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Climate of the Past Discussions

Interactive comment on "Changes in atmospheric variability in a glacial climate and the impacts on proxy data: a model intercomparison" *by* F. S. R. Pausata et al.

F. S. R. Pausata et al.

francesco.pausata@bjerknes.uib.no

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We wish to thank the reviewers for their insightful comments which we believe have substantially improved our manuscript. We feel that reviewer #1 had different expectations for the paper than what we intended, looking for more detailed model analysis such as sensitivity studies in order to understand why the models produced different leading modes at the LGM compared to PI. Reviewer #2 also had some concerns regarding the motivation of our study, pointing out the need to clarify the goals of the manuscript. In response to both reviewers, we find that our previous abstract and introduction were somewhat confusing and did not adequately explain the motivation for

our study, which is not to demonstrate the pitfalls in an LGM reconstruction of the NAO, but rather to demonstrate the more general point that proxy-based data is sensitive to many categories of changed variability. These include interannual variability, dominant modes of atmospheric variability and the seasonal distribution of both. Significant changes to the abstract, introduction and conclusions reflect a more clear description of our intent. While the authors think that such a description of the changed patterns of LGM variability in space and time is useful in its own right, we are also sympathetic to the primary complaint of reviewer #1, that a more detailed and dynamic interpretation would be useful. While not exhaustive, we include new analyses (Figs. 5 and 6 and associated discussion) in section 3.3 and 4 that we believe address this complaint.

Reviewer #1

The major concern of reviewer #1 is that it is already well-known that modes of variability like the NAO are potentially impacted by non-stationarity in significantly different climate states, such as the LGM. The reviewer was expecting to see insights into why the models show different leading modes at the LGM with respect to the PI, and suggested the addition of some sensitivity studies. In our study, we are not trying to reconstruct the NAO at the LGM, but are rather hoping to aid the paleoclimate community by describing how altered variability patterns might impact proxy records. Even though a dynamic explanation of the changes to the leading modes of variability during the the LGM is not the main purpose of this manuscript, a sensitivity study has been carried out that shows that ice sheets are the most important LGM forcing in altering the mean climate state, and that changes to the NAO are model-specific. (see also Reviewer #2, point a and #4 below).

The abstract and introduction have been rewritten pointing out that the main contribution of this study is to show the impact on proxy records of changes in atmospheric variability. A certain location could reflect leading mode (NAO-like) variability in one climate, but not in another. Or, the location could reflect the leading mode in two different climates, but the leading mode's imprint on a proxy record at that location could change due to: a) a stronger / more dominant leading mode with the same pattern b) a spatial shift of the pattern, c) a different leading mode of atmospheric variability in the glacial climate. Changing the amount of atmospheric variability could impact the integrated signal recorded in proxies, as could a change in the seasonal cycle of that variability. While the models generally agree for the PI climate, their disagreement in the LGM makes it difficult to draw clear conclusions. For further details see Reviewer #2, point #4 and the revised section 3.3.

In the manuscript, we document how the leading mode of climate variability might have changed in a glacial climate, how this change could have affected the signal captured by proxy data and whether or not the variability recorded in proxies is still representative of the variability over larger spatial scales. In spite of the fact that there are discrepancies between the models, we try to identify which locations according to all models are able to detect a substantial amount of large scale variability in both climate states, i.e. locations where it is feasible to collect proxies since it is possible to compare the glacial with the modern climate. For example, one might choose different sites when dealing with a proxy that is sensitive to temperature compared to precipitation.

Reviewer #2

Reviewer #2 suggests a) an improvement of section 3.3 with a more detailed discussion of the mechanisms behind the changes in atmospheric circulation during the LGM and requests b) a clarification of some points in the methodology. We have dealt with all the editorial points directly in the manuscript and describe the significant changes below.

a) We have expanded section 3.3. In order to give a more substantial answer about

the differences in leading mode (NAO-like) variability between the two climates, we also include a sensitivity study in an attempt to diagnose the source of the described changes. The ice sheets and greenhouse gases are found to set the mean state and the amplitude of the leading mode of variability, while the sea ice/SST set the raw variability of the SLP field. Note that the atmosphere models themselves respond differently to the same ice sheet and greenhouse gas forcings, and thus also play a role in setting the leading mode of atmospheric variability. The analysis and experiments required for a complete treatment of what causes the LGM-PI and model-to-model differences in SLP variability are beyond the scope of this study, and will be presented in a future study.

b) Responses to the specific reviewer's comments appear below:

1/ "*Could the authors explain the exact meaning of Fig. 4 and 8c and how they are obtained?*"

These figures and their associated captions have been modified to increase clarity.

2/ "*The end of the introduction (end of page 914, beginning of page 915) is a bit awkward*"

The introduction has been rewritten to address the concerns of both reviewers (see response to reviewer #1 for more details).

3/ *"Section 2. Why only selecting 4 models.*"

An explanation has been added in Section 2. The other two coupled models available (FGOALS and CNRM) have not been considered because of the unsatisfactory representation of PI climate, particularly in the North Atlantic sector. In fact, FGOALS was withdrawn from the AR4 process and later replaced with other data from another version of the model. Therefore we decided not to consider those two models.

4/ *"Section 4. The discussion about the implication of the results presented on the reconstruction of climate variability is a bit weak. I would expect that in the majority of* *the cases people are aware that for a climate that is clearly different from present one, considering the stationarity of the relationship between climate variables is usually not a good hypothesis. Do the authors have examples of reconstructions that make such hypothesis?*"

The scarcity of good quality and high resolution proxy data has made it common practice in the paleoclimate community to use records from just a few locations to infer large scale climate changes over long time scales. For instance, the oxygen isotopes in the Greenland ice core have been used to reconstruct temperature as far back as the last interglacial (e.g. Dansgaard et al. (1993)), using the temperature-isotope relationship for modern climate. There is awareness of the potential problem of assuming stationarity in the relationship between climate signals and proxy signals, but few studies have tried to demonstrate the potential sources or relative importance of this non-stationarity. Our study, while primarily descriptive, attempts to present the issue in a more practical way that should aid in future discussions. The discussion in Section 4 on paleoclimate implications has been expanded and the introduction has been edited accordingly.

5/ *"Section 4. Could the authors develop a bit this idea (changes in seasonality can affect the signal recorded by proxies) and explain how their result could be related to this point.*"

The idea that changes in seasonality can affect the proxy data has been expanded with further analyses in in Section 4, and some additional discussion in Section 3.2. For example, the models suggest a change in the seasonal distribution of precipitation on Greenland (see Fig. R1 attached). Neglecting this change in seasonality might lead to a misinterpretation of the proxy record, since the δ^{18}O signal recorded at the LGM would have a different seasonal imprint compared to the PI.

6/ *"Section 4. The authors present only the results for 2 models while the results of the four models were presented in Section 3. For consistency, results of all four models should be discussed in this section too.*"

We decided to show only 2 models for clarity. The behavior of IPSL is similar to CCSM3 and the behavior of MIROC3.2 is similar to HadCM3M2. Therefore we decided to focus just on CCSM3 and HadCM3M2, i.e. two models that bracket the results of the 4 models (Fig. R2). This point has been clarified in Section 4.

7/ "*Section 4. The correlations are presented in Fig. 5 and Fig. 6 for winter only while in section 3, they are discussed for all four seasons. Why focusing here only on one season?*" (Figs. 5 and 6 are Figs. 7 and 8 respectively in the new version of the manuscript)

We focus on the winter months when discussing the NAO because NAO variability is more active in winter, as noted by numerous previous studies. Similarly generated annual correlations show a similar, but weaker, pattern with respect to the winter patterns shown in the manuscript (compare Fig. R3 (LGM winter months) with Fig. R4 (all year)). The reason for this selection has been clarified in section 4.

8/ "*The reason why 4 particular points are selected in Table 3 is not clearly discussed*"(Table 3 is Table 5 in the new version of the manuscript)

This information has been added in Section 4. In Table 5 and in Figs. 7 and 8 the four locations have been chosen as reference points: the locations on Greenland have been widely used for climate reconstructions and the other two are locations where the models agree that temperature and/or precipitation variability are due to the leading mode of variability in both climates.

9/ "*Page 921, line 20. It is mentioned that Southern Norway is a region where the correlation is particularly high on Fig. 7. For me only Southern Denmark-Northern Germany is highlighted in Fig. 7 in Europe.*" (Fig. 7 is Fig. 10 in the new version of the manuscript)

The sentence (pag. 920 line 18-20) has been rewritten because it was not clear. In a few areas where the models do agree, it is possible to infer that in *both climates*a substantial amount of regional variability can be reliably reproduced. Labrador (Fig. 10, Table 3) and southern Norway (Table 5 and Figs. 7 and 8) represent such sites for temperature and/or precipitation in simulations of both climates. Southern Denmark and Northern Germany are good proxy for precipitation only in the LGM, whereas Southern Norway always shows relatively high values both for the correlation (upper panels Figs. 7 and 10) and coherence (lower panels Figs. 7 and 10) maps.

Reference

Dansgaard, W. and Johnsen, S. J., Clausen, H. B., Dahjensen, D., Gundestrup, N. S., Hammer, C. U, Hvidberg, C. S., Steffensen, J. P., Sveinbjorndottir, A. E., Jouzel, J. and Bond, G.: Evidence for General Instability of Past Climate from a 250-Kyr Ice-core Record, Nature, 364, 218-220, 1993.

Figure

The figures are attached in the supplement file. Here below the figure captions

Figure R1: PI (red) and LGM (blue) seasonal cycle for temperature (lines) and precipitation (histograms) in CCSM3 (left) and HadCM3M2 (right) for two locations on Greenland (NASA-U and Summit).

Figure R2: LGM correlations between North Atlantic annual surface air temperature and PC1 (NAO-like index) (left panels). An indicator of temperature coherence in the sector (right panels): the value at each point is the absolute value of the area-averaged correlation between temperature at that point and the rest of the North Atlantic basin.

Figure R3: PI (left panels) and LGM (right panels) correlations between North At-

lantic winter surface air temperature (November to April) and PC1 (NAO-like index) for CCSM3 (a, b) and HadCM3M2 (c, d). An indicator of temperature coherence in the sector for CCSM3 (e, f) and HadCM3M2 (g, h): the value at each point is the absolute value of the area-averaged correlation between temperature at that point and the rest of the North Atlantic basin.

Figure R4: LGM correlations between North Atlantic air temperature and PC1 (the NAO-like index) using all months of the year for CCSM3 (top left panel) and HadCM3M2 (bottom left panel). An indicator of temperature coherence in the sector for CCSM3 (top right panel) and HadCM3M2 (bottom right panel): the value at each point is the absolute value of the area-averaged correlation between temperature at that point and the rest of the North Atlantic basin.

Please also note the Supplement to this comment.

Interactive comment on Clim. Past Discuss., 5, 911, 2009.