Response to Referee #1

We thank the reviewer for the helpful and detailed comments that allow an improvement of the manuscript. Here we provide a point by point response to all questions. The corresponding technical comments will be also included in the revised manuscript.

Response to the general questions:

1) First, could the dependence of equilibrium ocean state on initial ocean state in the glacial simulations be simply due to the fact that the ocean has not reached equilibrium with the imposed boundary conditions in these simulations? …

According to Referee 1's approach, equilibrium time scale of a model is about 3 century if k is equal to 0.0001 m^2/s. In our ocean model, k is set to a background value of 10^{-5} m^2/s that can introduce a longer equilibrium time. In an equilibrated ocean system, bottom water mass should be renewed by the upper-layer water mass by ocean circulation (e.g. lower cell of Atlantic meridional overturning circulation, AMOC). Thus, calculating the equilibrium time scale according to the concept about replacement of bottom water mass by ocean circulation can further improve our understanding on modeling the ocean system. In equation (1), T is the renewal time scale of bottom water, V is volume of deep water mass in the ocean and ϕ is the maximum of AABW-cell of Atlantic meridional overturning circulation.

$$T=V_{deep}/\phi_{AABW} \qquad (1)$$

Given this estimate, it takes more than 3000 years for the ocean system to get to an equilibrium state in our model, which is much longer than 300 years.

It is noted that the fundamental contrast between the two LGM states is their distinctive vertical stratification associated with AABW formation. Shown in Fig. 1 are the linear trends of sea salinity in the last 200 years along Atlantic basin in LGMW and LGMS. In LGMS, the water mass in the lower layers (> 3000m) and the Atlantic Southern Ocean is in a tendency of salinification while the opposite trend is shown in LGMW. This indicates that both simulations are still unstable with respect to deep ocean circulation. Note also that the trend in LGMS is almost twice larger than in LGMW, suggesting that the LGMW state is relatively stable. It is plausible that two LGM ocean states will potentially merge into an ocean state close to the LGMW if the simulations are integrated long enough.

Accordingly, we extended LGMW and LGMS simulations for another 1000 and 1700 years, respectively. As inferred, only one LGM climate state is achieved by that the evident decline of NADW-cell in LGMS merges with the slight increase of NADW-cell in LGMW in their intermediate level (Fig. 2). The more equilibrated LGMS ocean state, in terms of internal ocean structure, is well stratified and comparable to LGMW (Fig. 3). This implies that the final equilibrium ocean state is independent on different initial ocean states in our climate model and the LGM boundary conditions can generate a stratified ocean after a very long-term integration. In terms of AABW-cell, however, there is no pronounced transient feature in LGMS (Fig. 4), suggesting that the northward-invading AABW from the Southern Ocean in LGMS (Fig. 1) is the cause of descending NADW-cell due to continuous transportation of the dense bottom water mass to the abyssal Atlantic basin. This will gradually increase the vertical stratification in the Atlantic basin, resulting in the evident weakening of NADW-cell after ~ 3200 model year (Fig. 2).

2) Second, … Are non-linear terms ultimately responsible for the two ocean states obtained with identical glacial boundary conditions, as intuition gained from conceptual models would suggest? … Could the two ocean states reported in the present ms. be related to similar physics (associated to density advection) or to physics illuminated in subsequent but still conceptual models of ocean circulation?

We assume that this question presented by the first Reviewer is based on the assumption that the two glacial ocean states are stable and distinctive. As indicated by our long-term integration, this is not the case. Further more, the physics associated with the existence of the two ocean states are not related to the one in conceptual models that are generally linked to the hydrological balance in Atlantic. According to the hosing experiments, no matter how much amount of freshwater perturbations (+0.2 Sv or +1 Sv) imposed to North Atlantic, the transition between the two ocean states cannot be fulfilled, indicating the monostability of the AMOC with respect to hydrological balance.

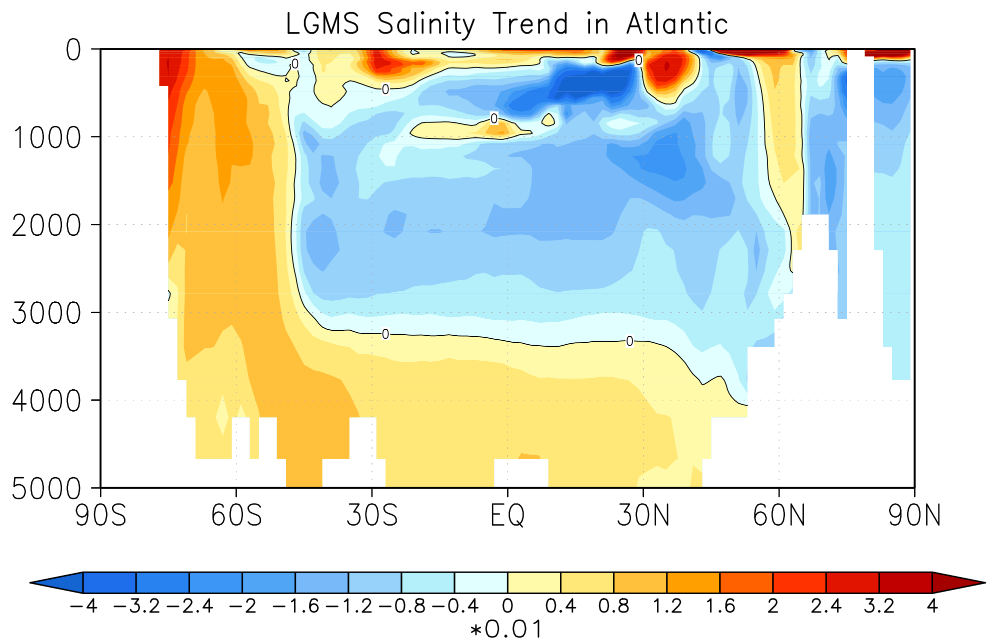
3) Finally, could the authors suggest an explanation for why pre-industrial simulations do not show the same level of dependence upon initial ocean state as that of the glacial simulations (p. 3021)?

To check whether dependence of transient characteristics of deep ocean upon initial ocean states is also present for PI simulation in our climate model, we have performed one additional simulation LGM2PI with prescribing identical boundary conditions as PI control run but initializing from the same glacial ocean as LGMW. The resulting vertical ocean structure after 3000-year model integration is comparable to our PI control run (Fig. 5), implying that the system has only one quasi-equilibrium state and that equilibrium time scale of deep ocean under PI boundary conditions is shorter than under LGM conditions.

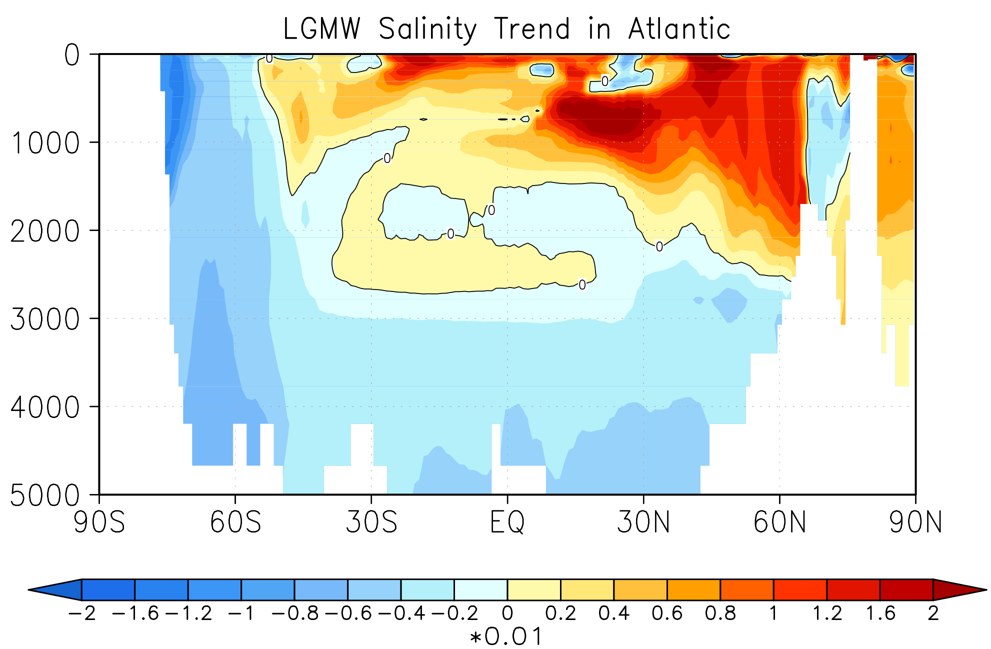
Shown in Fig. 6 are the changes of sea temperature and salinity with time during the spin-up of LGM2PI and LGMS. In the spin-up of the LGM2PI, the upper layers of the ocean are heated up due to the warm boundary conditions (Fig. 6A), reducing AMOC and the NADW formation (Fig 7). In this case the way that the bottom water mass interacts with the surface is mainly through the AABW formation in the Southern Ocean. In our climate model of which processes in ice shelf cavity are unsolved, the major regions of AABW formation in PI are around Antarctic on-shore area where the brine rejection occurs (Fig. 6A, B) due to sea ice formation and export. Given this, the warm upper-layer water mass can be transported to the bottom in the Southern Ocean (Fig. 6A) and destabilizes the ocean stratification. Under LGM boundary conditions, the equatorward-extended permanent sea ice edge will shift the major AABW formation regions to the open ocean (Fig. 6C, D) where the dilution of the brines released by sea ice is more important and the effect of the brine-generated dense water is much more reduced than in on-shore regions (Bouttes et al., 2012). In addition, the cooled upper-layer water mass favors a strengthened AMOC during the spin-up of LGMS (Fig. 7), decelerating the northward extending of glacial AABW. Thus, the asymmetry of the equilibrium time scale of deep ocean water mass between PI and LGM boundary conditions can be attributed to the shift of AABW formation sites and different responses of the AMOC to the boundary conditions during the spin-up.

Reference

Bouttes, N., Paillard, D., Roche, D. M., Waelbroeck, C., Kageyama, M., Lourantou, A., Michel, E., and Bopp, L.: Impact of oceanic processes on the carbon cycle during the last termination, Climate of the Past, 8, 149-170, 10.5194/cp-8-149-2012, 2012.



A



B

Figure 1 Trend diagnosis of sea salinity in Atlantic basin for 2800 to 3000 model years in LGMS (A) and LGMW (B). Noted that scale of color bar in LGMS is twice larger than in LGMW. Units: psu/century.

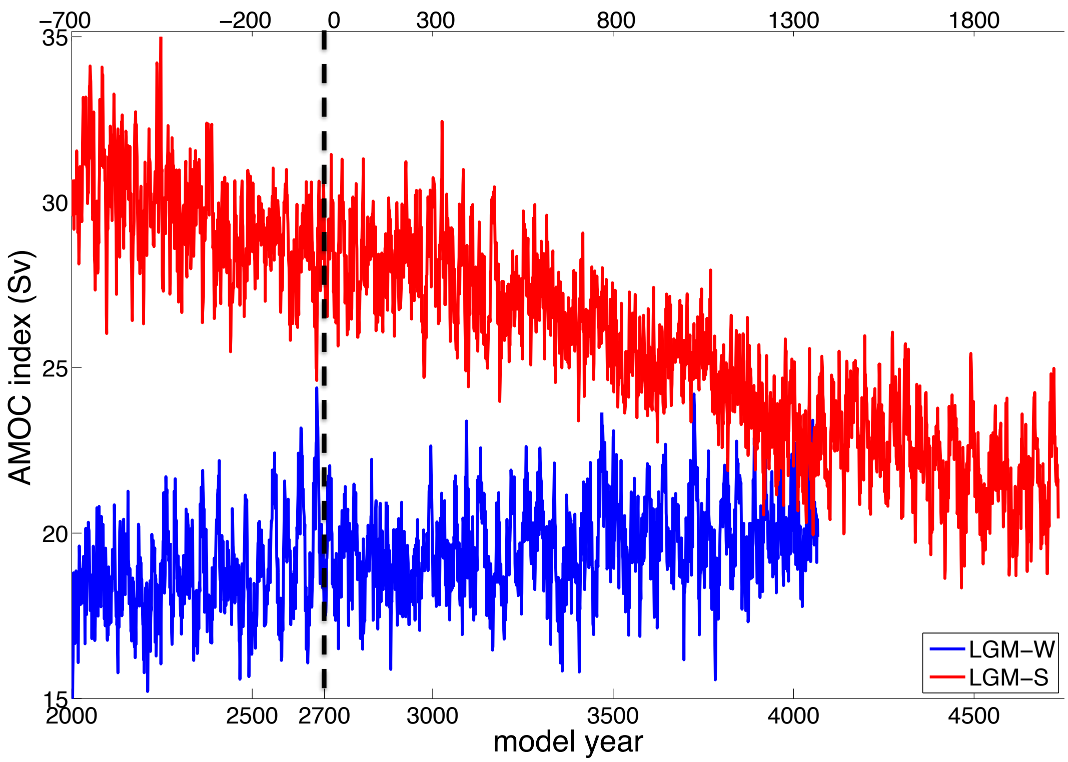


Figure 2 AMOC indices with respect to NADW-cell in the North Atlantic for LGMS (red) and LGMW (blue). Upper X-axis indicates the starting pointing of our hosing experiments while lower one shows the model year. Average between 2900 and 3000 year represents the corresponding quasi-stable climatology in the main text. Units: Sv.

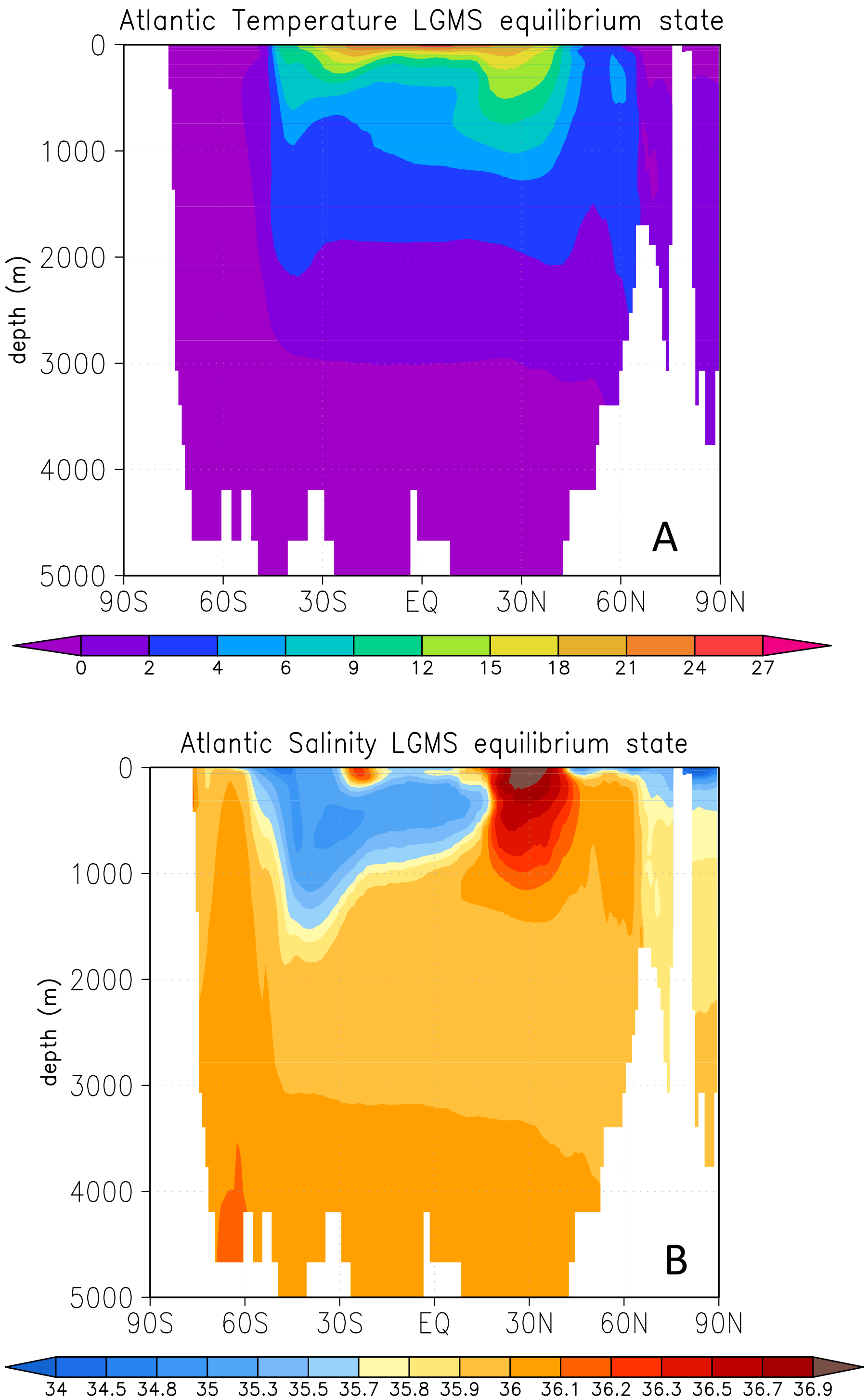


Figure 3 Meridional section of zonal mean temperature (A, units: °C) and salinity (B, units: psu) in equilibrated LGMS state (average of 4600-4700 model year in LGMS).

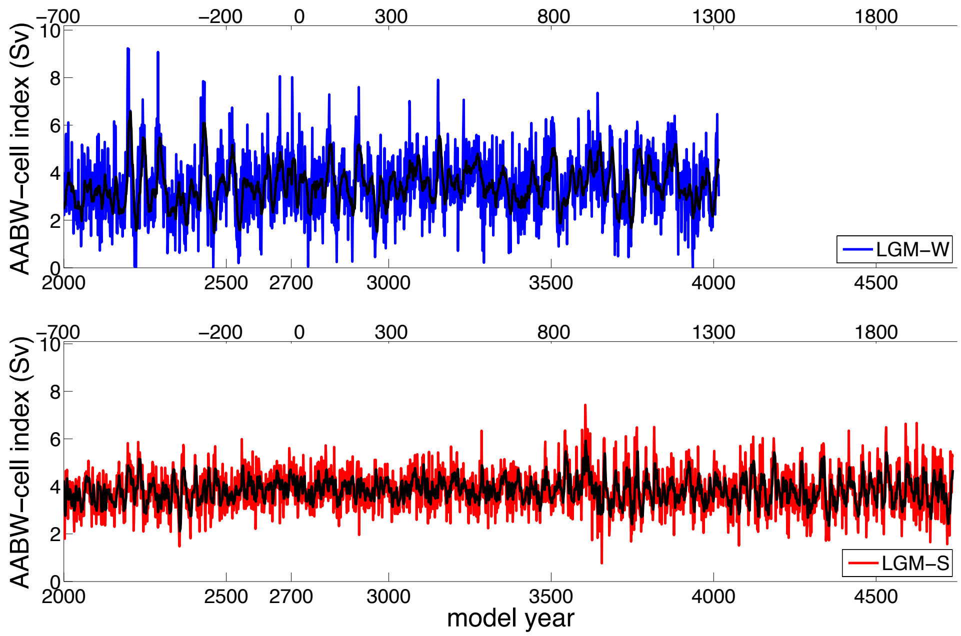


Figure 4 AMOC indices with respect to AABW-cell (defined as the minimum value of stream function below 2500m along 30°S) in the Atlantic basin for LGMW (blue) and LGMS (red). The corresponding black solid lines are the 10-year running mean. The indices are the absolute values.

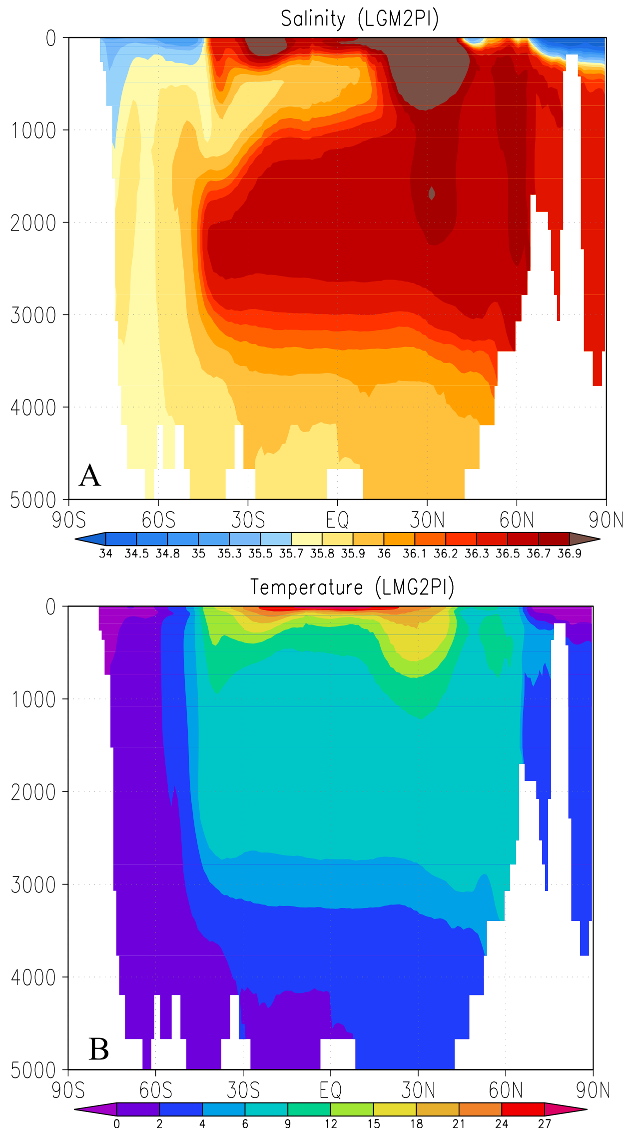
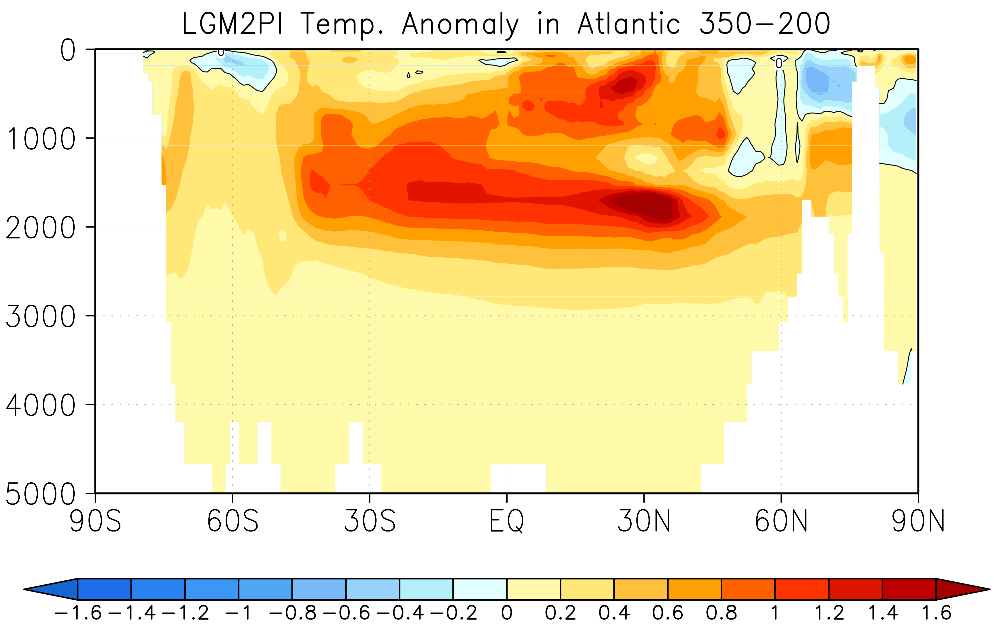
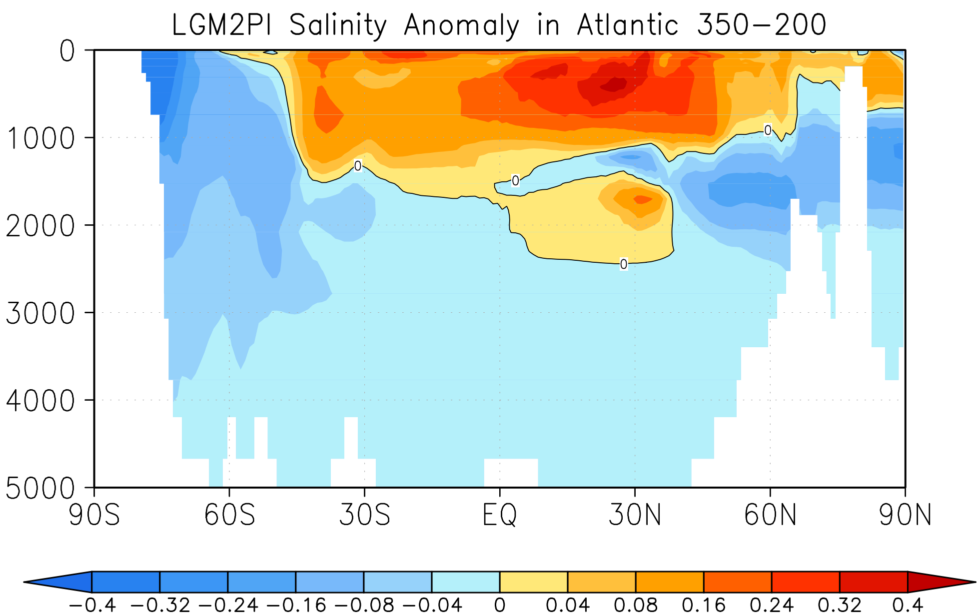


Figure 5 Meridional section of zonal mean temperature (A) and salinity (B) in Atlantic Ocean in LGM2PI. LGM2PI was imposed the same boundary condition as our control run but was initialized from the glacial ocean and was performed for 3000 years. The last 100-year average represents the corresponding climate state in LGM2PI. It is pronounced that the oceanic structure is almost the same as PI, indicating that Pre-industrial simulation is insensitive to the initial ocean condition and emphasizing that initial ocean-dependent feature is unique for LGM simulation.


LGM2PI Temp. Anomaly in Atlantic 350−200
0
1000
2000
3000
4000
5000
90S
60S
30S
EQ
30N
60N
90N
−1.6 −1.4 −1.2 −1 −0.8 −0.6 −0.4 −0.2 0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6

A


LGM2PI Salinity Anomaly in Atlantic 350−200
0
1000
2000
3000
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5000
90S
60S
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EQ
30N
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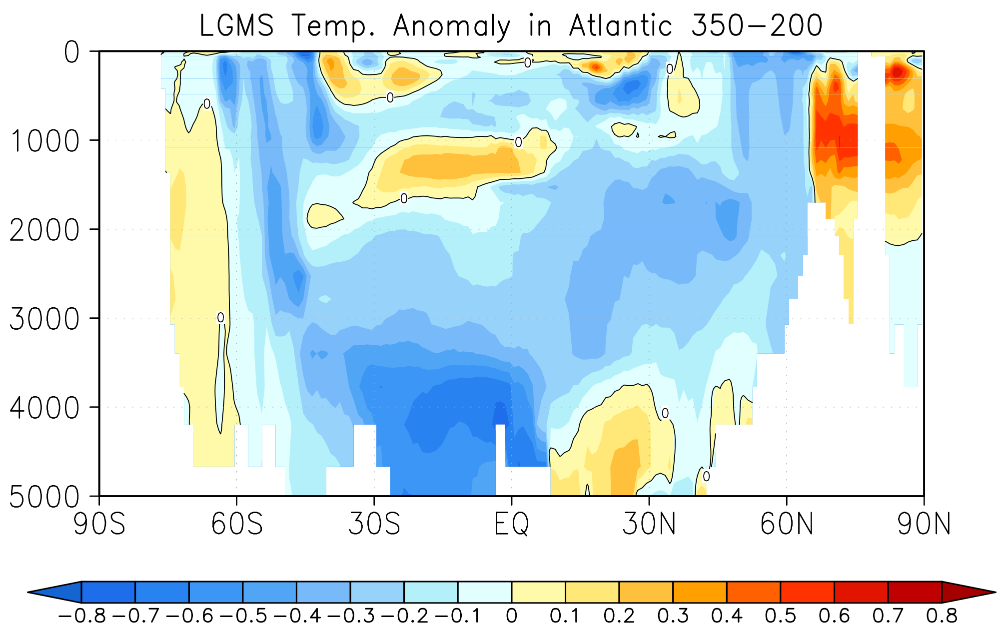
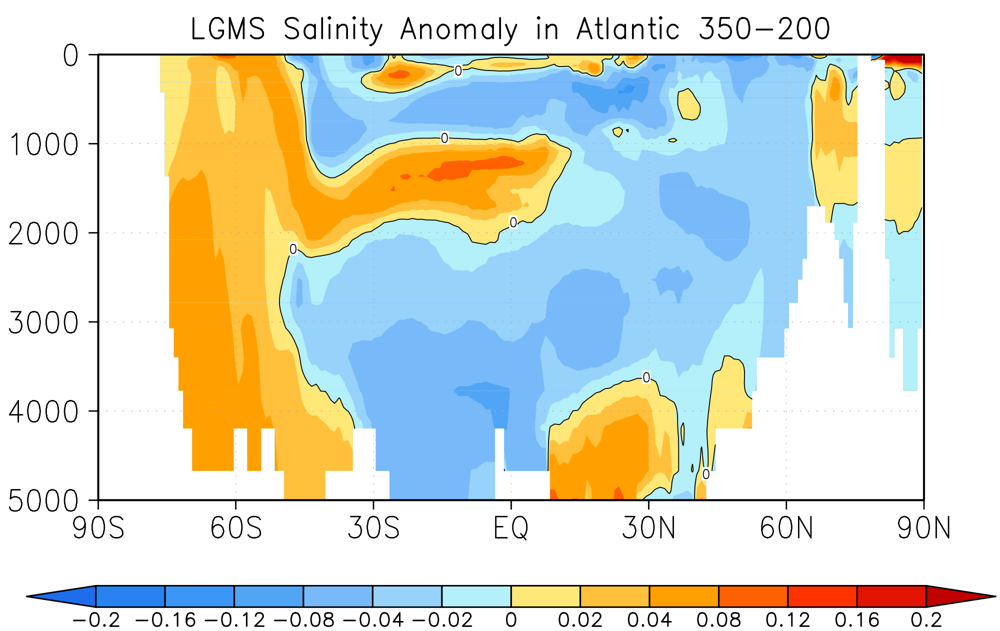
−0.4 −0.32 −0.24 −0.16 −0.08 −0.04 0 0.04 0.08 0.16 0.24 0.32 0.4

B



C



D

Figure 6 Zonal mean temperature (A, C) and salinity (B, D) anomalies between the 350th and 200th model year in LGM2PI (A, B) and LGMS (C, D). Note that the range of color bar in LGM2PI is twice larger than in LGMS.

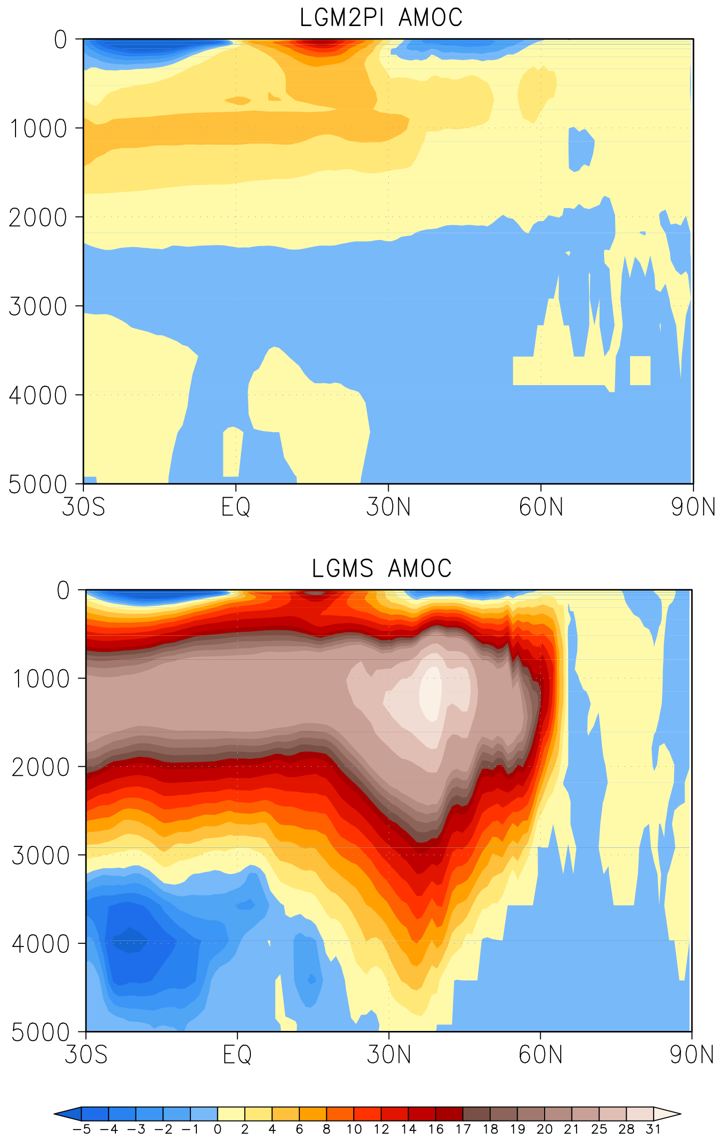


Figure 7 Spatial patterns of AMOC during the spin-up (the 350 model year) of LGM2PI and LGMS.

Response to specific questions:

1) It is stated at several places in the ms. that elements of the Atlantic circulation during the LGM, such as the meridional overturning circulation and the formation of NADW, were different from the modern according to sediment data (e.g., Abstract, p. 3021, p. 3023). Consequently, the authors seem to imply that the glacial simulation with shallower Atlantic meridional overturning circulation (AMOC) is more consistent with sediment data and is thus to be preferred. However, inversions of sediment data have consistently shown that the bulk of these data do not require a circulation state that is different from the modern, if due consideration is given to data and model errors (LeGrand and Wunsch 1995; Gebbie and Huybers 2006; Marchal and Curry 2008; Burke et al. 2011). Whereas an inversion of benthic foraminiferal d13C and Cd/Ca data showed that these data are consistent with a shallower AMOC (Winguth et al. 2000), these authors did not explore whether the same data could also be consistent with another circulation state. In a review of sediment data and model studies (forward and inverse), Lynch-Stieglitz et al. (2007) concluded that the AMOC "was neither extremely sluggish nor an enhanced version of the present-day circulation", although "evidence from multiple water-mass tracers supports a different distribution of deep-water properties, including density, which is dynamically linked to circulation" (their Abstract). Given our incomplete understanding of the AMOC at the LGM, the authors should probably exert caution when discussing the possible (in)consistency of their glacial simulations with sediment data.

=> Reconstructing the ocean circulation during the LGM has been a long-standing issue for decades. Uncertainties on the kinetic proxy data prevent us validating the model performance on LGM simulations. However, this can be done by the distribution of different water masses of the glacial ocean, which is well constraint by the nutrient tracers (e.g. d13C and Cd/Ca). At present day, North Atlantic deep water (NADW) is low-nutrient water mass with high $d^{13}C$ due to that the surface primary producers discriminate against the heavy isotope of carbon when taking up nutrient and carbon. Antarctic Bottom water mass (AABW) has a feature of higher nutrient concentrations and lower d13C as a consequence of that the waters are not well ventilated and collect nutrients and 13C-poor carbon from the decay of organic matter in the depth. According to the benthic foraminiferal isotope data, a general distribution of glacial water mass was drawn, i.e. a southern source water at ~1000 m (with low d13C), a northern source water at ~1500 m (high d13C), and a southern source water below 2000 m (low d13C; Curry and Oppo 2005). In addition, distribution of glacial Cd/Ca ratio, a proxy to reconstruct the distribution of ocean water masses, suggested that NADW was replaced by the shallower Glacial North Atlantic Intermediate Water (GNAIW), with significant northward expansion of AABW (Marchitto and Broecker 2006). Further more, the enhanced AABW and shallower GNAIS is critical for the ocean circulation models to reproduce the similar nutrient distribution during the LGM (e.g. Hesse et al 2011). In our LGM simulations, a significant northward expansion of AABW is well preserved in LGMW, accompanied with the shallower GNAIW. This ocean structure is much more reliable than the LGMS in which strong NADW still dominates the deep North Atlantic. Thus, we pointed out that the LGMW ocean state is more reliable in comparison to the sediment record.

2) Admittedly, I cannot see the value of the freshwater perturbation experiments in the current context (section 3.3). These experiments are time-dependent solutions and do not seem to provide any direct insight into the causes for the differences in ocean states between the two glacial simulations, LGMs and LGMw (which again I assume are equilibrium or quasi-equilibrium states). Unless the rationale for the freshwater perturbation experiments can be clarified, I would suggest that section 3.3 be removed from the ms.

=> In our main text, we mentioned that the two LGM ocean states were generated due to different initial ocean stratification. In previous studies about multi-stability of the ocean that is associated with hydrological cycle, the hosing experiments are employed to reveal potential transitions. In the section 3.3, two different amounts of positive freshwater perturbation (FWP) were conducted to test whether the two LGM states are transferrable and their responses to freshwater perturbation (FWP) are same. We found that the two states are not associated with the hydrology in Atlantic basin, emphasizing the important role of ocean stratification on maintaining these two states. In addition, the AMOC behaviors after the FWP are also distinctive. That is, there is AMOC overshoot in LGMW hosing experiment, accompanying with the abrupt Greenland warming, but this phenomenon is not robust in LGMS hosing experiment. This further highlights the ocean stratification on glacial AMOC behavior for the interpretation of geological data. Thus, we stress that this part should still be in the revised manuscript.