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Climate of the Past Discussions



# *Interactive comment on* "The simulated climate of the Last Glacial Maximum and the insights into the global carbon cycle" *by* R. J. Matear et al.

**Anonymous Referee #2**

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This manuscript provides an analysis of ocean biogeochemical distributions under the LGM climate state and shows how large the glacial physical and biogeochemical processes affect the atmospheric CO2 concentration and ocean carbon inventory using an atmosphere-land-sea-ice and ocean models with a simple biogeochemical module. Although the description of ocean carbon cycle sensitivity to the glacial climate is lengthy and their findings, small atmospheric CO2 variation to glacial ocean circulation and sea ice, follow the previous studies (for example, Tagliabue et al, 2009, Chikamoto et al. 2012a, Menviel et al., 2012), they are informative for providing the quantitative contribution of changing biogeochemical processes (organic/ inorganic carbon export or reminalization) to the carbon/oxygen distributions and aragonite saturation horizons.

I think this paper would be accepted with a request for modest revisions because this



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work provides a new perspective for multiple biogeochemical responses (O2, carbon, phosphate, and aragonite saturation) to the LGM climate state.

I have pointed out the experimental setting with the prescribed atmospheric CO2 level makes it difficult to evaluate the physical effects on the oceanic carbon distribution. For example, the total amount of oceanic carbon is down from 33,974 GtC in OHC-1 to 33,370 GtC in OLGM-1. As shown in the carbon budget difference between OHC-1 and OHC-2 experiments, the large carbon reduction is due to the carbon degassing from the ocean to the atmosphere to reach the equilibrium with the prescribed atmospheric CO2 of 185 ppmv. This is the opposite of the actual response – the oceanic carbon stock was increased during the LGM period (Table 4b). In addition, the subsurface carbon reduction in equilibrium with the lowering atmospheric CO2 obscures the upper-ocean physical effect on the carbon distribution that this paper focuses on. I would like to see a discussion what this prognostic approach has the advantage in studies of glacial-interglacial CO2 variations, comparing to the basic experiment with the diagnostic atmospheric CO2 concentration. And I think that it is worth to identify each impact as a result of glacial physical change and the carbon reduction (in equilibrium with the atmospheric CO2 of 185 ppmv) on the oceanic carbon distribution.

This work also highlights the variations of aragonite saturation state and lysocline depth under the LGM climate. However, the terminology, lysocline, misleads readers into thinking that the model diagnoses the calcite content in sediments. In Figs. 12 and 13, the lysocline depth is defined by depth where the aragonite saturation state equals one. Therefore it is more accurate to use the terminology, aragonite saturation depth, than the lysocline depth.

Specific comments and suggested revision are listed below.

Introduction: Despite the fact that many papers have debated glacial-interglacial atmospheric CO2 variations over three decades, the introduction is quite brief. Kohfeld and Ridgwell (2009) and Ciais et al. (2013) summarize the potential mechanisms of the



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glacial-interglacial atmospheric CO2 variations including the model uncertainty. The carbon cycle responses to glacial ocean dynamics (circulation or sea ice coverage) have been evaluated using GCMs (Tagliabue et al, 2009, Chikamoto et al. 2012a, Menviel et al., 2012). In addition, it is helpful to provide the information of previous studies that show modified biogeochemical processes in changing climate state. In terms of no inorganic carbon export, Archer and Maier-Reimer (1994) and Sigman et al. (1998) show the sensitivity of IC/OC export ratio to the ocean carbon cycle. In terms of organic export, Oka et al. (2009) evaluates iron fertilization impact on the export carbon and the atmospheric CO2 using the diagnosed glacial dust deposition. Regarding the remineralization processes, Chikamoto et al. (2012b) and Menviel et al. (2012) have evaluated the remineralization variation under the glacial climate state and discussed the remineralization impact on the carbon cycle.

p1097, l2. Please describe how you give the salinity setting in glacial experiments. In table 3, salinity increases by almost 1 psu in LGM experiments refer to HC experiments. Since the model would conserve the total salinity, I think that this 1-pus increase is artificially forced in the LGM experiment. If you give the salinity forcing in the model, does this forcing affect the ocean circulation, for example, AABW formation?

p1100, l2: maximum sea extent → maximum sea-ice coverage

p1100, l4-6: The strong seasonality of the NA sea ice is an interesting point, because the seasonal sea ice change causes the seasonal variations of carbon and oxygen uptake in the ocean.

P1101, l6: Bouttes et al. (2010) also shows the shoaling of the boundary of NADW and AABW using the reconstruction of the glacial-interglacial anomalies of stable carbon isotopes.

P1101, l10-12: Why isn't the stream function of AABW cell shown in figure 3b and 3d?

P1102, l11-14: It seems to me that upper-ocean DIC is also affected by another pro-



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cesses, such as changes in sea-ice driven gas exchange, solubility, or reorganization of Atlantic Ocean circulation. Is there a way to decompose or quantify each factor effect on the DIC? To understand the physical effects, it is helpful to remove the chemical equilibrium effect under the low CO2 pressure (for example, using OHC-2 and OLGM-1).

P1102, l21, Again, can the decline of DIC at the high latitudes in the northern hemisphere be explained by two factors only: the chemical equilibrium of lower CO2 pressure and freshening? Another factors I mentioned above are negligible?

P1103 l1-8: It is curious that how the remineralized phosphate responds spatially to the LGM climate. The meridional plot of remineralized phosphate anomaly is useful for the description of regenerated phosphate pattern in page 1107, l12. This also leads to the discussion of the variations in AABW-associated storage of preformed nutrient and efficiency of biological pump (Sigman et al, 2010).

P1103, l20-25: As you argue high productivity during the LGM period (in subsection 3.3.2), proxy records show a broad increase in export production during the LGM (Bopp et al. 2003; Kohfeld et al. 2005). This proxy evidence should be involved in the description of model-proxy comparison.

P1104, l10: Please specify the circulation area in terms of “LGM circulation”.

P1104, l11: It makes clear using Eq. (A4) in appendix for the explanation of the limiting factor.

P1105. L11-12: Please specify what rate you changed in an equation. And revise the equation number (“34” is type).

P1105, l17: It is unclear to argue limiting factor using the phosphate anomaly map. Limiting factor doesn’t change under the different climate state? Even at the eastern Pacific upwelling or in the subpolar North Pacific where phosphate is rather increased, phosphate is still limiting factor?



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P1105, l21: It is also interested in the productivity increase in the south subtropical Pacific Ocean.

P1105, l24: Eq. 010 → Eq. A10?

P 1106, l6-8: Previous papers argue the atmospheric CO2 sensitivity to changing PIC export, but a large change in PIC export accompanies the shoaling of lysocline depth, which may be inconsistent with the reconstruction (e.g., Archer and Maier-Reimer, 1994; Sigman et al., 1998). For example, calcite content reconstruction of the tropical Pacific Ocean presents relatively stable lysocline depth during the glacial periods (Farrell and Prell, 1991). You need to mention that this forcing violates the constraint of the lysocline reconstruction.

P1106, l9: you should say the "to store an additional 260 Pg C from the HC state"

P1106, l13: 830 → 840

P1108: l8-9: Individual effects on the carbon budget are large: for example, remineralization change increases the oceanic carbon of 260 PgC, which constitutes a substantial part of the LGM-HC oceanic carbon budget change (520 +/- 400 PgC).

P1109: l10-12: the sentences are unclear.

P1110, l17-20: this is an interesting point.

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Interactive comment on Clim. Past Discuss., 11, 1093, 2015.