Response to Referee #2

Reviewer Comment-blue shaded

We thank the reviewer 2 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) The authors should try to frame better the context of the study. That is, is it relevant to all glacial abrupt climate changes or mainly deglaciation and why?

The inference of our model simulations are much more relevant to the abrupt climate shift during the last deglaciation (e.g. Bølling-Allerød warming event, B/A). In this study, freshwater perturbation (FWP) was applied under the LGM boundary conditions. After the FWP, only the LGMW, the one with strong vertical stratification, has a feature of AMOC overshoot that results in abrupt warming over the high latitudes of North Atlantic (Fig. 1). This phenomenon has placed in previous studies (e.g. Knorr and Lohmann 2007, Liu et al 2009). However, the background climate in these studies was gradually changed, which prevents evaluating the contribution of the ocean stratification to the AMOC overshoot. In our study, we demonstrated that this feature is strongly related to ocean stratification that is well recorded at the LGM by the proxy data (Adkins et al, 2002). Liu et al (2009) also showed that during the B/A event the ocean was still well stratified. Therefore, it is reliable and reasonable to attribute the subsequent B/A event to the ocean stratification. During Marine Isotope Stage 3 (MIS3), abrupt warming events known as Dansgaard–Oeschger events (DO event, Dansgaard et al. 1993) repeatedly occurred. Bereiter et al. (2012) suggested that CO2 reservoir associated with Antarctic Bottom Water (AABW) gradually developed at the beginning of MIS3, however, limited reconstruction of sea salinity from the deep ocean still constrain to extend the relationship between ocean stratification and AMOC overshoot to DO events. Further investigations about this issue by model and data, thus, are highly desirable to uncover their potential relationship.

2) One of the main results is that the weak LGM AMOC is unstable due to persistent upwelling, but this is not illustrated in depth. The authors claim the strong AMOC state would be achieved in several thousand years starting from the weak one. I understand that due to computational limitations the runs cannot be continued that long, but additional results should be shown to support this claim.

In the old version of this study, one main finding is that the more reliable LGM simulation (LGMW) is inherently unstable due to the persistent upwelling in the Southern Ocean. Shown in Fig. 2 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. 3). The more equilibrated LGMS ocean state, in terms of internal ocean structure, is well stratified and comparable to LGMW (Fig. 4). 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.

Under the LGM (~21ka BP) boundary conditions the equilibrated ocean state in our climate model (LGMW) is comparable to the reconstructions (Duplessy et al., 1988; Curry and Oppo, 2005; Marchitto and Broecker, 2006; Lynch-Stieglitz et al., 2007). The reconstructed data indicate that δ^{13}C-depleted and nutrient-rich water mass dominates the bottom of Atlantic Ocean during the LGM, which is supposed to be resulted from northward invasion of AABW contemporarily. However, these available data merely stand for the existence of this glacial ocean configuration during the LGM rather its formation process. Furthermore, Schmitt et al. (2012) suggests that the carbon cycle in the climate system during the LGM was already in its dynamic equilibrium and the net transfer of carbon to the deep ocean had occurred prior to the LGM. In previous OGCM studies a well-reconstructed glacial ocean can be generated only if additional sea-ice export is imposed to the glacial Southern Ocean (e.g. Hesse et al. 2011), suggesting the water mass distribution as inferred from reconstructions is sensitive to the sea-ice dynamics in the Southern ocean. Using a sea-ice reconstruction based on diatoms, Allen et al. (2011) suggested that more extensive sea ice extent was found between ~22 ka and ~30 ka BP overlapping with the minimum temperature in Antarctica that is attributed to the lowest obliquity reducing solar income to high latitudes. This indicates that the brine rejection due to sea-ice formation might be stronger than during the LGM, resulting in a stronger AABW formation. Notably, there is also a sharp decrease of CO_2 and benthic $\delta^{13}C$ at the beginning of Marine Isotope State 2 (MIS2, ~27 ka BP) (e.g. Hodell et al., 2003; Ahn and Brook, 2008), implicating abrupt formation of an abyssal carbon reservoir. Accompanied is the northward invasion of AABW so as to the formation of reconstructed LGM ocean structure (Gutjahr and Lippold, 2011). Accordingly, it is conceivable that the reconstructed water mass configuration during the LGM might stem from the inception of MIS2 (~27ka BP). This is supported by our LGM simulation LGMS that was initialized from the present-day ocean and was integrated for about 5000 years to achieve the glacial ocean state that is more consistent with the reconstructions. In addition, this is further corroborated by our results from the 27ka experiment. It shows that formation of AABW during 27ka BP as well as the AABW-cell of the AMOC are more expanded than the LGM (Fig. 13), implying that the inception of MIS2 bears the potential to generate the LGM ocean inferred from the nutrient tracers (Duplessy et al., 1988; Curry and Oppo, 2005; Marchitto and Broecker, 2006). To further consolidate it by the isotopic models and data, however, is beyond the scope of this study and is desirable in future studies.

3) The weak LGM AMOC is here only reachable through the use of specific (glacial rather than Levitus) initial oceanic conditions and unstable due to persistent upwelling in the Southern Ocean. However, both features (the unreachability and the instability) seem to be model dependent. Other models do seem to attain stable weak AMOC LGM conditions. The authors should comment on this.

It has been a long-standing challenge to simulate the LGM ocean circulation comparable to the reconstructions (e.g. (Otto-Bliesner et al., 2007; Weber et al., 2007). Based on the model study using CCSM, Liu et al. (2005) proposed that the low CO_2 concentration during LGM contributes to the strengthened AABW associated with enhanced brine rejection due to pronounced sea ice formation in the Southern Ocean (Shin et al., 2003). Otto-Bliesner et al. (2007) further emphasized that the diversity in brine formation process over the Southern Ocean in LGM simulations is responsible for the huge spreads with respect to deep ocean properties amongst different PMIP2 models. Later on, via diagnosing the PI control runs of PMIP2 models and testing in the MIROC model, Abe-Ouchi and her group demonstrated that an SST cooling bias over the Southern Ocean in CCSM3 accounts for its enhanced sea ice formation during the LGM so as to its well-stratified glacial ocean (Fig. 6). This inference is further confirmed by our climate model, which is characterized by a weak SST cooling bias over Southern Ocean compared with CCSM3 (Fig. 6) and eventually introduces a well-stratified glacial ocean after a long-term integration (Figs. 3, 4).

One significant feature of our LGM simulations is the dependence of the transient features on the initial ocean states. When the present-day ocean serves as the initialization, the simulated LGM ocean will experience a quasi-stable state, which lasts for over 500 years but is inconsistent with deep ocean reconstructions. Due to the lack of the specification about the initial ocean state for simulating the LGM, however, all the PMIP2 models except CCSM3 and HadCM were started from the present-day ocean (Braconnot et al., 2007; Weber et al., 2007). Most notably, according to our criteria with respect to the classification of the LGM AMOC states, CCSM3 and HadCM belong to the glacial-like ocean and the others to present day-like ocean (Fig. 7), emphasizing the important role played by initial ocean states on LGM simulations. Furthermore, combined with the effect of SST warm bias over the Southern Ocean amongst these models, the resulted present day-like ocean states should be more stable than in our model. That is, either a much longer equilibrium time scale of deep ocean is necessary to fulfill the transition to the glacial-like ocean, or the present day-like ocean state is the final equilibrium state in their LGM simulations. Given this it is of utmost importance to specify one standard ocean state to initialize the glacial simulations in the PMIP protocol, not only for improvement of model inter-comparison but also for reconciliation with proxy data.

Reference:

Braconnot, P., Otto-Bliesner, B., Harrison, S., Joussaume, S., Peterchmitt, J. Y., Abe-Ouchi, A., Crucifix, M., Driesschaert, E., Fichefet, T., Hewitt, C. D., Kageyama, M., Kitoh, A., Laine, A., Loutre, M. F., Marti, O., Merkel, U., Ramstein, G., Valdes, P., Weber, S. L., Yu, Y., and Zhao, Y.: Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum – Part 1: experiments and large-scale features, Clim. Past, 3, 261-277, 10.5194/cp-3-261-2007, 2007.

Marchitto, T. M., and Broecker, W. S.: Deep water mass geometry in the glacial Atlantic Ocean: A review of constraints from the paleonutrient proxy Cd/Ca, Geochemistry Geophysics Geosystems, 7, 10.1029/2006GC001323, 2006.

Figures

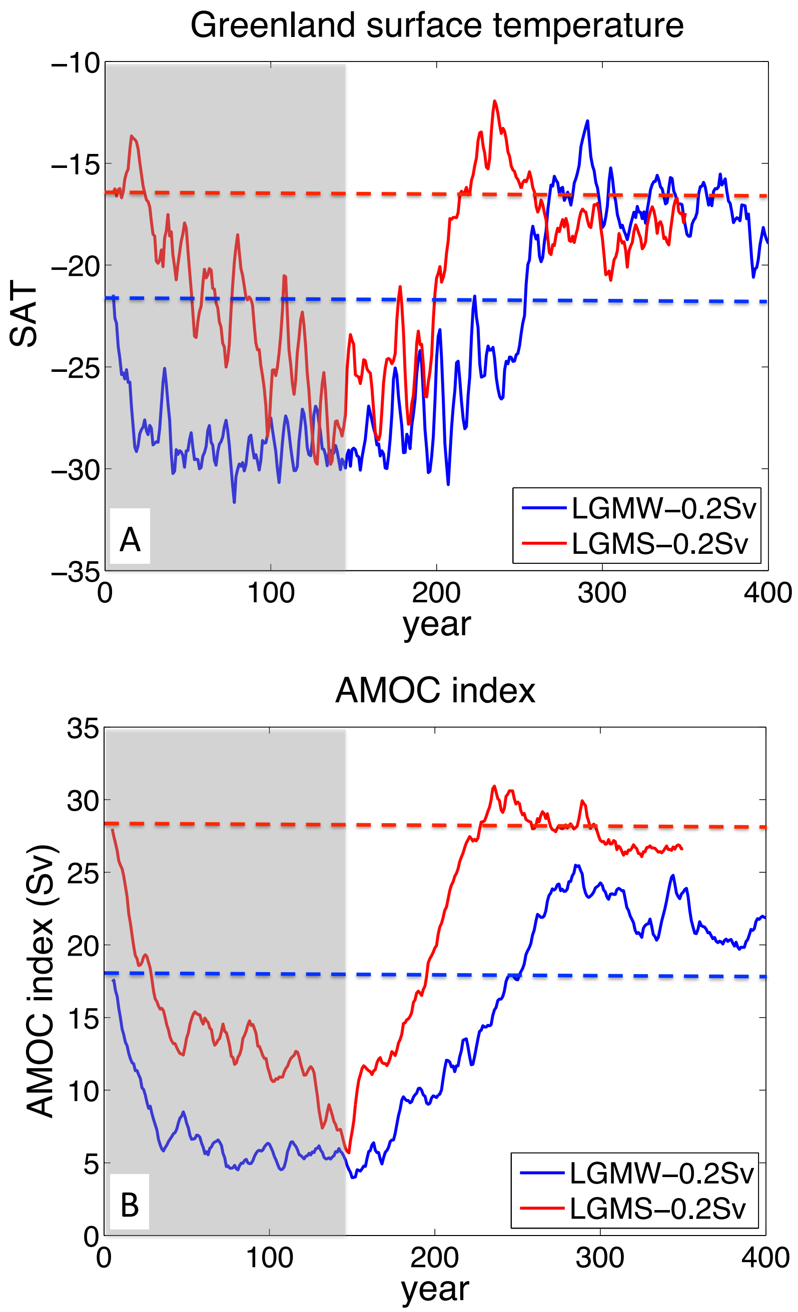
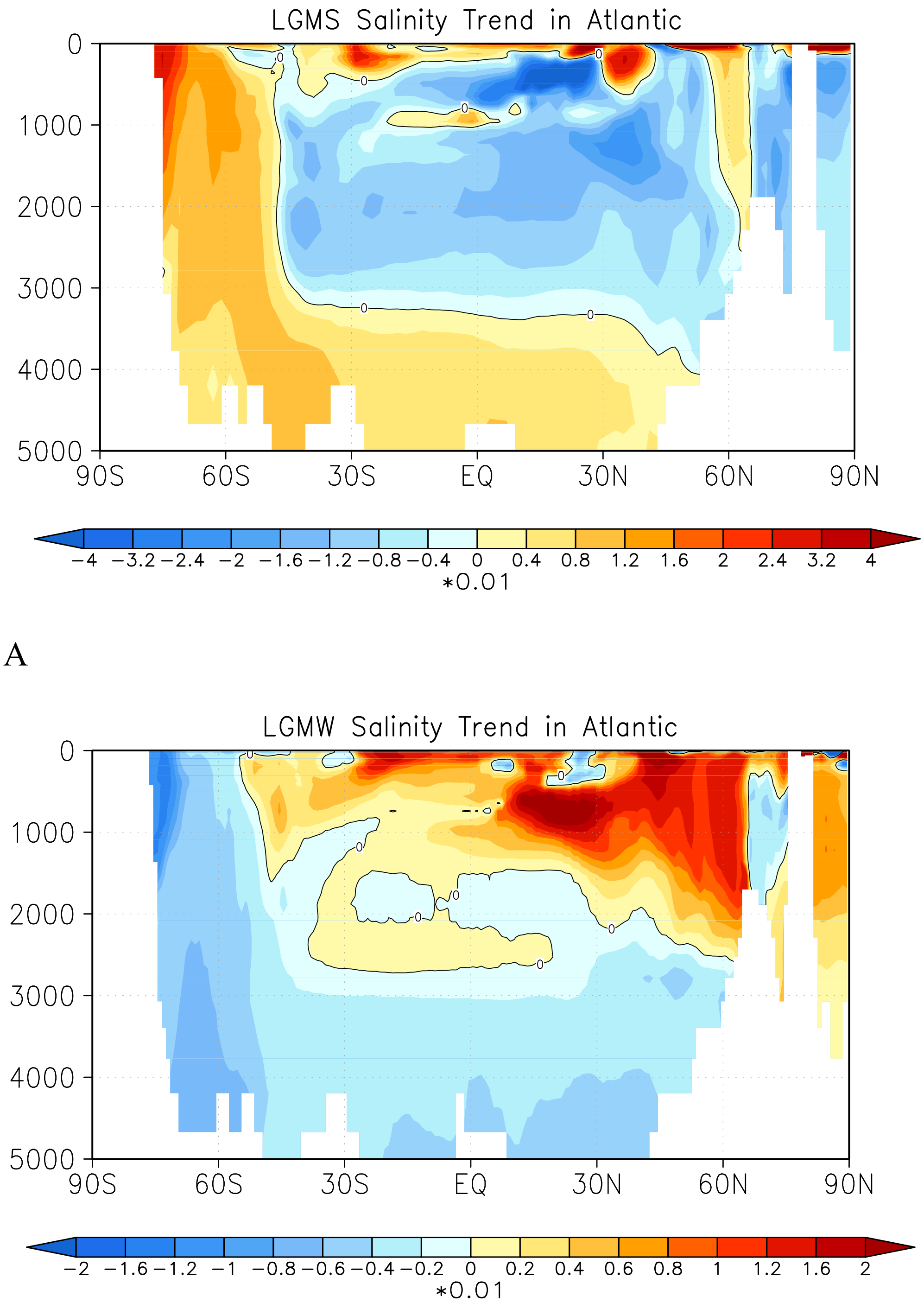


Figure 1 A) Surface air temperature (SAT) in the latitude of 60-70°N in North Atlantic in LGMW-0.2Sv (blue) and LGMS-0.2Sv (red). B) AMOC index in LGMW-0.2Sv (blue) and LGMS-0.2Sv (red). 5-year running average was used to filter out the high frequency signals of the SAT and the AMOC.



A

B

Figure 2 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.

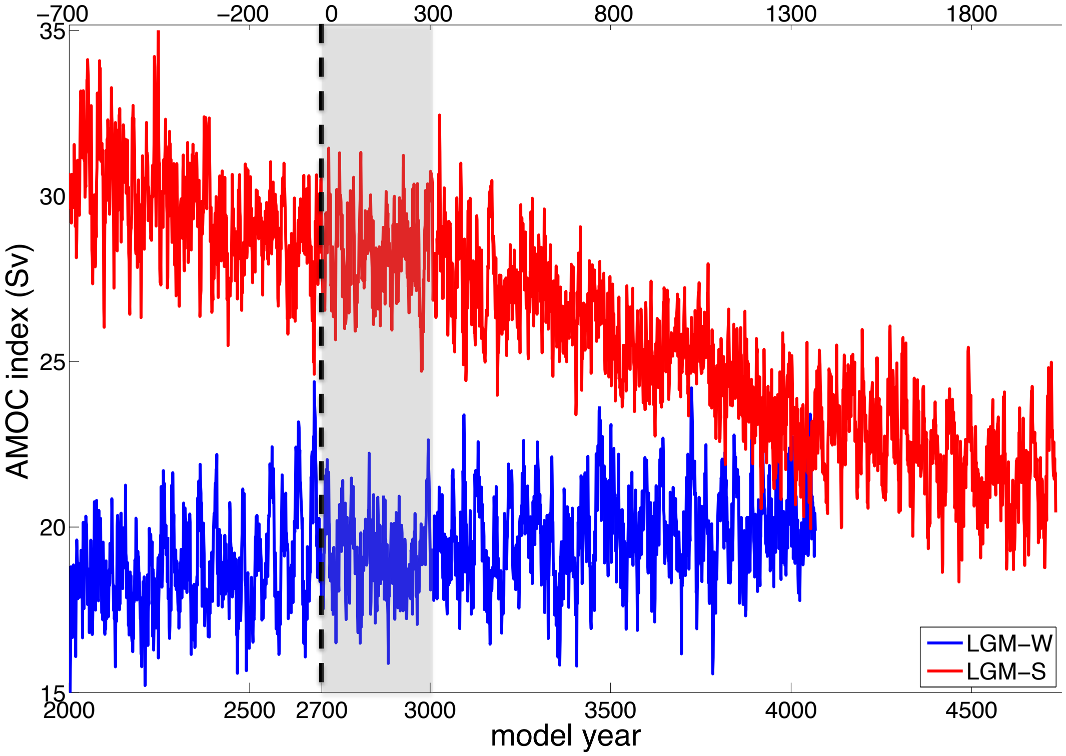


Figure 3 AMOC indices with respect to NADW-cell in the North Atlantic for LGMS (red) and LGMW (blue). Upper X-axis indicates the starting pointing of our hosing experiments while lower one shows the model year. Average between 2900 and 3000 year represents the corresponding quasi-stable climatology in the main text. Units: Sv.

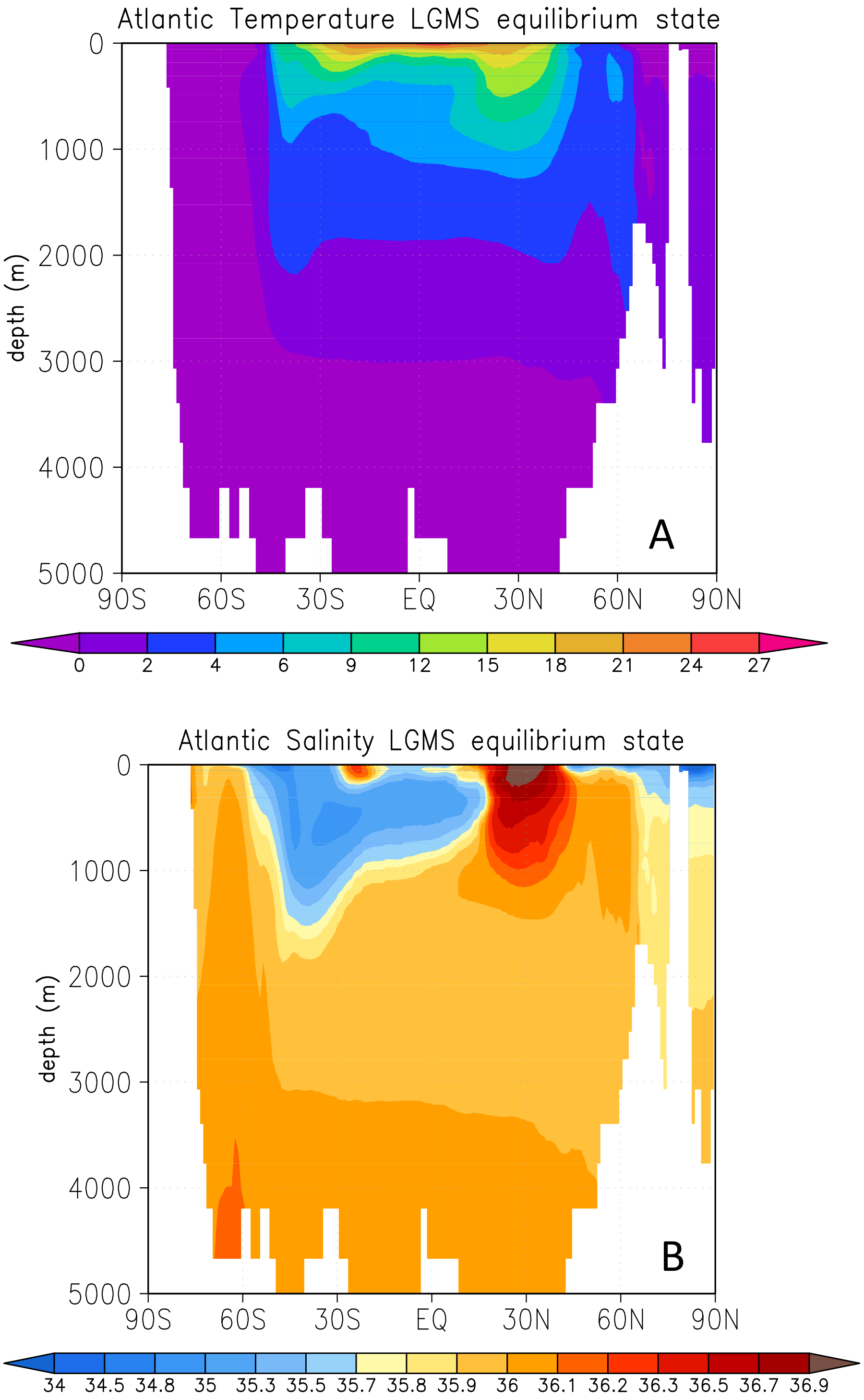


Figure 4 Meridional section of zonal mean temperature (A, units: °C) and salinity (B, units: psu) in equilibrated LGMS state (average of 4600-4700 model year in LGMS).

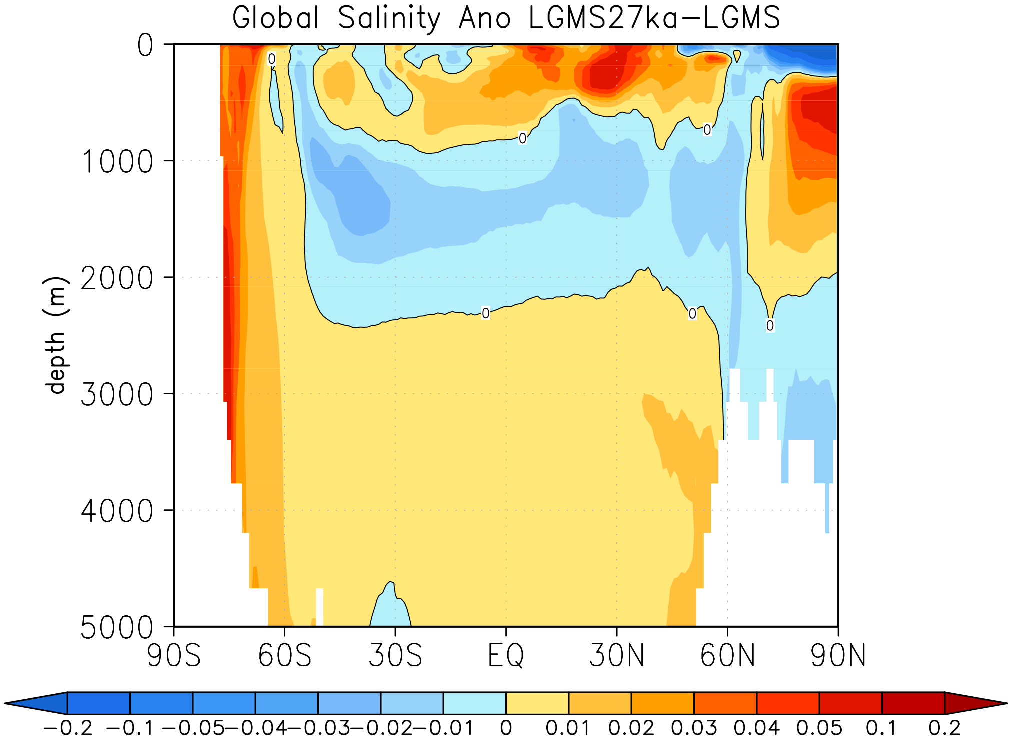


Figure 5 Meridional section of zonal mean salinity anomalies (shaded) in global ocean between LGMS27ka and LGMS. For the comparison, we averaged the corresponding model years 4600-4700.

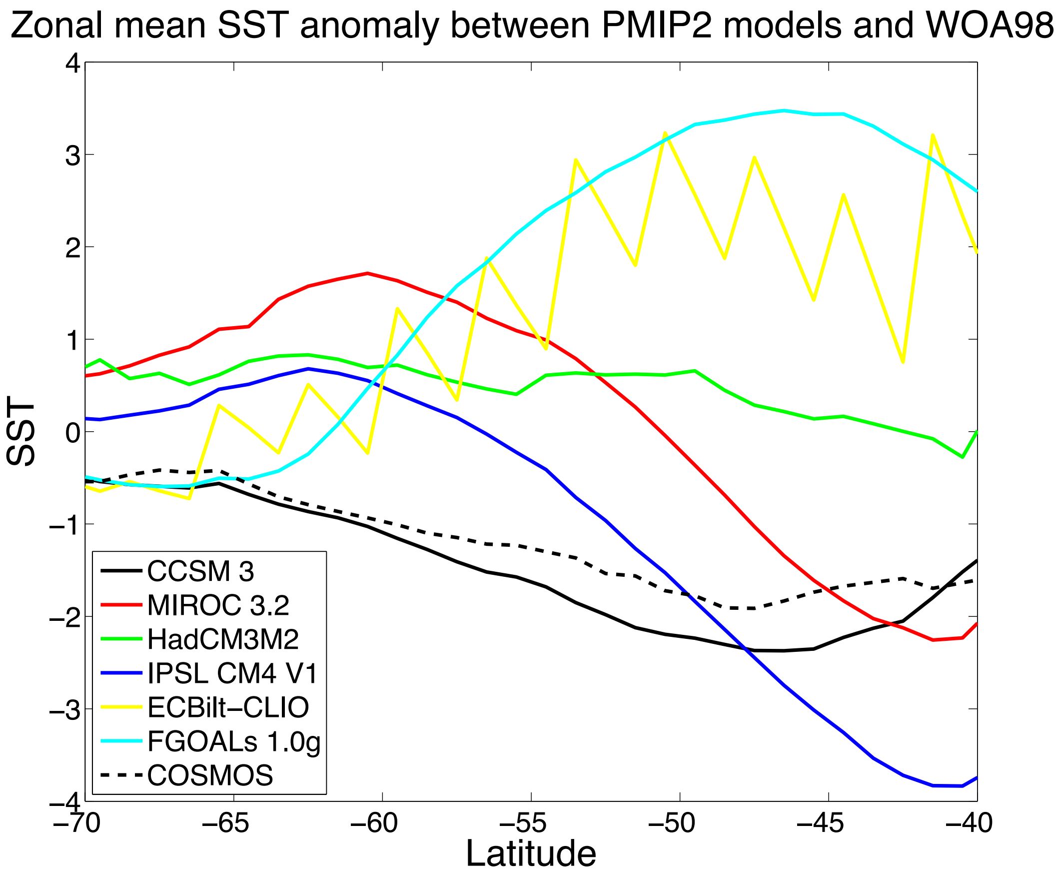


Figure 6 Zonal mean of SST anomaly between PI control run of PMIP2 models (i.e. CCSM3 (black solid), MIROC 3.2 (red solid), HadCM3M2 (green solid), IPSL-CM4-V1-MR (blue solid), ECBilt-CLIO (yellow solid), FGOALS-1.0g (cyan solid)) as well as the model used in this study (COSMOS, black dashed) and the observation data (World Ocean Atlas 98).

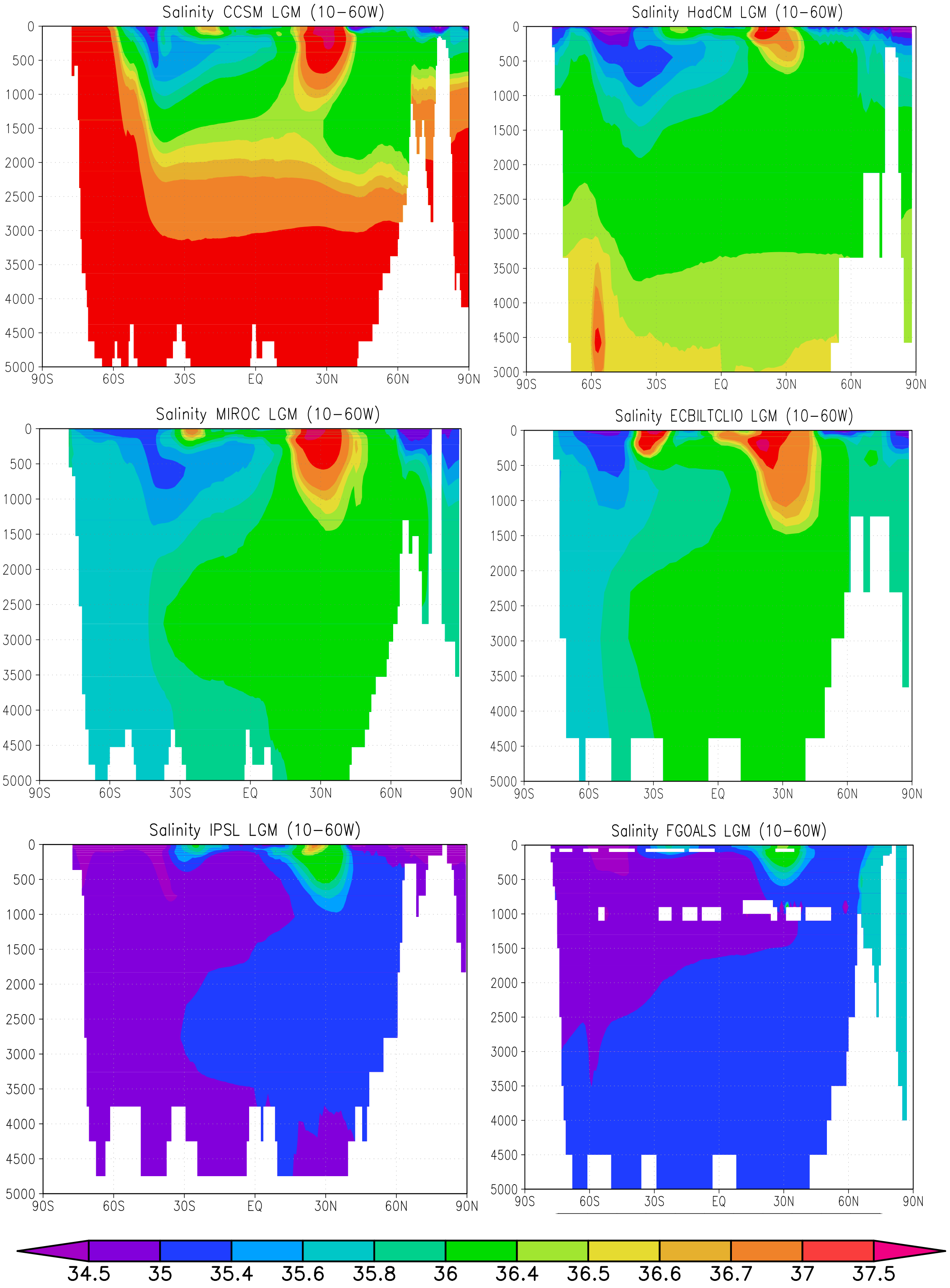


Figure 7 Meridional section of zonal mean salinity in Atlantic Ocean for six PMIP2 models (CCSM3, HadCM3M2, MIROC 3.2, ECBilt-, FGOALS-1.0g

and IPSL-CM4-V1-MR). The stratification in CCSM3 and HadCM3M2 is comparable with reconstruction (Otto-Bliesner et al., 2007), while the ocean structure in MIROC 3.2, ECBilt-CLIO, FGOALS-1.0g and IPSL-CM4-V1-MR is more like to present day with the saltiest deep-water mass in the north Atlantic. According to their salinity structure, one can divide the PMIP2 models into two main classes which are related to a highly stratified ocean, but weaker AMOC (i.e. CCSM3 and HadCM, as our LGMW) and weaker stratified, but stronger AMOC (LGMS).

Response to specific questions:

Here we show the main specific questions with respect to the scientific issues, while the one associated with technical problems will be modified in the final version of the manuscript.

P 3016 (Abstract):

Lines 2-4 (this is related to my first general comment): The sentence "the understanding of the underlying dynamics is still limited, especially with respect to abrupt cli- mate shifts" is unclear. The connection between deglaciation and abrupt climate shifts should be made clearer. If the authors are referring to the abrupt character of deglaciation this could be stated more clearly.

=> Nevertheless, the understanding of the underlying dynamics is still limited, especially with respect to abrupt climate shifts and associated changes in the Atlantic meridional overturning circulation (AMOC) during glacial and deglacial periods.

P 3017:

Line 10: The sentence "However, the principal difficulty for climate models is to determine the proximity of our present climate to potential thresholds (Rahmstorf et al., 2005)" is confusing, please clarify.

=> "... the principal difficulty for climate models is to determine the background climate state of our real climate in the bistable regime (Rahmstorf et al., 2005)."

Lines 12-14 (also related to general comment 1): Is "Since the last glacial period" really meant here? What is the focus of the study? Deglaciation, glacial abrupt climate changes, or both?

=> "During glacial-interglacial cycles, large and abrupt shifts in the AMOC are thought to have repeatedly occurred and to be associated with large and abrupt changes in the climate system (e.g. Dansgaard et al., 1993; Bard et al., 2000; Ganopolski and Rahmstorf, 2001; Knorr and Lohmann, 2003).”

P 3020

Lines 14-16: In this study the two water-mass configurations correspond also to two different LGM AMOC states, weak and strong. This can also be identified in the PMIP simulations shown here, with CCSM and HadCM showing relatively weak glacial AMOC, and MIROC and ECBilt-CLIO stronger ones. Is this the general case for other PMIP models? If so, it should be stated here in order to make a stronger case.

=> In the revised version of manuscript, we collect all the models of which LGM simulations (new added: FGOALS-1.0g and IPSL-CM4-V1-MR) are available in the PMIP2 database. It is pronounced that the weak AMOC is related to a stratified ocean structure (CCSM3 and HadCM), and vise versa (the rest models). This result substantiates our conclusion that the ocean stratification constrains the glacial AMOC behavior.

P 3022:

Lines 5-7: I think a very interesting result of this study that is not well stressed is the fact that an AMOC overshoot can be obtained only by introducing a freshwater perturbation at the weak state, while this does not happen from the strong one. To my knowledge this is the first study which starting from a glacial climate perturbed with (positive) freshwater fluxes alone results in an AMOC overshoot (in Barker et al. 2010, Knorr and Lohmann 2007 and Liu et al 2009 the background climate was gradually changed from glacial to interglacial conditions). To understand the implications, it would be very interesting to see how North Atlantic (ideally Greenland) SATs are evolving. If the SAT change were abrupt, this study could point to a possible reason why coupled climate models might have failed to simulate glacial abrupt climate changes associated to an overshoot of the AMOC-

=> “After the FWP, the overshoot of AMOC in LGMW results in abrupt warming over the Greenland for several decades, but not in the LGMS case (Fig. 10 and Fig. 11). Given that vertical structure of ocean interior in both runs is still distinctive during and after the hosing experiments, our study emphasizes the critical role played by the glacial ocean stratification on the AMOC overshoot and associated abrupt Greenland warming. After AMOC recovery, both runs restore to their former AMOC states (Fig. 10), consistent with the hypothesis of a monostable freshwater regime during glacials (Ganopolski and Rahmstorf, 2001; Prange et al., 2002; Romanova et al., 2004).”

Line 26-28 (this relates to my general comment 2): here and in Figure 9’s caption the authors claim that LGMS would be attained starting from LGMW after several thousand years. In figure 9, 5000 years are specifically mentioned. The authors should explain how this estimation was calculated. I understand due to computational limitations the runs cannot be continued that long, but at least the AMOC timeseries should be shown for the whole period, before and after the perturbation, including the additional 500 years. Moreover, the same timeseries should be shown for the simulation starting from Levitus to show there is no comparable trend in that case.

=> In the revised version, we addressed as follows.

“It is noted that the fundamental contrast between the two LGM states is their distinctive vertical stratification associated with AABW formation. Shown in Fig. 4 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. 5). The more equilibrated LGMS ocean state, in terms of internal ocean structure, is well stratified and comparable to LGMW (Fig. 7). 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. 6), suggesting that the northward-invading AABW from the Southern Ocean in LGMS (Fig. 4) is the cause of descending a 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. 5)."

P 3023

Lines 1-23 (related to my general comment 3): this discussion seems to imply that the LGMW state that provides a more realistic LGM ocean state might not be reachable simply by imposing glacial boundary conditions, but this result seems to be model dependent (therefore the 'might'). Other models do achieve steady weak-AMOC glacial states. Thus, the capability to reach this state would be model dependent. In relation to this, the authors suggest the persistent upwelling is the reason for the instability of the LGMW state, but the existence of models capable of achieving steady weak-AMOC glacial states would again suggest that the instability of this state is model dependent. Is this the case? The authors should discuss this issue, even if afterwards they provide with proxy data supporting their case.

=> We discussed this issue in our revised version as follows.

"It has been a long-standing challenge to simulate the LGM ocean circulation comparable to the reconstructions (e.g. (Otto-Bliesner et al., 2007; Weber et al., 2007) (Fig. 12).

Based on the model study using CCSM, Liu et al. (2005) proposed that the low CO_2 concentration during LGM contributes to the strengthened AABW associated with enhanced brine rejection due to pronounced sea ice formation in the Southern Ocean (Shin et al., 2003). Otto-Bliesner et al. (2007) further emphasized that the diversity in brine formation process over the Southern Ocean in LGM simulations is responsible for the huge spreads with respect to deep ocean properties amongst different PMIP2 models. Later on, via diagnosing the PI control runs of PMIP2 models and testing in the MIROC model, Abe-Ouchi and her group demonstrated that an SST cooling bias over the Southern Ocean in CCSM3 accounts for its enhanced sea ice formation during the LGM so as to its well-stratified glacial ocean (Fig. S7). This inference is further confirmed by our climate model, which is characterized by a weak SST cooling bias over Southern Ocean compared with CCSM3 (Fig. S7) and eventually introduces a well-stratified glacial ocean after a long-term integration (Figs. 5, 6).

One significant feature of our LGM simulations is the dependence of the transient features on the initial ocean states. When the present-day ocean serves as the initialization, the simulated LGM ocean will experience a quasi-stable state, which lasts for over 500 years but is inconsistent with deep ocean reconstructions (Fig. 3). Due to the lack of the specification about the initial ocean state for simulating the LGM, however, all the PMIP2 models except CCSM3 and HadCM were started from the present-day ocean (Braconnot et al., 2007; Weber et al., 2007). Most notably, according to our criteria with respect to the classification of the LGM AMOC states, CCSM3 and HadCM belong to the glacial-like ocean and the others to present day-like ocean (Fig. 4), emphasizing the important role played by initial ocean states on LGM simulations. Furthermore, combined with the effect of SST warm bias over the Southern Ocean amongst these models, the resulted present day-like ocean states should be more stable than in our model. That is, either a much longer equilibrium time scale of deep ocean is necessary to fulfill the transition to the glacial-like ocean, or the present day-like ocean state is the final equilibrium state in their LGM simulations. Given this it is of utmost importance to specify one standard ocean state to initialize the glacial simulations in the PMIP protocol, not only for improvement of model inter-comparison but also for reconciliation with proxy data.”

P 3024:

Lines 4-6: The authors claim the persistent upwelling could have lead to enhanced CO2 outgassing from the Southern Ocean, consistent with Anderson et al (2009) and Ahn and Brook (2008). But in their model the enhanced upwelling is apparently due to enhanced mixing, while Anderson et al (2009) claimed the CO2 increase was mainly wind-driven. The authors should comment on this.

=> We delete this statement in the revised version.

Lines 12-13: The authors claim that at the last deglaciation the increase in CO2 could have fed back onto climate by facilitating the termination. This discussion seems to imply that the LGMW glacial state is inherently unstable due to the persistent upwelling in the Southern Ocean. Is that the case? If so, would it not be applicable to Dansgaard- Oeschger events? In relation to this, the authors should show whether the LGMS state is or not stable.

=> We delete this statement in the revised version.