Clim. Past Discuss., 8, C3670–C3682, 2013
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Discussions

Interactive comment on "Variations of oceanic oxygen isotopes at the present day and the LGM: equilibrium simulations with an oceanic general circulation model" *by* X. Xu et al.

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Received and published: 29 April 2013

We thank D.M. Roche for his careful review and comments. They are very helpful in improving our paper. In the following, we provide point-by-point responses to his comments.

Major comments 1. Description and analysis of the simulation. In this part, the referee asked for: 1) Improving the explanation of the model setup. 2) Including a brief comparison between our LGM simulation and the COSMOS LGM result focusing on obtained freshwater fluxes obtained as well as the differences in surface condition and deep ocean conditions. 3) Providing a comprehensive discussion of the dynamic changes of

LGM ocean in comparison to the present-day (e.g. LGM AMOC).

1) To ensure maximum consistency, the climatological and the isotopic boundary conditions for the PD and LGM isotope enhanced oceanic simulations are derived from the atmospheric general circulation model ECHAM5-wiso (Werner et al., 2011) under the present day and the Last Glacial Maximum conditions. The boundary conditions prescribed in the in the ECHAM5-wiso PD simulation used AMIP-conform (Gates et al, 1999) present-day conditions, including monthly climatological sea surface temperatures and sea ice cover of the period 1979-1999. For LGM, the SST and sea ice conditions were calculated from the PD and the LGM simulations by climate model COSMOS under present and glacial conditions (Zhang et al., 2012). We obtained the anomaly between the control run and LGMW (Zhang et al., 2012), and added it on the AMIP-conform conditions to form the LGM boundary condition for the ECHAM5-wiso LGM simulation. We have improved the first paragraph in sub-section 2.3 of the manuscript to clarify how we the atmospheric forcing for the LGM simulation. 2) In oceanography, the use of stand alone models is a well-known problem: once you prescribe an upper boundary this implies an atmospheric model (e.g., Nakamura et al., 1994; Lohmann et al., 1996). The use of a freshwater boundary condition for salinity shows undesired effects and instabilities (e.g. Bryan, 1986). The use of restoring salinity avoids such effects and was therefore used in several paleoceanographic studies (e.g. Paul et al.). We are aware that the implementation of the restoring in sea surface salinity (obtained from the COSMOS LGM results) imparts an implicit freshwater flux to the surface. We argue that this is not the optimal solution, but we can not see an alternative for the ocean only setup. Because the surface salinity is not completely free to develop, we did not include any analysis of the oxygen-18-salinity relationship in this paper. 3) Our MPI-OM LGM simulation does not show substantial changes as compared to the COSMOS LGM results. A brief comparison between our results and the COSMOS ocean state has been added in the first paragraph of the Discussion section. In our simulation, the NADW shoals to about 2500 meters as Glacial North Atlantic Intermediate Water (GNAIW) due to the enhanced northward invasion of AABW, and the

strength of AMOC under LGM condition is only around 1Sv weaker than present day, which suggest an active circulation for deep water masses in the Atlantic. The model results are consistent with the estimation of glacial water mass configuration reconstructed from nutrient and radiocarbon tracers (Keigwin, 2004; Curry and Oppo, 2005; Marchitto and Broecker, 2006; Hesse et al., 2011) as well as the 231Pa/230Th ratios observed in deep ocean sediments deposited during the LGM (Yu et al., 1996, Marchal et al., 2000, McManus et al., 2004). As already stated by the reviewers, there is presently no consensus view on the LGM ocean circulation based on reconstructions, however a robust AMOC scenario constrained by observations suggests a shoaled NADW, but no sluggish circulation in the Atlantic (Lynch-Stieglitz et al., 2007). Our model results in general agree with this AMOC scenario, therefore we assume that the simulated isotope distribution also represents a reasonable glacial state. In the revised manuscript version, we rearranged the Results and Discussion part. The variations in the oceanic isotope distribution due to the changes in isotopic fluxes and ocean circulation are presented in sub-section 3.3 (Sensitivity experiment) and discussed in the last part of the Discussion. In general, the effects of isotopic fluxes and ocean circulation are small as compared with ice-sheet impact. But for the surface water at north of 40°N and the intermediate water in the northern North Pacific, the changes of circulation and topography also play important role in the isotope variations. More details are included in the 3.3 and the last two paragraphs in the discussion section.

2. d18Oc database. The referee asked for more clear and specifiable description in reconstructed LGM d18Oc database used in the model-data comparison.

We have revised the d18Oc database for the LGM. The new version of the database consists of the average depth (18-21ky, or single value depending on the resolution of sediment core) of Pangaea data and the data read from past publications. Descriptions are included in the second paragraph of 2.4. The details of the LGM data base (core locations, average depth/years, values and references) are listed in the Table S1-Table S4 in the supplement.

3. ‘Since the manuscript have been heavily changed between the initial submission and the first online author comment, the text should reflect that change. This is not the case in several places, in particular pages 4897, 4902..’

In the revised version, we modified the structure in the Results part. Sub-section 3.1 (Comparison of simulated LGM and PD oceans) presents and compares the sea surface temperature, sea ice cover, and the AMOC of the LGM and PD simulations. Distributions of d18Ow and d18Oc at PD and LGM, as well as the model-data comparison are given in sub-section 3.2 (Variations of d18Ow and d18Oc at PD and LGM). In the last sub-section 3.3 (Sensitivity experiment) we compared the ISOPD simulation with LGM and PD results to explain the isotope variations due to the change of surface fluxes and ocean circulation. In addition, we also refined the used LGM d18Oc database. The number of used d18Oc data points is reduced, especially for the warm species. However, this refinement does not lead to substantial changes of the data-model comparison results.

Other comments: 1. ‘p. 4888, line 2-3 "are implemented as passive tracers in terms of mass in MPIOM-wiso". How do you ensure conservation in the model? Does MPIOM ensure conservation of water mass as well as volume with variable layer thick-ness? Even in free surface models, the concentration is conserved, but rarely the mass.’

MPIOM is a primitive equation model (C-Grid, z-coordinates, free surface) with the hydrostatic and Boussinesq assumptions made (Marsland et al., 2003), which ensure conservation of volume. In our isotope module, we initiate the seawater isotope composition as 0‰ (H216O: 1000Kg/m3, H218O: 2.0052Kg/ m3) and 1‰ (H216O: 1000Kg/m3, H218O: 2.0072052Kg/ m3) in the whole ocean, which are implemented as passive tracer in term of concentration.

2. ‘p. 4889, line 11-12 "have been run for 3000 yr into a quasi-steady state.". Please indicate the drift in the deep north Pacific for example, in per mil per century so that the reader can appreciate the steady state. To ensure full steady state (which have no

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reason to be more representative of the LGM) ones classically needs 5 to 6 millenia.'

In our experiment, the ocean reached a quasi-steady state after 3000 yr under the prescribed boundary conditions. The drift of potential temperature in the last 1000 yr in the deep Pacific is around 0.003°C/century. This information is now added in the last paragraph of the chapter 2.2 (Experimental setup).

3. 'p. 4891 and figure 1: the sea-ice concentration given is 50%. This choice is odd. The classical sea-ice concentration that mark the sea-ice edge and favourably compares to data is 15%.'

The sea-ice concentration depicted in Figure 1b is changed to 15% to mark the annual mean sea-ice edge in the revised paper.

4. 'p. 4892 and figure 3: please shift the PD value by 1 per mil so that the reader can easily follow your description.'

A new line has been added to represent a shifted 1 per mil LGM value (LGM-1) in the Figure 3.

5. 'p. 4895, lines 3-23: in your discussion the waters are depleted everywhere albeit in the surface ocean. "Only the subsurface waters at tropical and subtropical regions are slightly enriched (+0.1 per mil)." How come? Since the total water isotopes mass is conserved, the volume of waters where the content is increase and decrease should be even (after correction of the glacial 1 per mil). Are the waters in the Indian Ocean (not shown) all positive? How is the re-distribution promoted in details?'

In the previous manuscript version we took the average oxygen isotope values between 28W and 32W to represent the characters of the Atlantic section, and the average between 178W and 2E to represent the features of the Pacific section. In the revised manuscript version, we average the sea water oxygen isotope compositions over the whole basins. The new results are presented in the Figure 12. In general, excluding the ice-sheet impact, the LGM Atlantic has enriched intermediate water and depleted deep water. The Pacific shows the different conditions, where the oxygen-18 values are lower at upper 1000-1500 meters and higher below.

6. ‘Figures 5, 7 and 9 the colorscales are not adequate. All the discussion in the manuscript concentrate on the two-three colors at the center of the colorscale. Please use a non-linear colorscale to highlight the interesting aspects you are discussing. Same applies to figure 13.’

In accordance with the text change of the Results chapter, the original Figures 5, 7 and 9 are now presented as Figure 11 and 12 in the revised manuscript version. We have not changed the color scales in these two figures as the full spectrum of colors is used in the plots. Figure 11 (old Fig.5) does have a non-linear color scale. The Figure 13 is now Figure 9 in the revised manuscript version, and the color scales has changed to highlight the interesting aspects in our discussion.

7. ‘p. 4899, line 14-15: "LeGrande and Schmidt, 2006" do not provide proxy reconstructions.’

Corrected accordingly

8. ‘p. 4899, line 17-18: "The decrease in d18Ow is possibly due to less evaporation during the LGM". You are using a ocean only GCM with fixed boundary fluxes: you can check that.’

According to the boundary fluxes, there is less evaporation during LGM (∼0.5-1mm/day) at most regions. And the description has been revised accordingly.

9. ‘p. 4899, line 21-23: "During the LGM, the closed Canadian Arctic Archipelago prevents the depleted Arctic water from entering Baffin Bay, which induces a further enrichment of Baffin Bay and Labrador Sea water masses.". I do not agree with that explanation. If you compare figure 4 panels a and c, there is a clear advection of high d18Osw in that area from the Atlantic. Please discuss the changes in the surface currents and why the input of very depleted routing water in the Labrador Sea from the

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neighbouring Laurentide ice-sheet do not act as a counter factor.'

As we can see from the LGM-ISOPD and LGM-PD anomalies in Figure 11 (revised version), the change of the surface fluxes is the main factor for the isotope enrichment in the Baffin Bay and the Labrador Sea during LGM as compared with the PD results. This indicates there are less depleted fluxes into these areas during LGM. The anomaly between ISOPD and PD shows that the glacial change of topography induces depleted route water influxes at the western Baffin Bay and Labrador Sea. The extended sub-polar gyre and weak northward transport through North Atlantic Drift enable the advection of the enriched water into the Labrador Sea. In addition, the closed Canadian Arctic Archipelago prevents the depleted Arctic water from entering Baffin Bay, which induces an enriched northern Baffin Bay. When we combine the fluxes, circulation and topography effects together, we find that the depletion effect by glacial route water is (over)compensated by the enrichment due to the less depleted influxes. As a consequence, the Baffin Bay and the Labrador Sea are enriched during LGM as compared to PD.

10. 'p.4900, line 13-14: "No direct measurements of the LGM sea surface waters' isotopic composition exist, which makes it difficult to validate the related model results." That is true but Jess Adkins provided some pore waters measurments for deeper waters. Please include thoses in your discussion. Cited ref: ADKINS, J., MCINTYRE, K. et SHRAG, D. (2002). The Salinity, Temperature, and d18O of the Glacial Deep Ocean. Science, vol. 298:pp.1769–1773.'

We have included these pore water measurements and the relevant reference in the revised version of our manuscript.

11. 'p.4901, line 14-16: "The other way to look at this point is that either the prescribed global mean ice sheet effect in this region is underestimated, ...". What do you mean? A prescribed global change cannot be locally underestimated if it is applied globally! Please rephrase.'

We agree with the reviewer and revised the text, accordingly.

12. ‘p. 4901, line 26: "This assumption, which excludes any temporal storage of glacial precipitation on the ice sheets, may introduce unrealistic river discharge into the polar seas, leading to highly depleted waters in this region.". I do not agree with this argument. The LGM is the period when the ice-sheet stabilised. Thus, the water budget is in reality similar to yours. Even more so, since the European ice-sheets are already shrinking around the LGM, so the input of freshwater with very negative isotopic content should be important in the Artic.’

In our experiment, the continental discharge was calculated from the net precipitation occurring over land. Based on a general mass balance assumption, all precipitation over the ice-sheets is considered as immediate freshwater input due to the ice-sheet melting. This simplification ignores the complexity of ice-sheet dynamics; e.g., the ice of the melting zone of an ice-sheet may have a different isotopic composition that the ice within the accumulation zone. There may also another reason. The N. Pachyderma is dwelling specie, and it may migrate to deeper layers during glacial time. In our LGM simulation, the seawater below 150m is not strongly depleted as seen at surface. Therefore they may didn’t see the strong depletion in the surface water and maintained relatively enriched shells. So we would like to leave the explanation open in the discussion part.

13. ‘p. 4902, line 23-25: "differences as compared with the observations point to around 3C cooling of the SST, which is comparable to the estimation by combining different proxies". This is true only if your surface d18Osw is perfect. Since the temperature effect is dominant, this is not very problematic but should be mentionned. Please rephrase to take all uncertainties into account.’

Revised accordingly

14. ‘p. 4903, line 1-3: "Additionally, the closed water mass balance assumption in runoff calculation will obtain impractical river discharge into the polar seas, and sim-

ulate too depleted d18Oc values at these areas.". See my previous comment on the topic.'

Please see our answer to comment 12.

15. 'Figure 12 (figure 2 of comment): please explain in details what is going on with Pachyderma.'

There are extremely high values simulated with N.pachyderma. These high values are mainly located in the Eastern Nordic Sea. In that region we simulated strong cooling, the SST is much lower when compared with the reconstructions. This induces extremely enriched N.pachyderma in our simulation, since it is calculated by the empirical-temperature equation. The explanation is now included in the Discussion part.

Please also note the supplement to this comment:
http://www.clim-past-discuss.net/8/C3670/2013/cpd-8-C3670-2013-supplement.pdf

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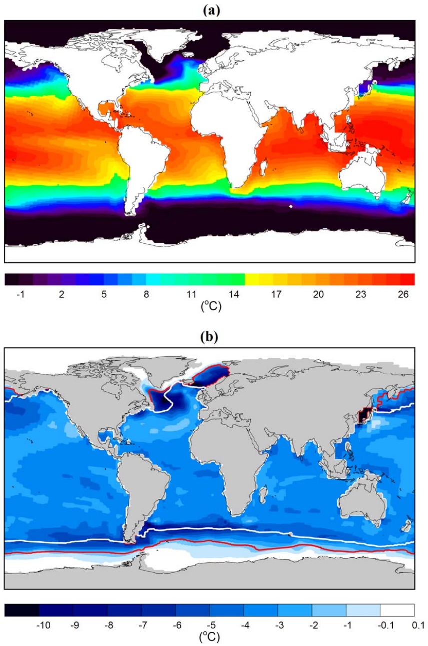

Figure 1 (a) Modelled annual mean sea surface temperature (°C) distribution at the LGM. (b) SST anomaly between LGM and PD simulations. Red line: 15% sea ice cover at PD; white line: 15% sea ice cover at LGM.

Fig. 1.

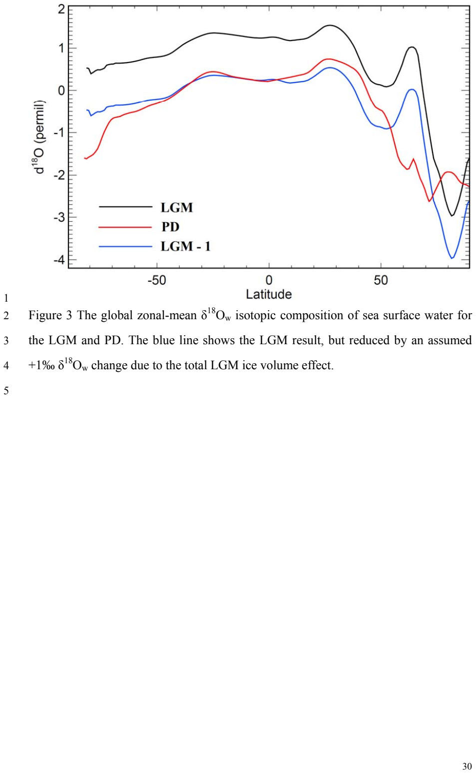

Figure 3 The global zonal-mean $\delta^{18}O_w$ isotopic composition of sea surface water for the LGM and PD. The blue line shows the LGM result, but reduced by an assumed +1‰ $\delta^{18}O_w$ change due to the total LGM ice volume effect.

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Fig. 2.

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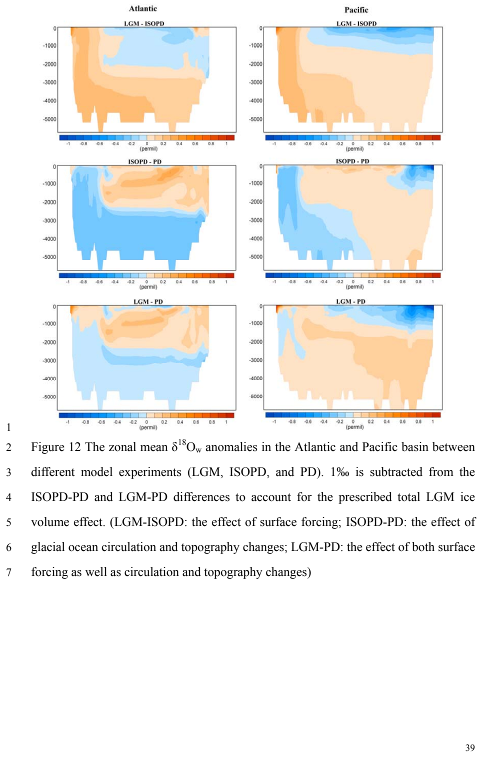

Figure 12 The zonal mean $\delta^{18}O_w$ anomalies in the Atlantic and Pacific basin between different model experiments (LGM, ISOPD, and PD). 1‰ is subtracted from the ISOPD-PD and LGM-PD differences to account for the prescribed total LGM ice volume effect. (LGM-ISOPD: the effect of surface forcing; ISOPD-PD: the effect of glacial ocean circulation and topography changes; LGM-PD: the effect of both surface forcing as well as circulation and topography changes)

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Fig. 3.

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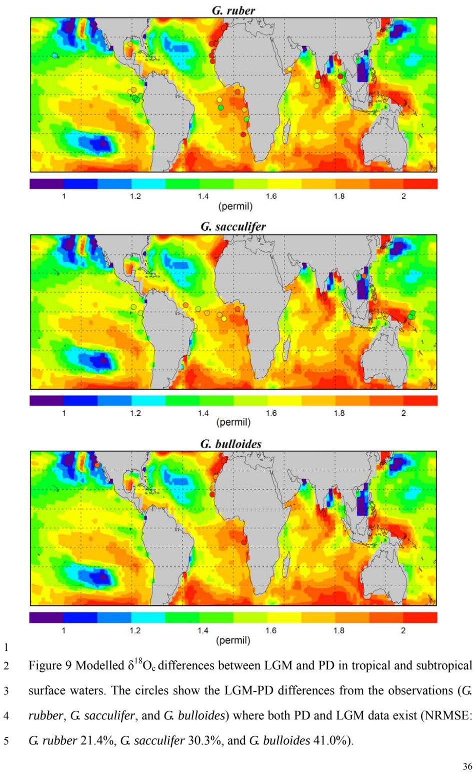

Figure 9 Modelled $\delta^{18}O_c$ differences between LGM and PD in tropical and subtropical surface waters. The circles show the LGM-PD differences from the observations (*G. rubber*, *G. sacculifer*, and *G. bulloides*) where both PD and LGM data exist (NRMSE: *G. rubber* 21.4%, *G. sacculifer* 30.3%, and *G. bulloides* 41.0%).

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Fig. 4.