Response to Referee #1

[Anwers are provided in Italic, all section numbers relate to the new manuscript, unless otherwise stated]

This is a well written paper on the changes in climate that are associated with a reduced/collapsed AMOC in a glacial background state. It is based on three simulations with the IPSL coupled AO-GCM (glacial control, reduced AMOC and collapsed AMOC) and contains excellent literature reviews on 1) paleodata showing millennialscale variations that have been connected to AMOC abrupt events and 2) earlier modelling experiments, mostly with a modern or pre-industrial background state. Although the paper reads well, it suffers from a lack of focus and too much detail. I would suggest to concentrate on the climatic response to AMOC changes, to evaluate that response against data, which is not done (surprisingly) in the present manuscript, and to summarize where the present results from glacial experiments differ from earlier modern/pre-industrial experiments. The paper would improve considerably from these (mainly editorial) changes and would then be acceptable for publication in CP.

We thank the reviewer for his/her advice. We have changed the structure of the manuscript in order to increase its focus. In particular, we have moved the contents of sect 4.1 to section 3.1 (description of oceanic changes) and tried to better explain the main objectives of our work at different places in the manuscript and in a dedicated subsection of the introduction (section 1.4). Section 3 now deals with the AMOC and global climate response to different freshwater anomalies (i.e. we analyse of LGMa, LGMb and LGMc). Section 4 and 5 focus on specific mechanisms and only investigate experiment LGMc with respect to LGMb. We believe that this new structure clarifies and focuses the study. We have also included a short, qualitative comparison with the available paleo-records at the end of section 3.3 and a discussion about the pertinence of the experimental design w.r.t the specific problem of model-data comparison in Section 6. More details about these structural changes are given in the responses to Referees 2 and 3.

Main points of criticism

1) Lack of focus, too much detail. A few suggestions to improve this: Sections 3-6 describe the model response in very much detail. This could be condensed, let some Figures speak for themselves. Section 4.1 (Figs 8-10) could be summarized in a few sentences (no Figs). Only show the right-hand-sides of Figs 11-12, could even be combined in one Fig. Evaporation (Fig. 14) is the end result of many different processes in the coupled atmosphere-ocean system: not clear what we learn here. Section 6: it is distracting to discuss a feedback on the AMOC collapse here (why one only and not others?) – should go out.

In addition to the changes described above, we have also reduced the number of figures, as suggested by the reviewer. Figure 8 has been integrated in figure 2, and figures 12 and 14 have been combined, dropping the results of LGMb alone. We have also removed the discussion about the feedback of the hydrological change on the AMOC in the last section. This will be dealt with in a separate manuscript.

However, we have chosen to keep the description of the differences between LGMa and b at a detailed level (previously in section 4.1, now in section 3) because we believe such changes have not been described very often and show one reason for which climate changes related to

AMOC variations are not linear compared to these variations. In our opinion, the fact that we can obtain non uniform temperatures responses over the North Atlantic and Nordic Seas is important for paleo-records interpretation, which otherwise would a priori assume a homogeneous response, linear w.r.t to the forcing (in this case, a change in AMOC). This idea is now stated in our conclusion.

2) An evaluation of the simulated large-scale patterns of response against available paleodata, which are already discussed in the introduction, is warranted in the conclusion section. Do the present results support the hypothesis that AMOC variations are the underlying cause of the millennial events seen in the data?

We have modified the presentation of our experiments to express this fact that AMOC changes are indeed a hypothesis to explain global climatic features at the millennial time-scales during the last glacial. We then have introduced a short comparison to available paleo-data and we discuss the relevance of our experiments in the last section.

3) The authors motivate their present work partly from the lack of similar model experiments with a glacial background state. This is a good point. However, they do not discuss to what extent the present results differ from earlier results with a modern/preindustrial background state (i.e. should we really do these experiments against a glacial state)? If the response is similar for glacial and modern states, that would be an interesting conclusion too.

This is actually the main focus of a companion paper (Swingedouw et al, 2009) which is accepted for publication in Journal of Climate and is now cited in many places in our manuscript. We have also added a sentence to point out that the sensitivity of this model to fresh water fluxes for present day boundary conditions in within the range of model results given in Stouffer et al (2006).

It should be possible to evaluate this, based on the published literature. There are some references missing with respect to pulse experiments conducted with a glacial background state (Bitz et al., 2007; Weber and Drijfhout, 2007; Hu et al., 2008).

We have added these references in our introduction to show that AMOC recovery depends on the background state, but mentioning that they were not specifically comparing the climate response to AMOC changes for glacial and present boundary conditions.

Smaller points

1) Introduction: at many points it is stated that AMOC changes CAUSE climatic changes (stadials and interstadials) around the Atlantic and elsewhere. This is stated too strongly and I would avoid such (cause and effect) terminology. For example, section 1.1 would more appropriately be titled ‘paleorecords of millennial-scale changes in climate’, as this is what we see in the data. We do not know a-priori that this reflects the climatic sensitivity to the AMOC state. Rather, this is a hypothesis to be tested with the modelling experiments (see also main point 2 above).

We have modified the introduction in several places (and in particular the title of section 1.1) so that it does not suggest from the start that glacial variability is only due to AMOC changes. We have added the citation of the recent review of Clement and Peterson, 2008, to give alternative proposed mechanisms for glacial variability and expressed more clearly the goal

of our study: to analyse surface climate differences related to AMOC changes, to evaluate whether this can explain some features of the paleo-records and if so, analyse the mechanisms for the simulated teleconnections between the North Atlantic and climate changes at other locations on the Earth.

2) Section 2: the three different experiments are not very well defined. Please be more precise.

At the request of all reviewers, we have largely rewritten the description of the simulations. In particular, we have added details on the starting point of each simulation and on the closure of the freshwater budget through the ice sheet snow mass balance parametrisation. The description of the experiments is now hopefully clearer.

References

Bitz, C.M., J.C.H. Chiang, W. Cheng and J.J. Barsugli, 2007. Rates of thermohaline recovery from freshwater pulses in modern, Last Glacial Maximum, and greenhouse warming climates, Geophys. Res. Lett., 34, L07708, doi:10.1029/2006GL029237.
Hu, A., B. L. Otto-Bliesner, G. A. Meehl, W. Han, C. Morrill, E. Brady, B. P. Briegleb, 2008: Response of thermohaline circulation to freshwater forcing under present day and LGM conditions. J. Climate, 21, 2239-2258.
Weber, S.L., and S.S. Drijfhout, 2007. Stability of the Atlantic Meridional Overturning Circulation in the Last Glacial Maximum climate, Geophys. Res. Letters, 34, L22706, doi:10.1029/2007GL031437.

These have been added in the manuscript, thank you.