The authors present a study that aims to address the uncertainty in simulated LGM climate, particularly where biogeochemical parameters are set to pre-industrial conditions. The study is very thorough, exploring a wide range of parameter combinations, sensitivity experiments corresponding to different physical and biogeochemical settings, and variable stoichiometry. I find the paper very interesting, as it highlights the large variance in simulated pCO_2 responses arising from different parameter calibrations under LGM forcings.

The authors show that, out of all combinations, iron flux exerts the most profound influence on marine biogeochemistry. However, it is important to distinguish the contributions of increased aeolian dust deposition and decreased sedimentary input, as they contribute oppositely to CO_2 drawdown.

Overall, I consider this study a valuable contribution to Earth System Dynamics, subject to the comments outlined below.

Dear referee,

Thank you very much for your positive comments and suggestions. We listed our responses to all of your points below and hope the manuscript is now satisfactory.

General comments:

The manuscript is well written in terms of the structure. However, it is heavily results-focused, with numerous numerical values presented, while the overarching message and broader implications are somewhat buried. Carbon dioxide removal (CDR) is mentioned in the Introduction, but this motivation is not revisited in the Discussion or future directions. Reconnecting the findings more explicitly to this framing would strengthen the manuscript.

Section 4.2 is too brief for such an important topic. There is little discussion in the context of previous studies, particularly regarding winds, which have been widely investigated, but also moisture diffusivity, which represents a relatively new perspective. A more detailed comparison with the existing literature would help better contextualise the findings.

Reply: We thank the referee for the suggestions. We have revised the manuscript accordingly as follows:

1. To distinguish the contributions between dust deposition and sedimentary input of Fe, we revised the sentence in the abstract to "Our results show that changes in iron input, including increased aeolian dust deposition and decreased sedimentary input, exert the most profound influence on marine biogeochemistry and pCO_2 drawdown."
2. We emphasise increased Fe deposition as a potential CDR method in the introduction and reconnected our findings to this method in the discussion (Section 4.4). Specifically, we have added "A stronger Fe supply from atmospheric deposition, such as in the LGMFedep condition, could have enhanced the utilisation of PO_4^{3-} and NO_3^{-}, leading to an expansion of ocean regions depleted in those major nutrients. This 'nutrient robbing' effect, whereby stimulated productivity in one area depletes macronutrients in downstream regions, is a primary criticism of Ocean Iron Fertilisation (OIF) as a marine CDR strategy, as it could limit long-term global net carbon sequestration. Nevertheless, our results suggest that the variable stoichiometry implemented in our model may partially mitigate this effect. By increasing pC:P and pC:N in response to nutrient stress, the model sustains NPP even when macronutrient concentrations decline. This negative feedback mechanism does not exist in models that assume fixed stoichiometry, and warrants further investigation to determine its global significance in CDR scenarios."
3. We also tried to improve the discussion on the interactions between physical and biogeochemical boundary

> conditions in Section 4.2. In the revised manuscript, we have added references to relevant literature (e.g., Somes et al., 2017, and other studies discussed earlier) and expanded the discussion to better interpret the interactions between physical and biogeochemical boundary conditions. The revised paragraph is: "Lower temperatures, different wind patterns, and reduced moisture diffusivity over the Southern Ocean in the three LGM physical configurations result in different general circulation patterns, which affect biogeochemical cycles, as demonstrated in previous modelling studies (Somes et al., 2017; Muglia and Schmittner, 2015). The LGM boundary conditions affect inventories and fluxes differently. For example, DIC is $14.7\,\mathrm{mmol\,m^{-3}}$ higher for LGMatmpi-$*$ than for PIctl-$*$, while the differences between LGMatmws-$*$ and LGMatmpi-$*$, and between LGMatmctl-$*$ and LGMatmpi-$*$ are only $-0.3\,\mathrm{mmol\,m^{-3}}$ and $0.8\,\mathrm{mmol\,m^{-3}}$, respectively (Fig. 7o). On the other hand, N_2 fixation shows contrasting responses across the simulations. Relative to PIctl-$*$, it decreases by $19\,\mathrm{Tg\,N\,yr^{-1}}$ in LGMatmpi-$*$, but increases by 20 and $18\,\mathrm{Tg\,N\,yr^{-1}}$ in LGMatmws-$*$ and LGMatmctl-$*$, respectively. This indicates that, in our experiments, the glacial-interglacial changes in the DIC inventory are dominated by the lower temperature, while N_2 fixation is also sensitive to the changes in the physical conditions.

Across all biogeochemical conditions, our LGM configurations have lower pCO_2 by -35, -21, and -19 ppm in LGMatmctl-$*$, LGMatmws-$*$, and LGMatmpi-$*$, respectively. Thus, the LGM wind pattern and moisture diffusivity over the Southern Ocean contribute about 16 ppm, similar to the 19 ppm drawdown of pCO_2 owing to the lower temperature. We also notice that the effects of the biogeochemical configurations depend on which physical configuration they are combined with and vice versa. For example, pCO_2 decreases by 0.8 ppm from PIctl-PIallbgc to PIctl-LGMallbgc, by 9.3 ppm from LGMatmctl-PIallbgc to LGMatmctl-LGMallbgc, by 34.2 ppm from PIctl-PIallbgc to LGMatmctl-PIallbgc, and by 42.7 ppm from PIctl-LGMallbgc to LGMatmctl-LGMallbgc. This non-linear interaction between physical circulation and biogeochemical processes is consistent with previous studies showing that the glacial pCO_2 drawdown arises from the combined and often synergistic effects of ocean circulation changes and biological processes such as Fe fertilisation (Tagliabue et al., 2009; Buchanan et al., 2016)."

Line 103: Why was higher moisture diffusivity chosen, and how does the wind pattern differ? An explanation is required here.

Reply: We have added the information in the text. We also added a new figure in the supplement to show the difference in the wind pattern. We actually applied a 'lower', not 'higher' moisture diffusivity over the Southern Ocean and apologise for this mistake in the text.
The revised sentences are "Besides the different orbital parameters, LGM conditions, including the strength of the AMOC, likely also deviated from the pre-industrial era by a lower moisture diffusivity over the Southern Ocean and a different wind pattern (Muglia and Schmittner, 2015; Muglia, Skinner, and Schmittner, 2018). We adopt these forcings from Somes et al. (2017) and Muglia and Schmittner (2015) to investigate their influence on the marine biogeochemistry and carbon cycle. Specifically, meridional moisture diffusivity over the Southern Ocean was reduced by a factor of 2, and the wind stress patterns are from monthly average of models which participated in PMIP3 (Fig. S1)."

Line 315: No influence of winds? That is surprising. Providing some explanation would be useful here.

Reply: The original sentence was trying to say that the LGM wind and moisture diffusivity forcings have much weaker effects on NPP than the lower temperature. We now rewrote the sentence and explicitly mention the effect on NPP: "Compared with the effect of the lower temperature, switching to LGM moisture diffusivity and wind patterns has only relatively small effects on NPP. Compared with LGMatmpi_$*$, NPP increases by $1.3\,\mathrm{Pg\,C\,yr^{-1}}$ ($3\,\%$) and $0.4\,\mathrm{Pg\,C\,yr^{-1}}$ ($1\,\%$) in LGMatmws_$*$ and LGMatmctl_$*$ simulations, respectively."

Lines 386–387: This statement appears somewhat speculative. A supporting time series figure could help substan-

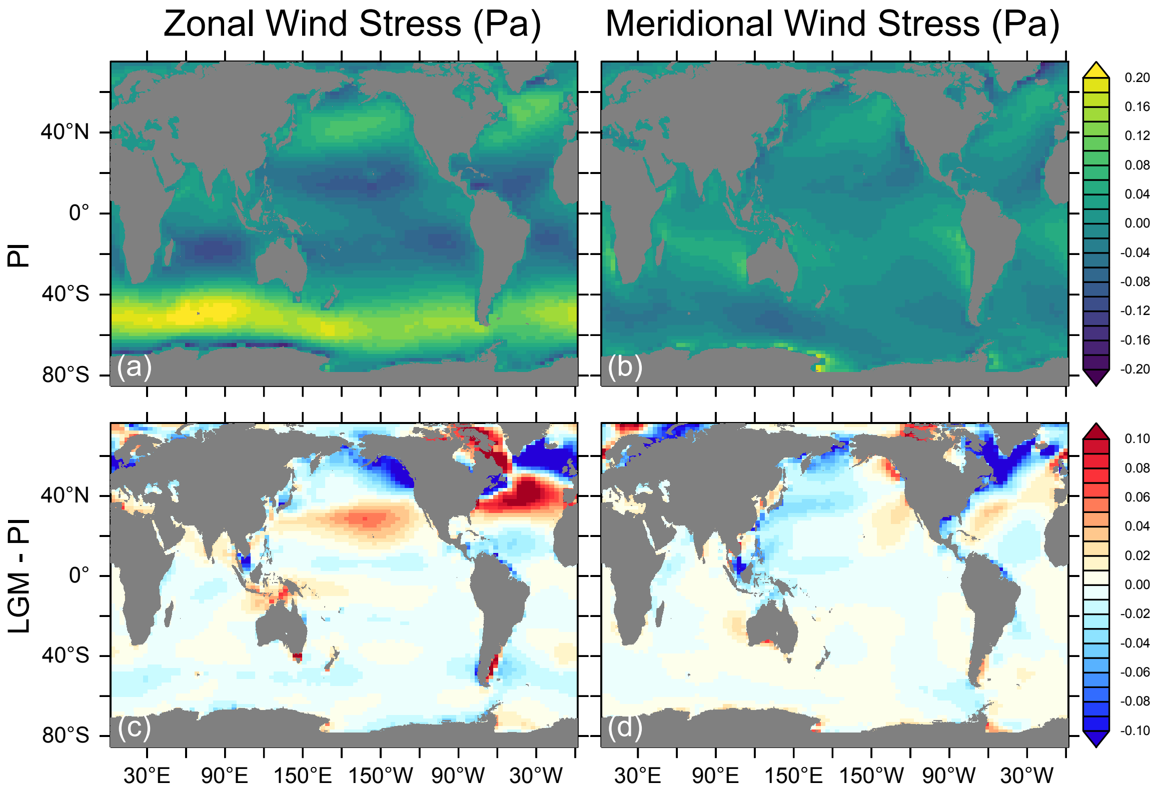

Figure S1: Zonal and meridional wind stress in the pre-industrial condition (a, b), and the differences between the LGM and pre-industrial conditions (c, d).

tiate this claim.

Reply: We thank the reviewer for this very important comment. We recognise that our original argumentation was not sufficiently accurate. We find that, within the first 10 years of the spin-up, NPP and POC export under LGM biogeochemical conditions already decrease and approach their equilibrium levels. The lower atmospheric pCO_2 in the $*$_LGMallbgc simulations compared to $*$_PIallbgc is therefore primarily driven by the redistribution of surface DIC and the associated changes in global air–sea CO_2 fluxes before equilibrium is re-established. To clarify this point, we have added a figure (Fig. S4) showing the air–sea CO_2 flux in PIctl_LGMallbgc, PIctl_PIallbgc, and their differences.

Specific comments:

Line 27: "Last Glacial Maximum" (LGM).

Reply: Fixed.

Lines 27-30: It would be worth mentioning the low CO_2 values explicitly, including how much lower they were and

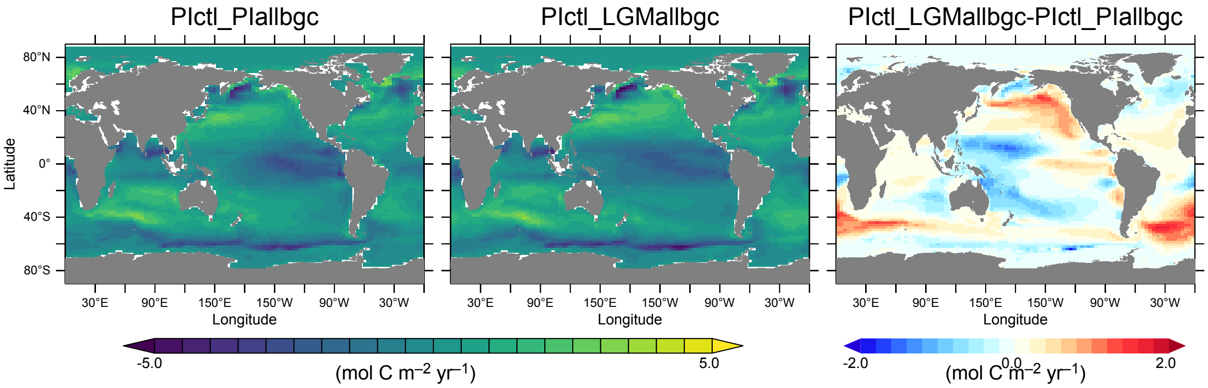

Figure S4: Air-sea CO_2 flux (positive downwards) in PIctl_PIallbgc (a), PIctl_LGMallbgc (b), and the difference (c).

compared to which baseline.

Reply: We added ”..., around 90 ppm lower than the pre-industrial (Monnin et al., 2001), ...”

Lines 30-31: Relevant references should be added for these processes (lower SST and higher solubility). The same applies to orbital parameters mentioned in Line 101.

Reply: We added Jaccard and Galbraith (2012) for lower SST and higher solubility during the LGM, and Weaver et al. (1998) for the effects of changes in orbital parameters.

Line 104: How was a 120 m lower sea level configured while keeping bathymetry the same? Since bathymetry is an important LGM-specific parameter (e.g., Nickelsen et al., 2015; Somes et al., 2017), some clarification would be useful.

Reply: The 120 m lower sea level was not implemented through an explicit modification of model bathymetry. Instead, it was represented diagnostically in the parameterizations of benthic processes. Specifically, we excluded benthic denitrification and sedimentary Fe input in regions shallower than 120 m relative to the pre-industrial sea level, thereby mimicking the exposure of continental shelves under LGM conditions. All other physical and biogeochemical processes were computed using the same bathymetry as in the pre-industrial control simulation. This approach allows us to isolate the impact of shelf exposure on benthic fluxes without introducing additional changes to ocean circulation or ecosystem structure that would arise from a fully modified LGM bathymetry. We have now included this information in the text.

Line 121: Typo ”the”.

Reply: Removed.

Line 126: Last how many years?

Reply: We use the last one year. Now it is ”...from the last one year of ...”

Line 180: I may have missed the definition of ’*-’ used from here onward? What does it denote?

Reply: ’*-’ stands for all physical boundary conditions, we have added the definition when it appears for the first time.

Section 3.1: Why is LGMFedep compared first with PIallbgc? Would it not be more appropriate to first compare it with one of the LGM simulations to isolate the impact within the same climatic background?

Reply: You probably refer to Section 3.3.1 here. Our choice in this respect is meant to emphasise differences between LGM and pre-industrial conditions. We think that also comparing all biological conditions within the same physical condition at this place is not warranted, and we thus decided to compare each biological condition across all physical conditions, and vice versa. We have included this information in the first paragraph of Section 3.2: ”We then evaluate the effects of different biogeochemical conditions across physical conditions, and vice versa, on marine biogeochemical inventories and atmospheric pCO_2.”

Line 344: Typo ”Wighting”

Reply: Corrected.

Line 455: It would be worth mentioning the range of decline reported in other models and experiments.

Reply: We respond to this suggestion together with the next one.

Line 457-461: Why is this not compared with the previously simulated (and rather large) range of CO_2 drawdown from increased iron deposition?

Reply: We have included the values simulated by the cited references. We also found the sentences are not accurate since there are changes also in other boundary conditions. We have revised the sentences to ”Some earlier experiments using Earth system models were able to generate a larger decline in the pCO_2 (-64 to -84 ppm, Ödalen et al., 2020; Vollmer, Ito, and Lynch-Stieglitz, 2022; Matsumoto, Rickaby, and Tanioka, 2020). However, these model experiments only consider the increase in atmospheric Fe deposition but not the decline in the supply from the sediment, which was included in our $*$_LGMallbgc conditions. When considering only the effects of Fe deposition, the average pCO_2 in the LGMatmctl_LGMFedep simulations is 63 ppm lower than in PIctl_PIallbgc, i.e., 20 ppm more than for LGMatmctl_LGMallbgc. Further, different parameter combinations also affect the changes in pCO_2, e.g., the maximum pCO_2 drawdown in LGMatmctl_LGMFedep is 75 ppm (Fig. 7x), which is close to the observations. It is worthwhile to mention that increased Fe deposition alone reduces atmospheric pCO_2 by 22.7 ppm from PIctl_PIallbgc to PIctl_LGMFedep, which is close to the changes in other model experiments considering only LGM dust deposition under pre-industrial climate conditions (14 – 22.8 ppm, Nickelsen and Oschlies, 2015; Ödalen et al., 2020; Matsumoto, Rickaby, and Tanioka, 2020).”.

Line 460: It would be worth referring to a figure here.

Reply: We refer to Fig. 7x for the 75 ppm draw down in pCO_2.

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