Climatic impacts of fresh water hosing under Last Glacial Maximum conditions: a multi-model study

Response to Anonymous Referee #2

The comments from the reviewer are repeated in black and our responses are given in blue/italic.

General Comments

The paper reviews the response to various amounts of hosing (amplitude, duration) during LGM conditions in a "ensemble of opportunity", that is, a multi-model ensemble that was not devised for model-intercomparison, but still allows to compare model results.
The set-up is promising enough. The paper somewhat falls short of expectations, in being almost merely descriptive, giving a catalog of responses, but hardly addressing the. physics that might cause different response to the hosing. I will give a few examples/ suggestions where the paper could gain body, but realize that following all suggestions is probably too much asked for. I urge the authors to follow at least some of these, going a bit more into depth while revising this paper.
In addition I remark that I have read the comments of reviewer 1. I agree with almost every point made there and will not repeat the same points.

We agree that this work is mostly descriptive. We see it as a first step before further analyses. Each section could be the starting point for more detailed analyses on the mechanisms explaining the climate changes in each model and model-model differences. In this manuscript, our goal was to document the surface climate responses in glacial fresh water hosing experiments. Determining why the AMOC responses were so different from one model to another was not our main objective. Indeed, although we agree that this is a very interesting topic, we think that it would deserve a truly coordinated experiment (with hosing applied at same location with the same amount, as was done in e.g. Stouffer et al, 2006). This is one reason why we did not attempt to develop the analysis on the AMOC response (points 1 and 2 below). The second reason is that we really wanted to focus on the climate response, as this is the one for which we have most information from palaeodata.

Specific comments

My first and main comment addresses the wide range of response to hosing, indicating large differences in the sensitivity of the models. There is much more that can be said here. I'll suggest two different analyses.

Yes, it is true that we could develop more on this topic, but we did not wish to put a strong focus on it in this paper because the experiments are not coordinated and are therefore difficult to compare and because we wanted to focus on the climate response.

1. The authors seem to have missed the paper: Weber, S.L. and S.S. Drijfhout, Stability of the Atlantic meridional Overturning Circulation in the Last Glacial maximum climate, Geophys. Res. Lett., 2007, 34, doi:10.1029/2007GL031437. This paper shows that the response to hosing crucially depends on M_ov, or F_ov, depending which school you adhere. This quantity is Stommel's advective salt feedback and essentially determines the response of the AMOC on hosing. Recent experiments with HadCM3

clearly illustrate this, and also recent analyses form CMIP3/5 ensembles indicates that differences in the response of the AMOC to changes in the hydrological cycle might be explained by different M_ov in the models. It would be good if the authors tried to analyse this indicator from the model output.

Following this comment and some comments from reviewer 1, we have largely modified the introduction to explain the different rationales for running fresh water hosing experiments (i.e., in brief, characterizing the stability of the AMOC vs studying the climate response to a more or less realistic fresh water discharge for comparison to data). However, in the current version of the revised manuscript, we have not introduced the M_{ov}/F_{ov} diagnostics of the AMOC stability because, as explained above, we did not wish to put a strong focus on this topic. This diagnostic was not saved for many of the experiments so we would have had to resort to a subset of them, which is not fully satisfactory for a comparison work.

2. The AMOC scales with the meridional pressure gradient in the Atlantic. If the AMOC gets weaker, this should be reflected by a decrease in the pressure and density gradient. Part of this decrease is forced by the hosing, making the density smaller in the "Ruddyman belt". Part of this forcing is counteracted or amplified by advective feedbacks. Also the density in the South may be affected by advective feedbacks. This feedback analysis is nicely explained in a paper of Swingedouw et al., co-author of the present paper, and working in the same institute of the first author. So, it wouldn't be too difficult to apply this method, if the first author has the ocean data from all models at his disposal.

Very few ocean data were available and the methodology from Swingedouw et al. (2007) was really demanding in terms of data needed, since it consists in computing the density budget averaged over depth, thus requiring large amount of 3D ocean data. Nevertheless, we have tried to have a first look at the changes in density for the few models for which we had temperature and salinity data for the control and hosing experiments (averaged over the same time period as for the rest of the study). We have computed density changes in North Atlantic and South Atlantic boxes. We have tested different boxes and found that, generally speaking, among the few simulations used (5 out of 11), the changes in AMOC were not really linear with density changes. In Fig. 3 below, we show the best results we obtained for a North Atlantic box defined between 20°N to 60°N and a South Atlantic box between 60°S and 20°S. The AMOC changes are not scaling well with density differences between north and south boxes and not very well with those of the North Atlantic box (although a little bit better). We believe that this first result prevents to expand the analysis since each model seems to scale differently with density changes. Indeed when looking at stratification changes (Fig. 4 below), we notice very different responses depending on the model, with notably very different behaviours for the COSMOS models (which indeed show weak density changes while their AMOC weakening were very strong). These differences could be related to a transient effect. We conclude from these two figures that understanding the oceanic adjustment to freshwater hosing in these different simulations is certainly very interesting but deserve a dedicated study to go sufficiently in depth. Moreover, as stated before, the focus from the present study was mainly on the climatic response.

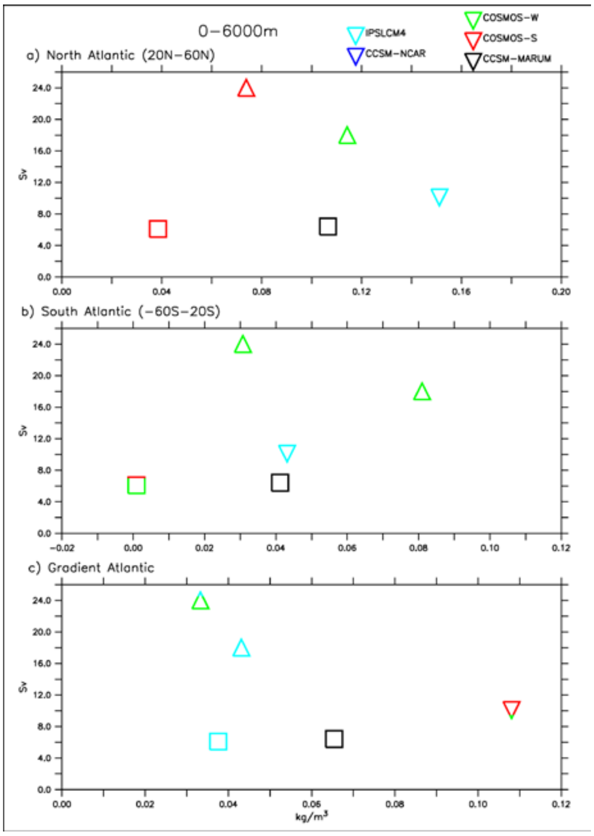


Figure 3: Decrease in density vs decrease in AMOC (all counted as positive). The density has been average over the whole depth of the ocean for a) North Atlantic (20°N-60°N), b) South Atlantic (20°-60°S) and c) the differences North Atlantic minus South Atlantic boxes. Only 5 simulations out of 11 were available.

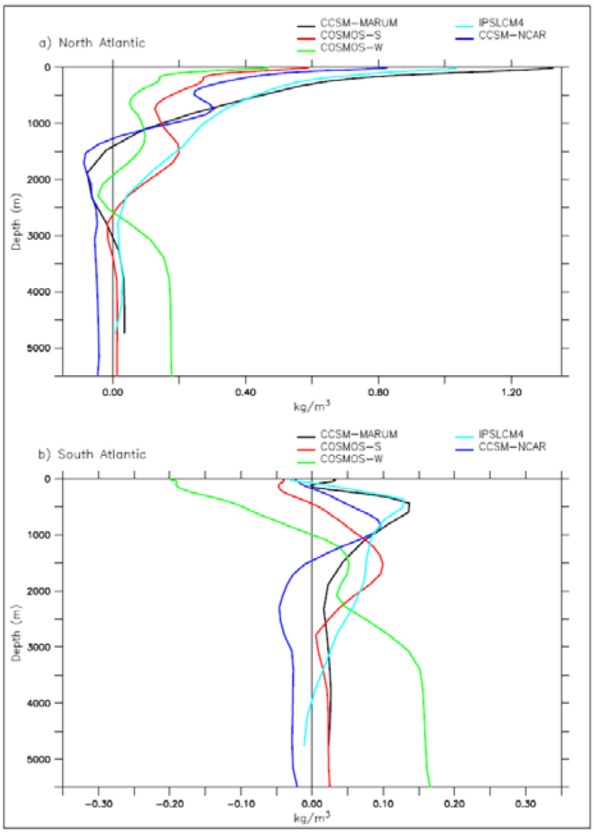


Figure 4: Changes in density stratification control minus hosing experiments for a) the North Atlantic and b) the South Atlantic as defined in Fig. 3

3. The WES feedback. First, I do not understand why the WES feedback is mentioned in response 1 and not also in response 2, page 3837.
This is right, the WES would work for both types of responses. We have modified the text accordingly.

On page 3842 the authors describe the different propagation of the cooling signal along the Atlantic subtropical gyre. This points to models having different WES-feedbacks. Isn't this a point where the authors could say and analyse a bit more, in terms of why the WES feedback operates more strongly in 1 model than in another?
Yes, Figures 2 and 7 point to the fact that there is no correlation between the mid-latitude North Atlantic cooling and the northern tropical Atlantic one. This could indeed be due to different strengths of WES feedbacks in the different models, or that other processes come into play and that the balance between these processes are not the same in the various models. Tropical Atlantic → North Atlantic oceanic connections have also been shown, e.g. by Mignot and Frankignoul (2010). Unfortunately, we do not have enough data to analyse this topic further. However, we have added a few word in section 5.2 (in which Fig. 7 is discussed) to point to potential reasons for inter-model differences in the tropical response to hosing. We have also added the reference to the work cited above in the main text.

4. What is the best scalar for the temperature response? Also Rev. 1 discusses this point, but I would like to go a bit further. the largest temperature signal occurs in the North Atlantic. The main driver for temperature changes there is the decrease in heat transport convergence, due to a decreased AMOC. This implies that to understand the temperature response there, the better index for the AMOC is the strength at 30-40N instead of 30S. An even better scalar might be the northward ocean heat transport at these latitudes. Also in Figs 6 and 7 I would use the heat transport convergence in the selected boxes as a scalar to interprete the temperature changes. Linking the responses to both heat transport and AMOC changes allows for a more physical interpretation of what's going on.
Our initial idea was indeed to work on the heat transport/temperature changes relationship but some models did not save this transport. This is now explained in the text (Section 5.1). We hope that in the future the heat transport by the ocean and the atmosphere will become available for more experiments but for the time being we cannot address this very interesting analysis, unfortunately. By the way, there was a mistake in the AMOC definition in the original manuscript: all numbers for the AMOC are for the maximum in the stream function in the northern hemisphere under 500m depth.

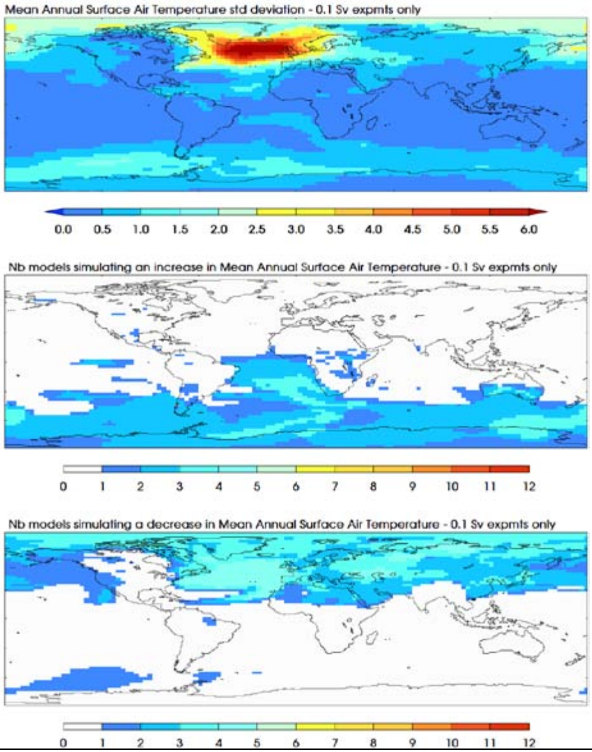
5. Minor point. Also, if the temperature change s dominated by changes in convergence/ divergence of heat transport, it is not obvious to expect a bipolar seesaw signal without much zonal detail. I would not expect SH-warming where the heat transport associated with the "global Conveyor Belt" was not divergent before the hosing was applied.

Yes, again, we regret to miss this variable for some of the models.

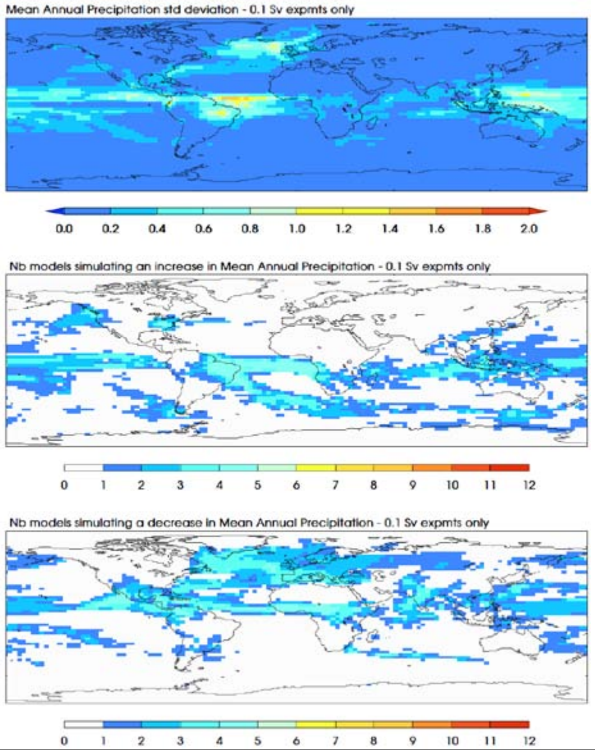
6. Minor point. I accept that your ensemble of opportunity puts is not ideal and that you cannot always make a clean comparison between the various experiments. But

calculating an ensemble-mean standard deviation from model exps that used different amplitudes of the hosing is stretching things a bit too far. I suggest to redraw Figs. 3a and 5a only for the 7 runs that featured 0.1 Sv hosing.

There are only 5 models with 0.1 Sv hosing. There was a mistake on Fig. 1 where the COSMOS runs are plotted with a 0.1 Sv hosing, while they are correctly described in Table 2 with a 0.2 Sv hosing. Fig. 1 has been corrected, the conclusions from it are unchanged. We think that 5 models are a little too few to compute a standard deviation but have gone ahead with redrawing Figs 3 and 5 with this subset of experiments. They are shown below and are not significantly different from Figs 3 and 5. So we prefer to show the full range of model results, but could add these panels to Figs 3 and 5 if needed.



Same as Fig 3 but for the 0.1 Sv hosing experiments only



Same as Fig 5 but for the 0.1 Sv hosing experiments only

7. Minor point. You might also want to remark that different signals, as discussed on page 3844, are likely related to the difference forcing applied in part of the model ensemble.
This is precisely what is difficult to do because of the different sensitivities of the models... This difficulty is highlighted by Figure 6, discussed in section 5.1. We have therefore added a sentence in the last paragraph of section 4.1 (on which this comment applies) to point to this difficulty and refer the reader to section 5.1.

8. Minor point. With the precipitation response being so diffuse outside the Tropical Atlantic, I suggest to shorten this section considerably.
We assume that this comment is about section 5.3 (African and Indian monsoons). But we do not really understand this comment as this section is only two paragraphs long.