provided, this sentence appears as an overstatement and should be removed.

Response:
This sentence is clearly somewhat misleading. It is now reformulated and reads:

"Consistently with the discussion above, the stormtrack undergoes a similar transition as the jet stream and retains much of its meridional tilt in MIS 5b and MIS 4 (Fig. 4). At the LGM, however, it becomes almost completely zonalised over the Atlantic Ocean."

Page 1394: "The anticyclone over North America is therefore split up into one part forced thermally, and one part induced mechanically by the ice sheet topography at higher latitudes". It took me a little time to understand from which feature in figure 5 this statement was derived. Therefore, I think that this figure should be commented and explained in more details to be understandable by a larger audience not fully familiar with atmospheric dynamics.

Response:
Also this sentence was a bit hard to understand. It is now revised and reads:

"The anticyclone associated with the divergent flow in the upper troposphere over the North American continent is gradually being weakened and shifted southward as the glacial progresses. At the same time a secondary high anomaly develops at higher latitudes due to forcing of the ice sheet. This development is particularly evident when transitioning from MIS 5b to MIS 4 where the upper tropospheric anticyclone is partitioned into two distinct centers, and, at the LGM, there is even a band of relatively low geopotential in between rendering the separation even more apparent."

Page 1394: For a better understanding of the relative effects of mechanical and thermal forcings, it would be useful to show the evolution of the 300 hPa eddy geopotential corresponding to the sensitivity experiments of the "no-ice sheet cases" (described on page 1395).

Response:
The reviewer is quite right. To better illustrate the importance of the ice sheet topography in shaping the planetary-scale circulation we have added figures of the 300 hPa eddy geopotential from all of our simulations in a supplementary document. There we show the eddy geopotential field for all fully forced simulations as well as the sensitivity simulations with eliminated ice sheets. We present results both for the winter (DJF) and summer (JJA) seasons and with the pre-industrial and LGM ocean heat flux convergence for full disclosure. A reference to these figures is provided in the text.

Page 1394: Could the authors better justify the last sentence "Due to the relatively weak mean flow...diabatic cooling over the ice sheet". Which is the feature in figure 6 that allows to derive such a conclusion?

Response:
There are two main sources of stationary waves in this region, the topography and the diabatic cooling from the ice surface. The topographic forcing goes as $\mathbf{u} \cdot \nabla h$ and is thus limited by the flow speed. The diabatic cooling yields a high pressure ridge over the ice sheet (Ringler and Cook, 1999; Liakka, 2012) that locally reinforce the (weak) topographic wave.
The wave energy propagates with the group velocity, which is proportional to the mean wind speed as $|\mathbf{c_g}| = 2\bar{u}\cos\alpha$, where α is the angle between lines of constant phase and the latitude axis. This means that for a weak mean flow the wave energy is dissipated over a relatively small distance away from the source region and, hence, the resulting wave train is short. We have reformulated the above mentioned statement in the following way:

"The relative importance of topographic and diabatic forcing of stationary waves is controlled by the magnitude of the low-level winds (Held and Ting, 1990), where a weak mean flow yields a dominance of diabatic over mechanical forcing. A weak flow is also unfavourable for wave propagation as the wave energy tends to be dissipated closer to the source region. The high pressure ridge over the ice sheet is, however, strongly amplified by the diabatic cooling (Ringler and Cook, 1999; Liakka, 2012)."

Page 1396 Line 24 : In which figure are the westerly winds displayed?

Overall, I think that some features do not appear clearly in the

figures, such as the contours of the continents in figures 2 to 6 or the contours of the ice sheets in figures 4 and 6. My suggestion is to change the thickness and/or the colour of the lines, increase the width of the figures and indicate both latitudes and longitudes. Also, arrows indicating the advection of warm/cold/dry air should be added in figures 3 and 5.

Response:
We have added a reference in the text to Fig. 2 that shows the low-level winds.

Figures 2-8 are also revised with clearer background map, included labels for the latitudes and longitudes and we have also changed the color mapping in some of the figures to more clearly illustrate the important features.

Page 1391, line 26: south Iberia (instead of south to Iberia)

Response:
We actually mean "south to Iberia" as the winter sea-ice line reach northern Portugal in our LGM simulation.

Page 1399, line 2: add "from" between "result" and "the choice"

Response:
Done

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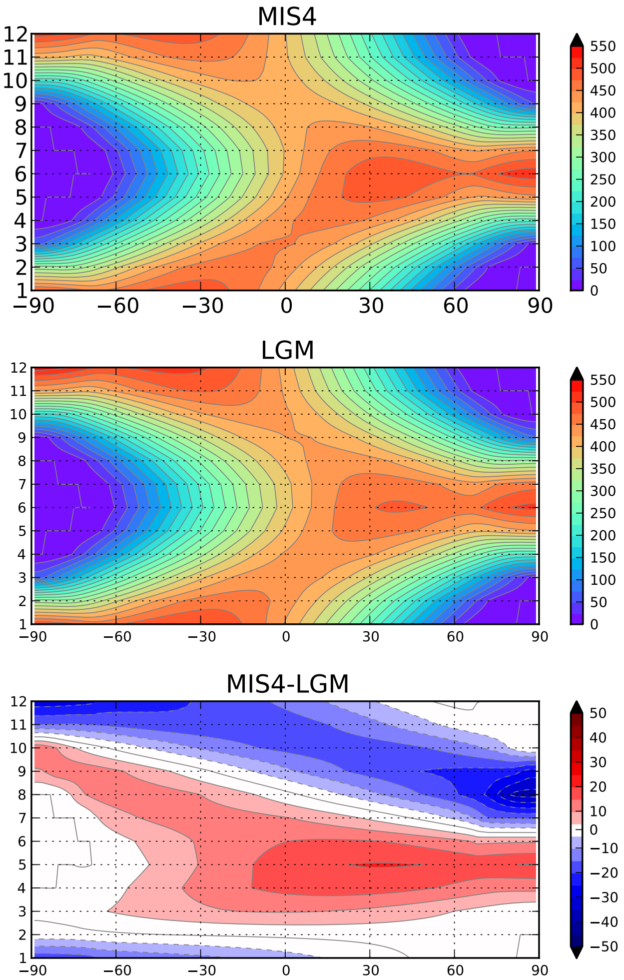

Figure 1: The latitudinal distribution of the monthly average TOA insolation (months on the vertical axis, 1 means January and 12 December) in Wm^{-2}. The upper and middle panels show the full fields for MIS 4 and the LGM respectively and the lower panel MIS 4 – LGM.