Response to Reviewers

We wish to thank the reviewers for their insightful comments which we feel have substantially improved our manuscript. We believe we have addressed all of the major and minor comments that were raised by the reviewers and, in doing so, have crafted a paper that is more rigorous in content and clearer in presentation.

Reviewer #1 (Jenny Brandefelt)

We thank the reviewer for her thoughtful and helpful review. In the revised manuscript we have made almost all of the changes she has suggested. We have addressed the major concerns of the reviewer, related to the lack of a clear distinction between results presented in the present manuscript and previous results presented in Pausata et al (2009), the missing details concerning the experimental design and the statistical significance of the results we presented. Finally, we have also included a discussion about the trends in the simulated climate towards the end of the simulations. First, we copy below the reviewers' comment/concerns (in bold), and then we describe how we have addressed each of the issues.

Major concerns:

1. **The lack of a clear distinction between results that apply to the Northern Hemisphere and results that apply only to the North Atlantic sector/region.**

   Thank you for pointing this out. We have rewritten the Results section. We have divided the first section in 2 subsections, discussing first the results concerning the Northern Hemisphere and then the results linked to the North Atlantic as suggested later on by the reviewer.

2. **The lack of a clear distinction between results presented in the present manuscript and previous results presented in Pausata et al (2009). Specifically, the results regarding the importance of oceanic differences (SST and sea ice extent) for the atmospheric circulation differences between LGM and PI should be removed from the Abstract and the Conclusions, since these belong to Pausata et al (2009)**

   We have added a paragraph in the introduction that briefly summarizes the Pausata et al. (2009) results, and made other small edits throughout the introduction and conclusions that we feel clarify the distinction between the two manuscripts. The addition of a new sensitivity experiment (see second paragraph below) further distinguishes the present study from the previous.

   Pausata et al. (2009) investigated SLP field and SLP variability in LGM and PI simulations from four different coupled models; however, the relative influence of SST and sea ice on atmospheric circulation was investigated using one atmosphere-only model (AGCM only). The AGCM sensitivity experiments tested the effect of SST/sea ice forcing on the atmosphere, with the SST/sea ice fields taken from the coupled model with the two most different – in terms of SLP pattern and variability – LGM simulations.

In the present study, the main focus is entirely different from that of the Pausata et al. 2009: to more cleanly investigate the relative roles of each LGM boundary condition (greenhouse gases, ice sheet topography, ice sheet albedo) in a fully coupled framework, but using just one fully coupled model (IPSL). Furthermore, this study complements and extends the result presented by Pausata et al. 2009, because it (1) deals with the interactive, fully coupled role of the ocean (rather than the "boundary condition", uncoupled), and (2) confirms the small influence of SST/sea ice on atmospheric circulation in a second model setup (IPSL used here, CCCSM used in Pausata et al. 2009). This second point was made in the original submitted manuscript, but is now supported by another sensitivity experiment – a fresh water "hosing" experiment initiated from the full LGM simulation (LGMfw; Kageyama et al. (2009)). This new analysis (also suggested by reviewer #2) corroborates the statements on the secondary influence of SST and sea ice on SLP, relative to the dominant influence of LGM topography (see Fig. R4) showing that the SLP climatology and leading pattern of SLP variability in the LGMfw experiment is almost identical to the full LGM, i.e. mostly independent of changes in the underlying SST. The new analysis appears as Fig. 6 in the revised manuscript.

3. **The statistical significance of the results presented in the present manuscript should be assessed and presented.**

   We have calculated the statistical significance of the results, using a two-tailed Student t-test. Simulated differences from the control (PI) for both surface temperature (TS) and SLP are almost everywhere significant at 95% confidence level (see Fig. R2 and R3). This is not surprising given the length of the simulations (i.e. 100 years).

4. **The methods used to determine SLP gradients and locations of lows and highs are not explained.**

   The locations of lows and highs in the SLP fields were determined by finding the lowest and the highest climatological SLP values in the Atlantic (20-65°N; 0-60°W) and the Pacific (20-60°N; 120-180°W) ocean separately. The SLP gradient was calculated as the difference between the SLP low and high centers divided by their distance. Error estimates for the locations of the highs and lows and also for the gradients are not included since we would need a multi-member ensemble of each experiment to calculate these. This explanation has been added to the caption in Table 4.

5. **The setup of the analysed simulations needs to be improved (since the manuscript by Kageyama et al is not even submitted), e.g. the treatment of the 130 meter lower sea level in the LGM climate as compared to the PI.**

   We have expanded the Methods section to provide more details about the simulation setups. Specifically, the 130 m drop in sea level associated with LGM conditions has been applied for all the experiments with ice-sheet forcing (whether topography or albedo or both), whereas for the

LGMghg the sea level is the same that in the PI simulation. The new LGMfw experiment is now also described in the Model and Experiments" section.

6. **The trends in the simulated climate towards the end of the simulation should be discussed. Since the LGM climate is radically different from the PI climate one would expect a longer equilibration time than 500 years. Brandefelt and Otto-Bliesner (GRL; 2009) and Brandefelt et al (CPD; 2011) find that there are significant differences in the North Atlantic climate after 500 years of integration as compared to after 1500 years of integration.**

   In this section, we have now discussed the trend in the global surface air temperature that appears to be below 0.05 K/Century (for more details see first point under "specific comments" for Reviewer #2).

Minor comments:

1. **line 4: The ice sheets did not cover "large parts of Eurasia", I suggest changing Eurasia to Europe.**

   Thank you. Done.

2. **line 10: Change "(SLP), 200-hPa" to "(SLP) and 200-hPa"**

   Thank you. Done.

3. **line 14-16: The sentence starting "We also show that North Atlantic .." This is not shown in the present study!**

   Please see response to the second point under "Major concerns".

Introduction

1. **Since this work is a follow up on Pausata et al (2009) I suggest you give a description of that study; data, simulations, analysis, results.**

   We have included a summary of Pausata et al. (2009) in the introduction (see also Major concern #2)

2. **Further, as shown by e.g. Pausata et al (2009) the simulated LGM climate and the LGM - PI differences are model-dependent. This should be taken into account when the results of the present study are interpreted.**

   We have noted in the discussion that our exploration of the relative importance of different LGM boundary conditions in the coupled model framework we employ here is limited by the fact that we use only one model.

3. **Refer to and compare your results to Laine et al (Clim. Dyn.; 2009) who study storm track variability in the PMIP2 LGM simulations.**

Laine et al. (2009) study refers to the model dependence of the simulated atmospheric circulation rather than the importance of each LGM boundary condition. A discussion about this study appears in the discussion section.

4. **Refer to Byrkjedal et al (Clim. Dyn.; 2006) when you discuss the importance of sea ice and SST for the LGM NH atmospheric circulation.**

   Thank you. Done.

5. **p 577, line 24: I suggest you remove "(GISS model II)", if you wish to keep this information you should give the complete name of the model.**

   Thank you. We have removed "(GISS model II)"

6. **p 578, line 10: remove "that itself adjusts to insolation, ice sheets and GHG changes".**

   We have removed this sentence.

Model and Experiments

1. **What are the trends in surface temperature, abyssal ocean temperature etc during the last 100 years of each experiment? Has the climate reached a quasi-equilibrium?**

   See Fig. R1 and please look at the first answer to "specific comments" for Reviewer #2.

2. **The methods used to determine the SLP gradients listed in Table 3 and the locations of the subpolar lows and subtropical highs should be described here. These determinations should be associated with some error bars.**

   Please, look at point 4 under "Major concerns".

3. **The statistical significance of the differences between different experiments should be assessed and presented for all parameters analysed! When dealing with climate data, we should always test differences for statistical significance.**

   Please see point 3 under "Major concerns".

4. **Information regarding the sea level in the different experiments is lacking.**

   We have added a sentence clarifying this point. Thank you.

5. **It is important to state that you are not expecting that LGM be exactly equal to (LGMghg+LGMald+LGMtopo), that there are non-linear interactions in the system.**

   We have considered this suggestion and we have made this point clear in the "Model and Experiments" section.

6. **p 579, line 2: the acronym AOGCM has not been defined.**

   Thank you. Done.

7. **p 579, line 12: change "orbital configuration is" to "orbital parameters are"**

   Thank you. Done.

8. **p 579, line 15: change "For both" to "In all"**

   Done.

9. **p 579, line 18: "Kageyama et al, in preparation", I thought only published work or accepted for publication could be referenced, but the instructions for authors on Climate of the Past's web are not very clear so I leave this to the editor.**

   We are not sure whether or not is possible to cite in-preparation work; however, Kageyama et al. (In prep.) was deemed appropriate to acknowledge those who have done substantial work setting up and running the experiments used in the manuscript.

Results

1. **The results section is quite confusing since the authors sometimes describe the results for the NH and mostly only for the North Atlantic sector. This section requires re-writing with focus on clarity. Perhaps you could move all the results regarding the NH to the first paragraph of the Results section and then state clearly that the rest of the section will deal only with the North Atlantic.**

   Thank you. We have re-written the section separating the results that apply to the NH from the results that apply only to the North Atlantic (see also first answer to "Major concerns").

2. **p 580, line 20: I suggest you remove "(see Fig. 1 as well as Fig. 1 in Pausata et al. (2009))". Add a new sentence "This is shown in Figure 1 where the location of the centers of the subtropical highs and subpolar lows are displayed."**

   We have changed "(see Fig. 1 as well Fig. 1 ...)" with "(Fig. 1)". We feel there is no need for the suggested sentence.

3. **p 581, line 1-5: Suddenly, without notice, the results are only valid for the N Atlantic region!**

   We have reorganized the section as described above.

4. **p 581, line 1: "LGMghg and LGMalb simulations exhibit stronger SLP gradients, ..." Stronger than what?**

   Thank you. We have clarified that we mean stronger than the control simulation.

5. **p 581, line 2: "but much less change (compared to the control simulation) in the location of the subtropical highs and subpolar lows." I do not agree, the shifts shown in Fig 1 for LGMghg and LGMalb are not "much less" than in LGMtopo**

   We have removed the word "much".

6. **p 581, line 8-10: "The sensitivity experiments presented here reveal that these ...." Simulations with one AOGCM can only "indicate" the importance of of topography, not "reveal".**

   We have changed "reveal" to read "indicate".

7. **p 582, line 11: add "(not shown)".**

   Thank you. Done.

8. **p 582, line 12: remove ", and has been verified by comparing maps of the climatological-mean response and its interannual variability."**

   We have clarified the statement and now it reads "...and has been verified by examining the climatological maximum and interannual variability of the zonal wind field in the simulations (not shown)."

9. **p 582, line 13: there is also a distinct northward shift of the zonal wind speed maximum**

   We have added this point in the manuscript. Thanks.

10. **p 582, line 14-25: It is quite possible that your discussion regarding the influence of the albedo on the temperature gradient influencing upper level winds is right. However, since the relation is not that simple for the present and future response of the upper level wind to enhanced GHG concentrations (Hoskins, Science, 2003) the ideas presented here need to be proven. Include a figure of the zonal mean (or sectorial mean) temperature as a function of latitude and pressure.**

    We are aware of the fact that the relationship between the surface temperature gradient and the upper level circulation is not straightforward, both for greenhouse gas scenarios (Brandefelt (2006),Raisanen (2003)) and the LGM (Rojas et al (2009)), with many factors including water vapour playing a role in determining the radiative-convective equilibrium and dynamical adjustments in a certain climate state. The summertime albedo effect of the ice sheet on the temperature gradient is in fact evident in zonal mean temperature profiles over the Atlantic sector (see Fig. R5). However, this statement was not meant to be a focus of the study, but rather an interesting aside, and we have edited it to reflect this.

11. **p 583, line 12-14: Why is SAT, and not SST, analysed in this section?**

    We plotted the surface temperature (TS) rather than SST in order to show some of the subsidence-related warming at the eastern edges of the ice sheets, a feature that we discuss in relation to several previous studies investigating the effect of ice sheet on atmospheric circulation. In the IPSL model, SST and TS over the ocean are defined to be equal except over sea ice.

12. **p 583, line 26-27: Add a note on the non-linear effects that are evident from Fig 4 (LGM $\sim =$ LGMtopo+LGMghg+LGMalb).**

    Done. Thank you.

Discussion

1. **Please clarify regarding which results are valid for the NH and which are valid only for the N Atlantic**

   Done. Thank you (see also first point under "Major concerns").

2. **p 584, line 21: suggest to change "...much smaller influence" to "smaller, sometimes even opposite, influence".**

   Done. Thank you.

3. **p 584, line26: "In a world with increased GHG concentrations ...." Remove or rewrite with reference to Hoskins: Enhanced GHG concentrations gives a weaker meridional temperature gradient at the surface, but a strengthened temperature gradient in the upper troposphere - lower stratosphere (i.e. at 200 hPa) which gives a strengthening of the 200 hPa wind (Hoskins, Science, 2003).**

   Thank you for the suggestion. We have followed your suggestion and blended it with our original sentence. Now it reads "Therefore, in a world with increased GHG concentrations meridional temperature gradient at the surface would be weaker, whereas would be increased in the the upper troposphere - lower stratosphere (i.e. around 200 hPa) which gives a strengthening of the 200 hPa wind (as shown for example in Raisanen (2003))." We use the reference Raisanen (2003), which we believe is more appropriate.

4. **p 585, line4: suggest changing ", even when ..." to ", also when ..."**

   We have rewritten the sentence as follow: "... with previous model studies (refs for ICE-5G studies), including those in which an older version of the ice sheet reconstruction (ICE-4G, Peltier 1994) was used (refs for ICE-4G studies)."

5. **p 585, line 7: suggest changing "discrepancy" to "difference"**

   We feel "discrepancy" better reflects our intended meaning.

6. **p 586, line 1-3: Rewrite to acknowledge the fact that this conclusion is based on only ONE model.**

   Done.

7. **p 586, line 5-7: Remove the sentence starting "Presumed links ...."**

   Since it is in the discussion section, we feel we can raise open issues and ideas for future studies such as this.

8. **p 586, line 8-11 and line 17-19: Do you have any reference for the statement that the atmospheric circulation mean state is very sensitive to model-model differences in the treatment of the topographic boundary condition? Else, rewrite making it clear that this is a speculation.**

   We have rewritten the sentence to clarify that this is a speculation, and it now reads: "...treat topography may be important for understanding..."

9. **p 586, line 11-13: Clarify if the "different coupled climate model simulations " were simulations performed with different models or different simulations performed with the same model.**

   Done.

10. **p 586, line 13-15: for the reader to judge the significance of getting "remarkably similar SLP fields" using SST distributions from two different coupled simulations we need to know how different the SST distributions were.**

    This is a good point. However, we feel there has been a slight misunderstanding, and we have worked to clarify this in the manuscript. This statement is referring to Pausata et al. (2009), where it was shown that when PI SSTs are used in an atmospheric model with all other boundary conditions set to LGM values, the resulting SLP field is remarkably similar to that of the full LGM simulation. The supporting details for this statement appear in the previous paper.

11. **p 586, line 17-19: suggest change "The results of this study" to "The results of the present study"**

    We have changed it. Thank you.

Conclusions

1. **Please clarify regarding which results are valid for the NH and which are valid only for the N Atlantic!**

   Done. Thanks.

2. **The role of the SST should not be regarded as a result of the present study!**

   The new result about the role of SSTs/sea ice, and how this new result related to those presented in Pausata et al. (2009), was not clear in the original submitted manuscript. We have edited the manuscript substantially in order to clarify this (see response to the second point under "Major concerns") and in addition have added a new LGMfw experiment that provides a much cleaner test of the role of SST/sea ice from an LGM "base condition" (also described in second point under "Major concerns").

3. **p 587, line 1-3: Specify if these effects are in the same or opposite direction as compared to the effect of the topography.**

Done. Thanks.

Figures and Tables

- **Table 4 is an almost duplicate of table 3. Please remove one table and check carefully that the correct information is given in the remaining table. It looks as if Table 4 is correct.**

  Thank you for pointing this out. Table 3 was incorrectly inserted when we uploaded the manuscript.

- *** Statistical significance of the differences in the SLP gradient**

  Please look at points 3 and 4 under "Major concerns" for a discussion of the statistical significance of the results.

- **New table * Suggest including a new table with the displacement of the locations of the subpolar lows and subtropical highs**

  We have added the suggested table.

- **Figure 1 * It would be easier to follow the reasoning in the Results section if isolines for the difference in climatological SLP (LGM*-PI) were shown for all experiments * Increase font size for titles and colorbar**

  We added the isolines for the difference in climatological SLP (LGM*-PI).

- **Figure 2 * Increase font size of title**

  Done. Thanks.

- **Figure 3 * Include 0-90N in the figure, interesting to see what happens on the southern flank of the jet.**

  We have include 0-90N in the plot.

- **Figure 4 * Statistical significance * Increase font size of title**

  We increased the font size of the title. The statistical significance is shown in Fig. R3 and described in the manuscript.

Reviewer #2 (Anonymous)

We thank the reviewer for the thoughtful and critical comments regarding the finding that North Atlantic sea surface temperatures are of minor importance in influencing the North Atlantic atmospheric circulation under LGM conditions. The reviewer points out that the fact that atmospheric circulation and its variability are similar under full glacial conditions (experiment LGM) and in a climate state with preindustrial boundary conditions but glacial topography (experiment LGMtopo) does not prove

that North Atlantic sea surface temperatures do not substantially affect North Atlantic atmospheric circulation in the LGM. The reviewer suggests an additional experiment ("a classic freshwater release experiment") under full glacial boundary condition.
We have added a fresh water experiment to the analyses that existed in the previous version of the manuscript to more clearly demonstrate that even the relatively large changes to SST and sea ice associated with the freshwater hosing experiment have relatively little influence on the mean or variability in the SLP field, thus they are mainly controlled by the topography (compare Fig. R4 with Fig. 2 in the original manuscript.)

Specific comments:

1. **- Line 23 Each equilibrium experiment is 500 years long – This integration length seems to be quite short in order to achieve equilibrium conditions. Therefore, it would be helpful if the authors present for instance the trend in global annual mean surface temperature, which should be no larger than -0.05 K/Century.**

   Figure R1 shows trends for the surface air temperature (SAT) and below we list the global annual mean trends of surface air temperature and abyssal ocean temperature for each experiment over the last 300 years and the last 100 years.

   Global SAT trends over last 300 years of run:

   drift over the last 300 yrs of run PI: 0.025 K/100yrs
   drift over the last 300 yrs of run LGM: -0.001 K/100yrs
   drift over the last 300 yrs of run LGMghg: 0.033 K/100yrs
   drift over the last 300 yrs of run LGMalb: -0.015 K/100yrs
   drift over the last 300 yrs of run LGMtopo: -0.016 K/100yrs
   drift over the last 300 yrs of run LGMice: 0.025 K/100yrs
   drift over the last 300 yrs of run LGMfw: 0.078 K/100yrs (this run is the fresh water hosing experiment (Kageyama et al. (2009))

   All equilibrium runs show a relatively small trend (a potential indicator of simulation drift) $<$ 0.05 K/100years in absolute value.

   The trends over last 100 years are sometimes larger than over 300 years because of the presence of centennial scale variability.

   Global SAT trends over last 100 years of run:

   drift over the last 100 yrs of run PI: 0.035 K/100yrs
   drift over the last 100 yrs of run LGM: -0.123 K/100yrs
   drift over the last 100 yrs of run LGMghg: -0.016 K/100yrs
   drift over the last 100 yrs of run LGMalb: -0.132 K/100yrs
   drift over the last 100 yrs of run LGMtopo: 0.017 K/100yrs
   drift over the last 100 yrs of run LGMice: 0.119 K/100yrs
   drift over the last 100 yrs of run LGMfw: 0.043 K/100yrs

Global bottom (deeper than 2000m) ocean temperature drift, last 300 years of run.

drift over the last 300 yrs of run PI:	0.066 K/100yrs
drift over the last 300 yrs of run LGM:	-0.025 K/100yrs
drift over the last 300 yrs of run LGMghg:	-0.015 K/100yrs
drift over the last 300 yrs of run LGMalb:	0.087 K/100yrs
drift over the last 300 yrs of run LGMtopo:	0.135 K/100yrs
drift over the last 300 yrs of run LGMice:	0.133 K/100yrs
drift over the last 300 yrs of run LGMfw:	-0.009 K/100yrs

Global bottom (deeper than 2000m) ocean temperature drift, last 100 years of run

drift over the last 100 yrs of run PI:	0.067 K/100yrs
drift over the last 100 yrs of run LGM:	-0.020 K/100yrs
drift over the last 100 yrs of run LGMghg:	0.014 K/100yrs
drift over the last 100 yrs of run LGMalb:	0.044 K/100yrs
drift over the last 100 yrs of run LGMtopo:	0.130 K/100yrs
drift over the last 100 yrs of run LGMice:	0.026 K/100yrs
drift over the last 100 yrs of run LGMfw:	0.000 K/100yrs

We reckon that the ocean bottom is still adjusting to the new boundary conditions but the drifts are rather small and the surface and atmospheric features we are focusing on our work are stable over the analyzed period.

2. **In the context of the presentation of the northward heat transport differences in Fig. 5, a brief discussion of the different Atlantic overturning states in comparison to data (e.g. strength and latitudinal extent) would be appropriate.**

   Although there are few if any good proxies for the strength of the AMOC, we have added a short description where we compare the expected LGM AMOC based on data (shallower with convective sites more to the South of their present day position) and the simulated LGM AMOC (relatively strong). This difference might be due to an "overreaction" to the topography forcing. However, focusing on the sensitivity within each of these boundary conditions would add an entire new dimension of complexity that we didn’t intend and perhaps could not interpret cleanly.

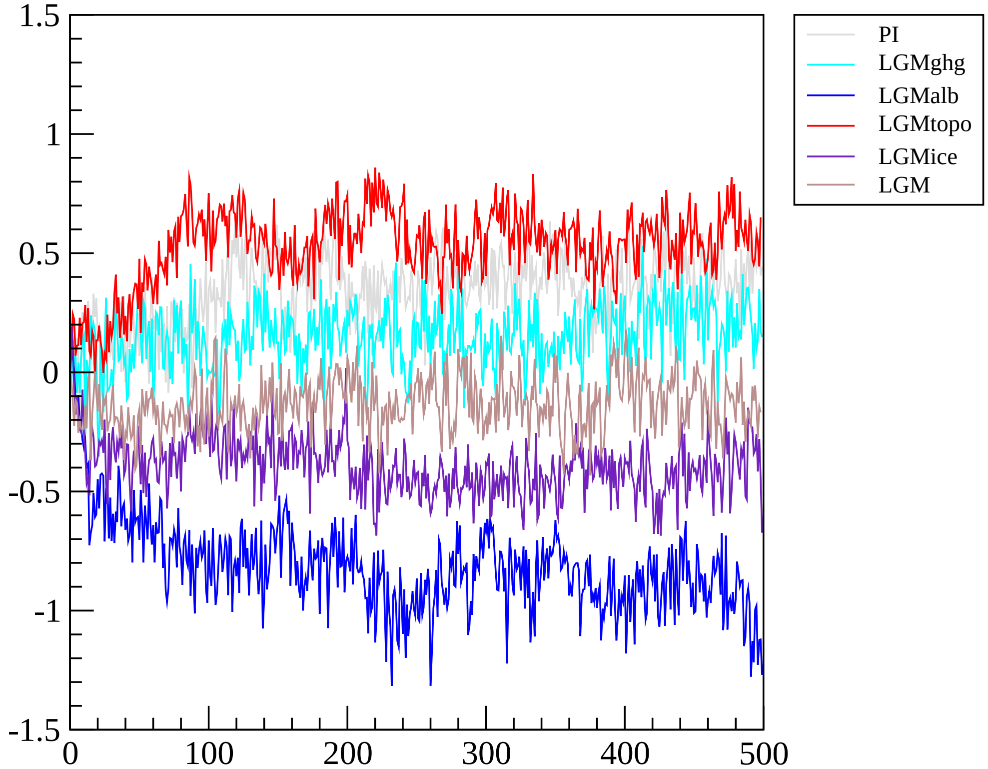

Fig. R1: Global annual mean of the surface air temperature time-series for all experiments (initial global annual mean removed for clarity).

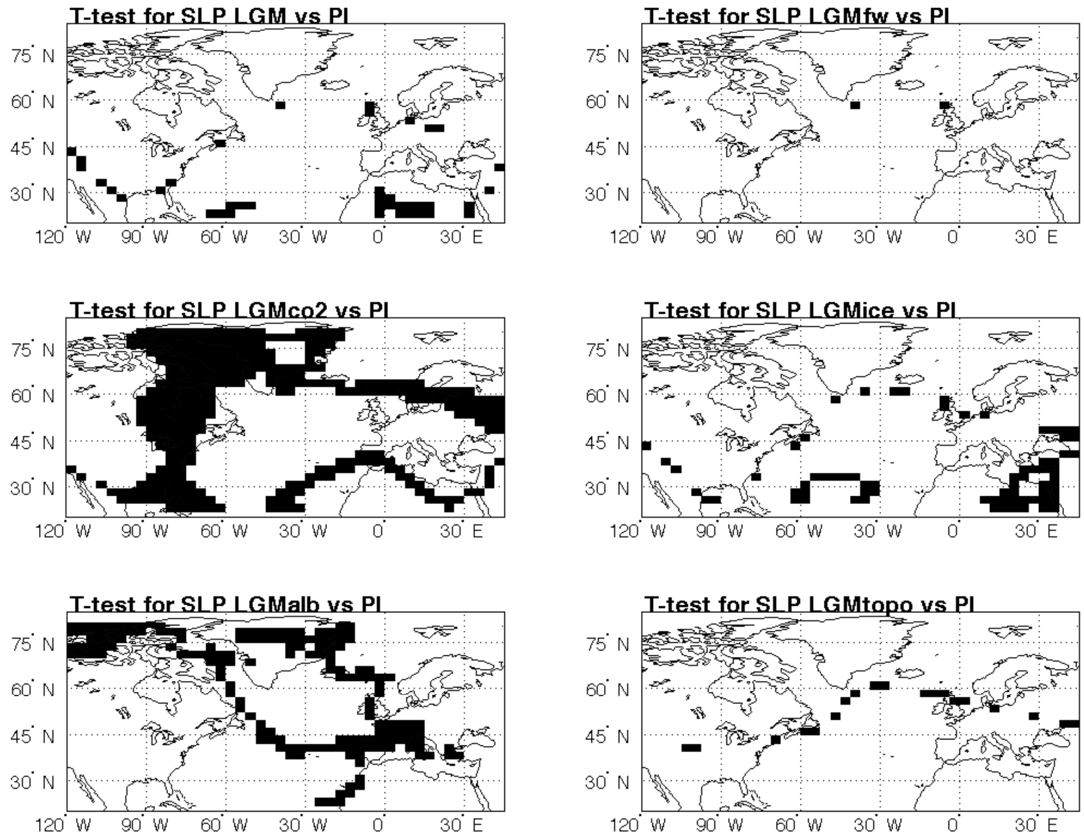

Fig. R2: Two-tailed Student T-test between the SLP of the PI simulation and the SLP of all the other experiments. White area represents the locations with significant differences at 95% confidence level.

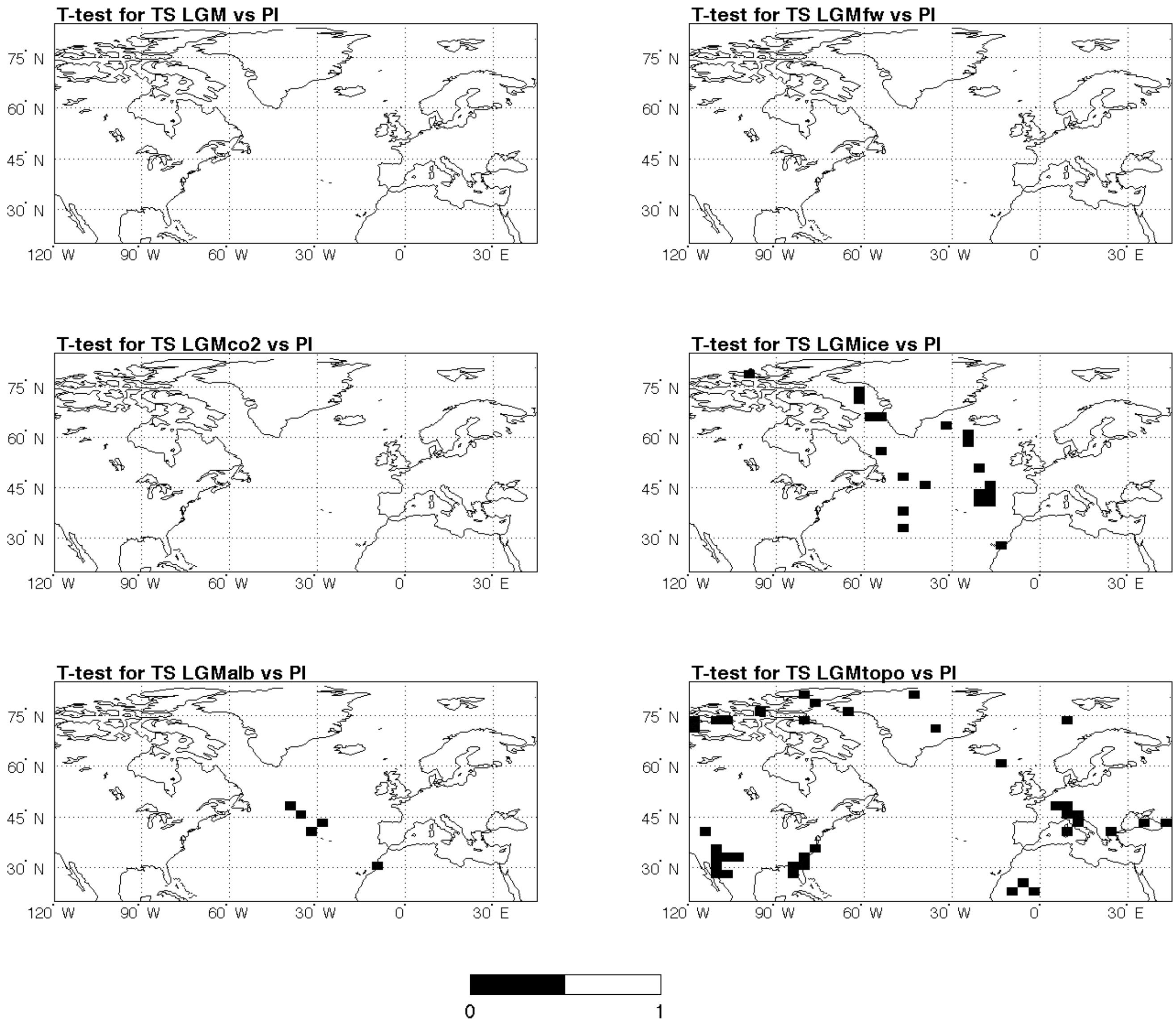

Fig. R3: Two-tailed Student T-test between the surface temperature of the PI simulation and the SLP of all the other experiments. White area represents the locations with significant differences at 95% confidence level.

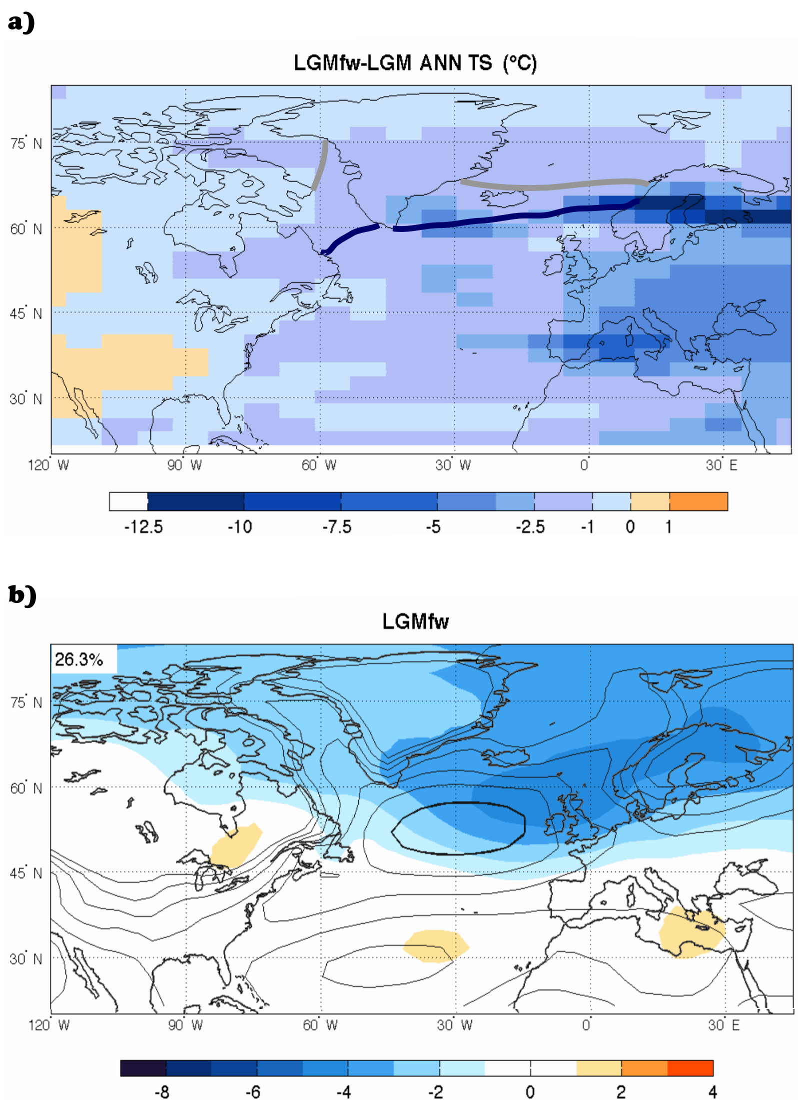

Fig. R4: a) Anomalies in annual mean surface temperature (TS) relative to the LGM climate for LGMfw experiment. The annual mean 50% sea ice concentration line is indicated by the gray line for the LGM experiment and the blue line for the LGMfw experiment. b) Leading EOF of monthly SLP anomalies (colored shading: hPa / standard deviation of PC) using data from all months and SLP climatology (contours: 4 hPa interval from 1000 to 1040 hPa; higher values omitted for clarity; bold contour denotes 1016 hPa) in the North Atlantic sector for LGMfw simulation. The number show the amount of variance explained by the first mode as a percentage of the total variance.

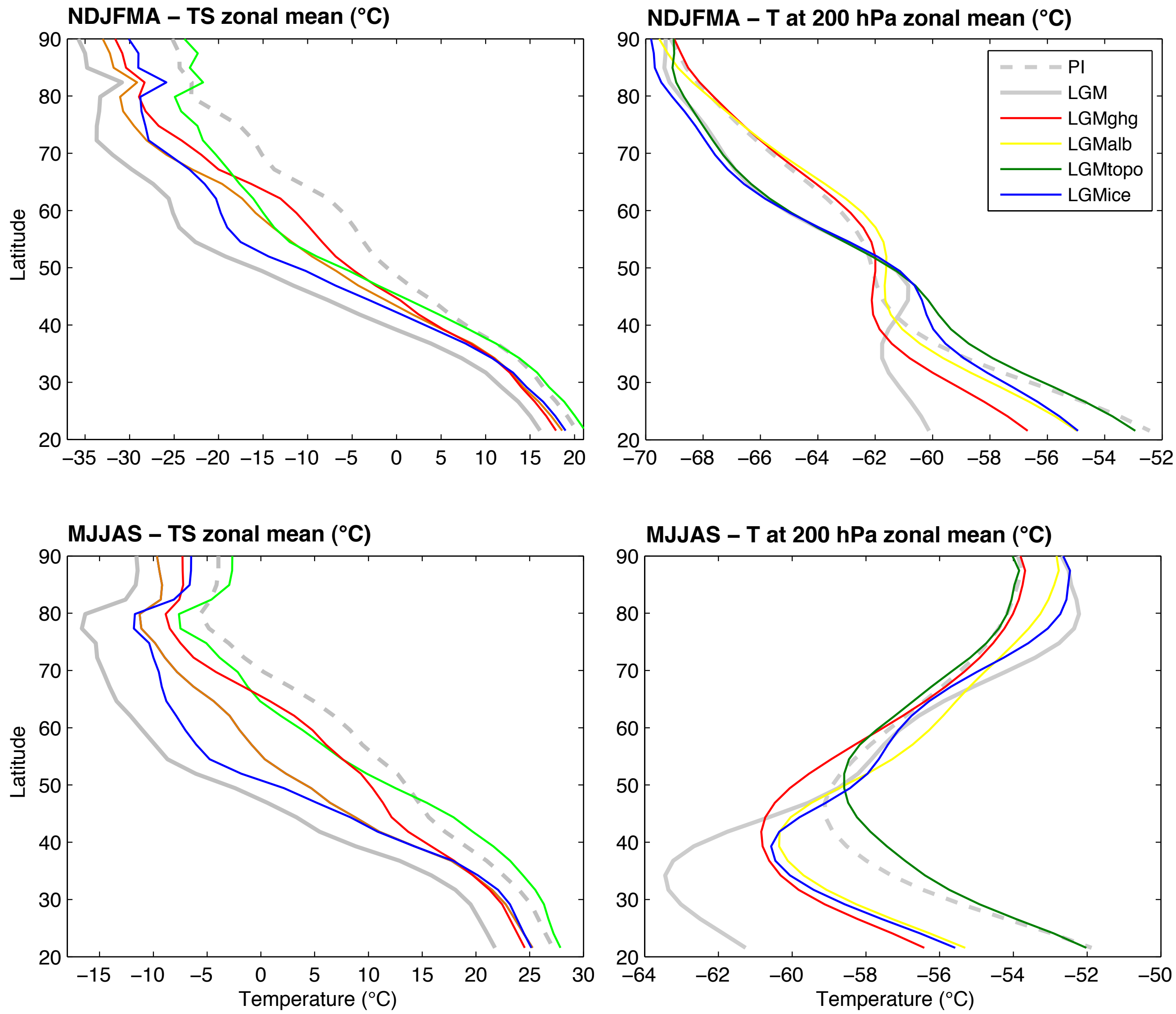

Fig. R5: November to April (upper panels) and May to September (lower panels) zonal temperature (Atlantic sector: 120°W - 45°E) as a function of latitude at the surface (right) and at 200 hPa (left) for the control (PI) and LGM simulations and LGMghg and LGMalb experiment.

References

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