Response to Fortunat Joos (Referee)

(Our response **highlighted gray**.)

General comment:

Yamamoto and colleagues present an interesting analysis of glacial change in atmospheric CO2 and marine oxygen. The authors investigate, using a range of factorial analyses, the impacts of glaciogenic iron input and an increased nutrient inventory in the glacial ocean. They apply an offline biogeochemical model for Last Glacial Maximum (LGM) and preindustrial (PI) conditions. They simulate an upper limit for the CO2 decrease due to iron fertilization of 20 ppm and a similar decrease due to an increase in whole ocean nutrient inventory. They present a novel model-proxy comparison for PI-LGM changes in O2. The results suggest a role of iron fertilization and changes in nutrient inventory for low glacial CO2 and for the reconstructed oxygen changes. The manuscript is concise and well written. Figures and tables are illustrative and support the conclusions.

I recommend publication of the manuscript after minor revision.

Response: We appreciate the positive recommendation and helpful comments from Professor Fortunat Joos. We reply to each specific comment below.

Comment #1

I find it interesting that the upper limit for iron fertilization is 20 ppm (p10, l215). I would appreciate if this finding is lifted to the abstract.

Response: Thank you very much for this positive comment. We also think that this result is interesting. However, as mentioned by another referee (Professor Andreas Schmittner), there remains a possibility that this upper limit for iron fertilization is not a robust result because present iron models have a large uncertainty. Thus, we will not mention the upper limit of iron fertilization in the abstract. To obtain a deeper understanding of the impact of iron fertilization on glacial CO_2 decrease, the variability of upper limit among iron models should be investigated in the future study.

Comment #2

Figure 8 shows results from WOA2009 and simulated anomalies. Results for the model for the modern ocean should be displayed as well. This would permit the reader to assess the quality of the simulated O2 field.

Response: According to the reviewer's comment, we will add the simulated O_2 distribution for the modern ocean to Figure 8. The following figure and caption are the revised version of Figure 8.

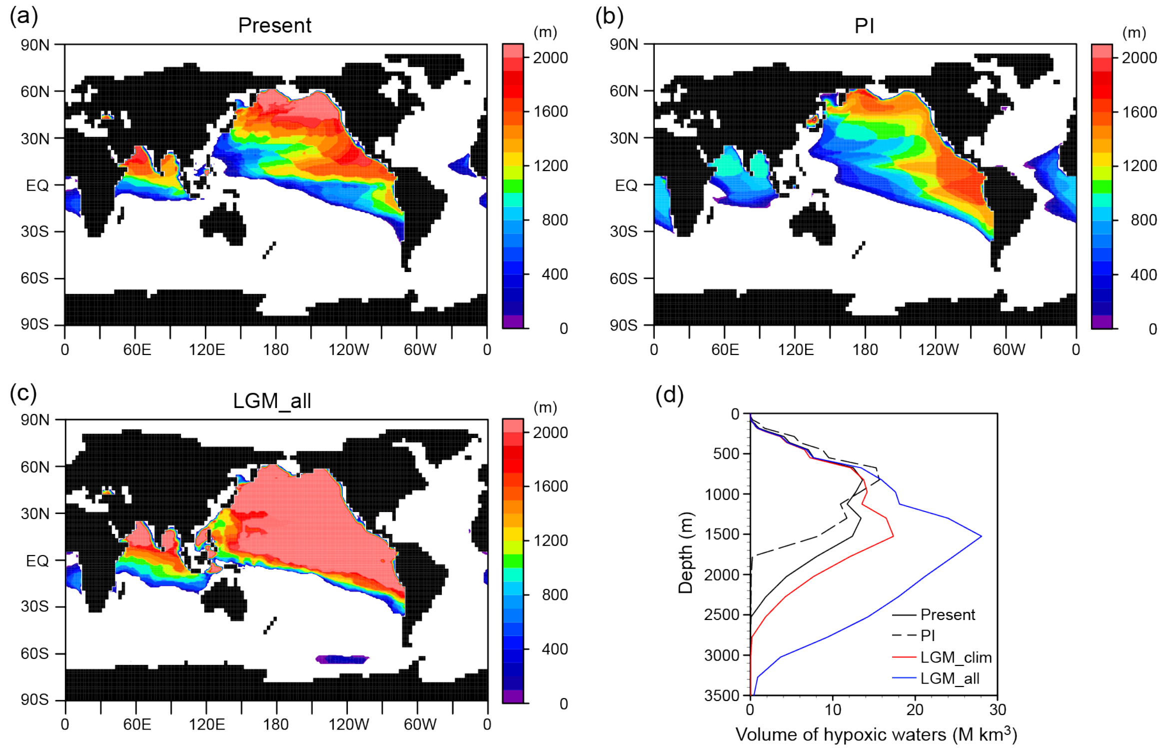

Figure 8. Expansion of hypoxic waters. Horizontal distribution of thickness of hypoxic waters ([O_2] <80 mmol m^{-3}) for (a) present, (b) PI and (c) LGM_all. (d) Vertical distribution of hypoxic waters for the present (black solid), PI (black dashed), LGM_clim (red), and LGM_all (blue). Because present coarse resolution models have difficulties in reproducing low oxygen concentration for the present day (Bopp et al., 2013), observed values from WOA2009 (Garcia et al., 2010a) are used for the present. For the LGM simulations, we combine the observed values with the modelled changes.

Comment #3

There are some language problems, e.g. missing articles, and the manuscript would benefit from proof-reading by a native speaker.

Response: We will ask a native speaker to performed proof-reading of our manuscript.

Comment #4

There is no discussion on the role of the burial-nutrient feedback and how burial-nutrient feedback may affect the results of this study. On page 10, l221, it is mentioned that CaCO3 compensation is not included. However, this study does also not consider how changes in iron fertilization affect the balance between weathering and burial of organic matter. This also applies to some extent to the experiment with the increase in whole ocean nutrient inventory.

Several studies point to the potentially important role of the ocean/sediment/lithosphere fluxes of organic matter and how the associated burial-nutrient feedback modifies the magnitude and time scales of the response in CO2 and other tracers to changes in the marine biological cycles (Wallmann et al., 2016;Roth et al., 2014;Jeltsch-Thömmes et al., 2018). (Tschumi et al., 2011), for example, quantify the implication of ocean-sediment-lithosphere coupling for an experiment where the ocean P inventory is increased. (Menviel et al., 2012) present results from factorial experiments with altered iron fertilization/dust input and altered P inventory plus variation in other drivers from transient glacial-interglacial simulations. I suggest that this caveat is addressed on page 10 and perhaps also in the discussion section.

Response: Thank you for your useful suggestion. We will add the discussion about the role of the burial-nutrient feedback to page 10, L221-224 as follow.

"Note that changes in sedimentation process (i.e., carbonate compensation and burial-nutrient feedback) are not considered in our simulations. The simulated increase in the bottom water DIC (Fig. 4) would enhance dissolution of calcium carbonate in the sediments and thereby increase ocean alkalinity, leading to further CO_2 decline (Bouttes et al., 2011; Brovkin et al., 2012; Kobayashi et al., 2018). Long-term balance between burial of organic material and nutrient input through weathering is also potentially important for the response in atmospheric CO_2 and related tracers to changes in the ocean biological cycles (Roth et al., 2014; Wallmann et al., 2016). For example, Tschumi et al (2011) show that the nutrient-burial feedback significantly amplifies the effect of increase in PO_4 inventory on glacial CO_2 decrease. Menviel et al (2012) quantify the implication of ocean-sediment-lithosphere coupling for factorial experiments with altered iron fertilization and altered PO4 inventory from transient glacial-interglacial simulations. Considering that EP increase due to iron fertilization and nutrient increase is smaller in our simulations than in previous studies (Tschumi et al., 2011; Menviel et al., 2012), the effect of burial-nutrient feedback on the reduction of glacial CO_2 may be smaller than previous estimation."

Minor and technical comments

#1

P1, line 11, p3, l46: ".. due to sea surface cooling" What matters is in my opinion the cooling of the whole ocean, including the ocean interior. Please modify the wording

Response: In the revised text "due to sea surface cooling" will be changed to "due to seawater cooling".

#2

P1, l16-18: This sentence is not so clear. The circulation changes itself likely induce a change in the efficiency of the biological pump (Volk and Hoffert, 1985) as may also be seen when looking at preformed/remineralized nutrients or AOU. I think it should rather read "whereas the other half is driven by iron fertilization and an increase in whole ocean P inventory" or similar.

Response: We agree fully with the referee on this point. We will revise this sentence as follow.

"Sensitivity experiments reveal that physical changes contribute to only half of all glacial deep deoxygenation, whereas the other half is driven by iron fertilization and an increase in whole ocean nutrient inventory"

#3

P5, l90: Is convection included in the offline model and how is this done?

Response: Yes, effects of convection are included in offline model by enhancing the value of the vertical diffusivity where the convection takes place.

#4

P9, l192, You may also refer to (Menviel et al., 2012)

#5

P8, l182: missing word: “shortwave radiation”

#6

P10, l207: you may include here EMICs results (e.g. (Muglia et al., 2017; Parekh et al., 2008; Menviel et al., 2012;Heinze et al., 2016).

Response: As for these three comments, we will add the suggested reference and missing word to the revised manuscript. We would like to thank the reviewer for the attention to detail.