

Comment for “Impact of iron fertilisation on atmospheric CO₂ during the last glaciation”

Saini and co-author present nice modelling study of glacial carbon changes at 70 ka BP. The authors investigate, using a range of factorial analyses, the impacts of iron input and increased efficiency of biological pump in the glacial ocean. They simulate an upper limit for the CO₂ decrease due to iron fertilization of 21 ppm. 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.

We thank the reviewer for their positive appraisal of the manuscript. The following comments have now been addressed.

I have one concern that require revision. The author showed that an exponential decay response of CO₂ decrease to iron input to the Southern Ocean (SO) is due to the saturation of the biological pump. I agree with this conclusion, but some descriptions of the reason why the efficiency of the biological pump saturates in response to iron inputs are missing. As a result of the saturation of the increase in EP/NPP in the SO in response to the iron input, has the efficiency of the biological pump also saturated? For example, please add figures for changes in EP/NPP in SO in response to iron inputs in SO to Figure 4 and describe the nonlinear response of the ecosystem to changes in iron inputs.

We thank the reviewer for this comment. We have taken the helpful suggestion of including a scatter plot of EP/NPP to show the non-linear response of Southern Ocean ecosystems to iron fertilisation. For low iron levels, EP/NPP increases sharply with increasing iron. However, at high iron levels, further iron input only increases EP/NPP marginally (Fig.R1a, now included in the Appendix as Figure A8a).

The saturation of the efficiency of the biological pump is also indicated by changes in P* as a function of iron input (Figure 4c). P* represents the ratio of regenerated phosphate over total phosphate. Fig. 4c shows that at high iron levels, further iron input only marginally impacts P*. The explanation behind the saturation in P* is included in the modified text at the end of the response to this comment.

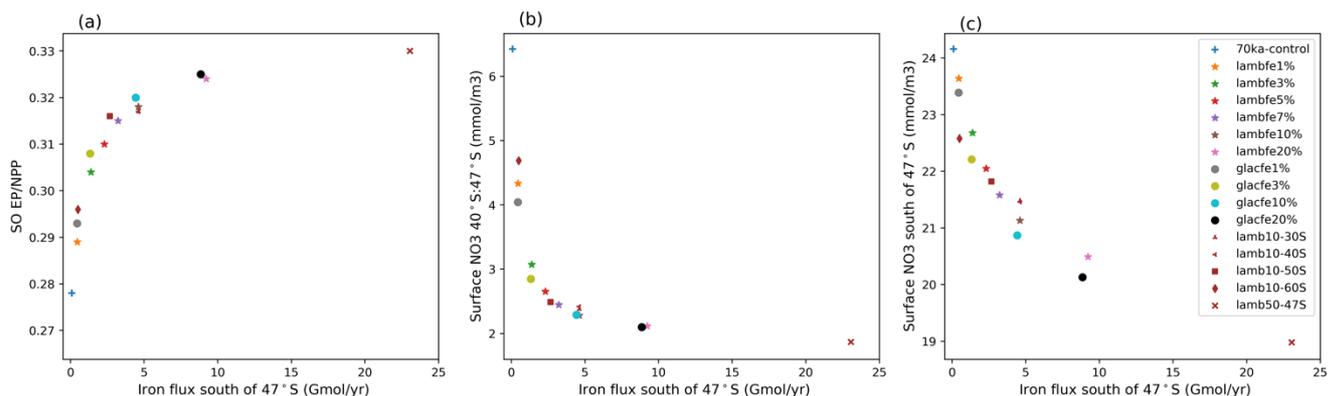


Fig.R1 (a) Ratio of EP to NPP averaged over the Southern Ocean (south of 30°S), (b) surface nitrate concentration averaged over 40°S:47°S (mmol m⁻³), and (c) surface nitrate concentration south of 47°S (mmol m⁻³) as a function of the aeolian iron flux (Gmol yr⁻¹) into the Southern Ocean south of 47°S.

It would also be important to add a similar figure for changes in nutrient concentrations to show changes in nutrient cycling with iron fertilization. In the case of large iron flux (e.g. *lambre50%-47S*), does the ecosystem response saturate due to nitrogen depletion instead of iron? I think these descriptions would be useful to the reader.

We are now including an analysis of the factors limiting the growth rate of diatoms and coccolithophores in the Southern Ocean.

Photosynthesis in this model is calculated by multiplying the concentration of the phytoplankton functional type in question with the minimum of three/four terms which are light, nitrate and phosphate for coccolithophores, and additionally silicate for diatoms (Equations 13-16 in Kvale et al., 2021). Please note that nitrate limitation depends on nitrate concentration scaled by iron availability and ocean temperature (Equations 3 and 5 in Kvale et al., 2021). The same is true for phosphate and silicate limitation. The light limitation includes light attenuation by plankton biomass and sea ice cover (Equation 12 in Kvale et al., 2021) and is also scaled by temperature and iron availability (Equation 9 in Kvale et al., 2021). In Fig. R2 and R3 we show Hovmöller diagrams showing the seasonal evolution of the proportion of ocean grid cells at each latitude band that are limited by each of these factors for diatoms and coccolithophores in our simulations.

At low iron levels (our 70ka-control run, Fig. R2, added as Figure A9 in the manuscript), light limits the growth of coccolithophores and diatoms south of $\sim 75^{\circ}\text{S}$ throughout the year (Fig. R2a, c), while nitrate limits the growth of these plankton functional types in more than 80% of the cells north of $\sim 40^{\circ}\text{S}$ (Fig. R2b, d). In the band between $\sim 40^{\circ}\text{S}$ and $\sim 75^{\circ}\text{S}$, the limitation moves back and forth between light and nitrate for coccolithophore growth (Fig. R2a, b) and between light, nitrate, and silicate for diatom growth (Fig. R2c-e). Phosphate only limits the plankton growth in the 70ka-control run for a very short time at the northern boundary of our region of interest ($\sim 20^{\circ}\text{S}$). We therefore concentrate on nitrate and silicate in our analysis.

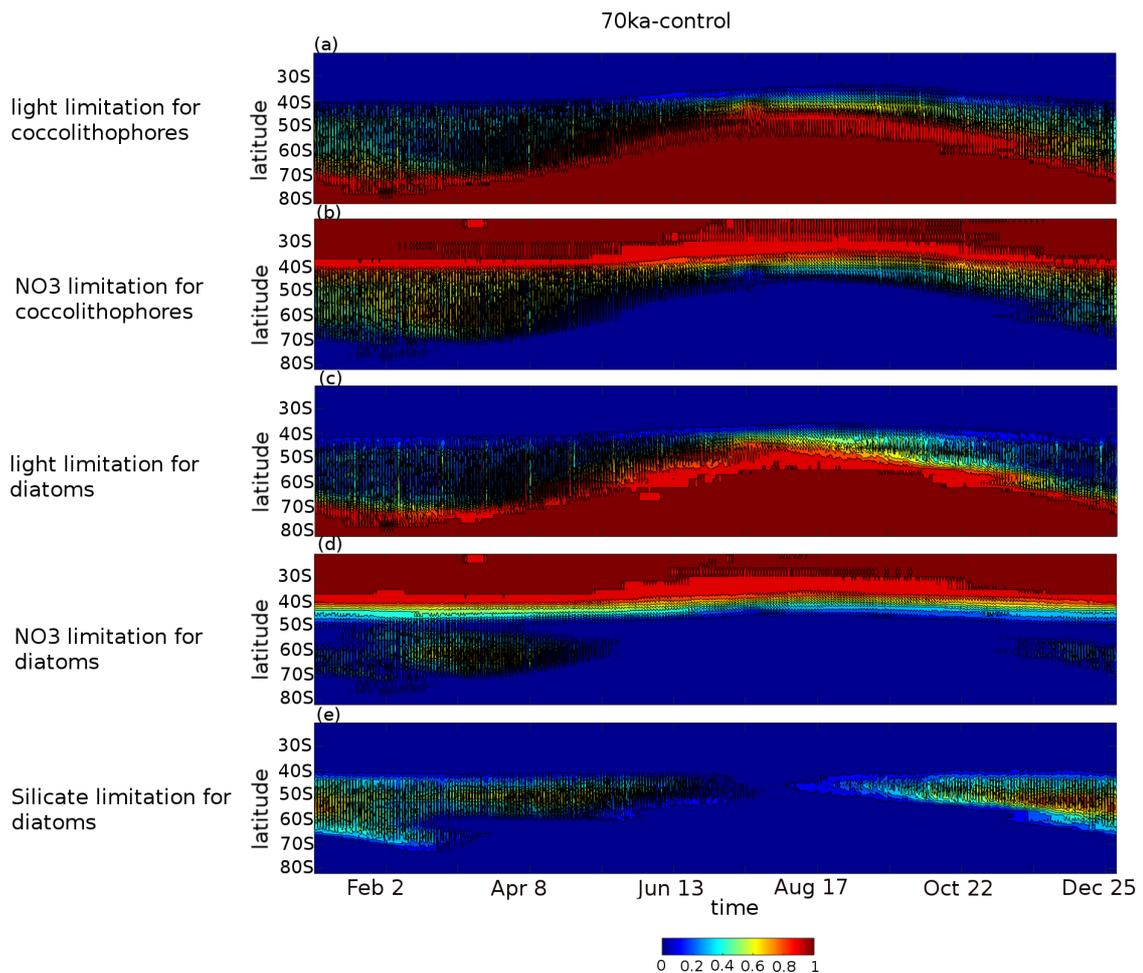


Fig.R2: Hovmöller diagrams of the proportion of ocean grid cells per latitude band for the 70ka-control experiment for which (a) light is limiting coccolithophore growth (b) nitrate is limiting coccolithophore growth, (c) light is limiting diatom growth (d) nitrate is limiting diatom growth, (e) silicate is limiting diatom growth. In all the subpanels, if shade=1, then all ocean grid cells at that latitude band are limited by the respective limiting factor, if shade=0.5, then half of them are.

To illustrate the changes occurring as more iron is added into the Southern Ocean, we show the changes in the proportion of ocean cells limited by each factor in experiment *lambfe20%* compared to the 70ka-control (Fig. R3, added as Figure A10 in the manuscript). The region between 40°S and 50°S becomes significantly more nitrate limited for both coccolithophores and diatoms in the *lambfe20%* experiment (Fig. R3a, b). With higher iron availability, NPP and export production south of 47°S increases, using nutrients more efficiently (Fig. R1c, now added as Figure A9c in the appendix) and reducing the northward nutrient advection (Fig. R1b, now added as Figure A9b in the appendix). At the same time silicate limitation for diatoms decreases in this region (Fig. R3c). This is because, as the iron flux increases, both coccolithophores and diatoms shift southward leading to a decrease in diatoms between 40°S and 55°S. This further enhances silica availability in this region, consequently leading to a decrease in silicate limitation.

We also show the proportion of ocean cells that are limited by either of the macronutrients (nitrate or phosphate for coccolithophores; and nitrate, phosphate, or silicate for diatoms) in Fig. R3d and e.

In this figure we see that the overall nutrient limitation between $\sim 40^{\circ}\text{S}$ and 50°S increases in the high iron flux experiment compared to 70ka-control.

Therefore, in agreement with the reviewer's comment, we now state that the saturation in the biological pump is indeed due to nitrate limitation in the northern band of the Southern Ocean as the iron fluxes increase.

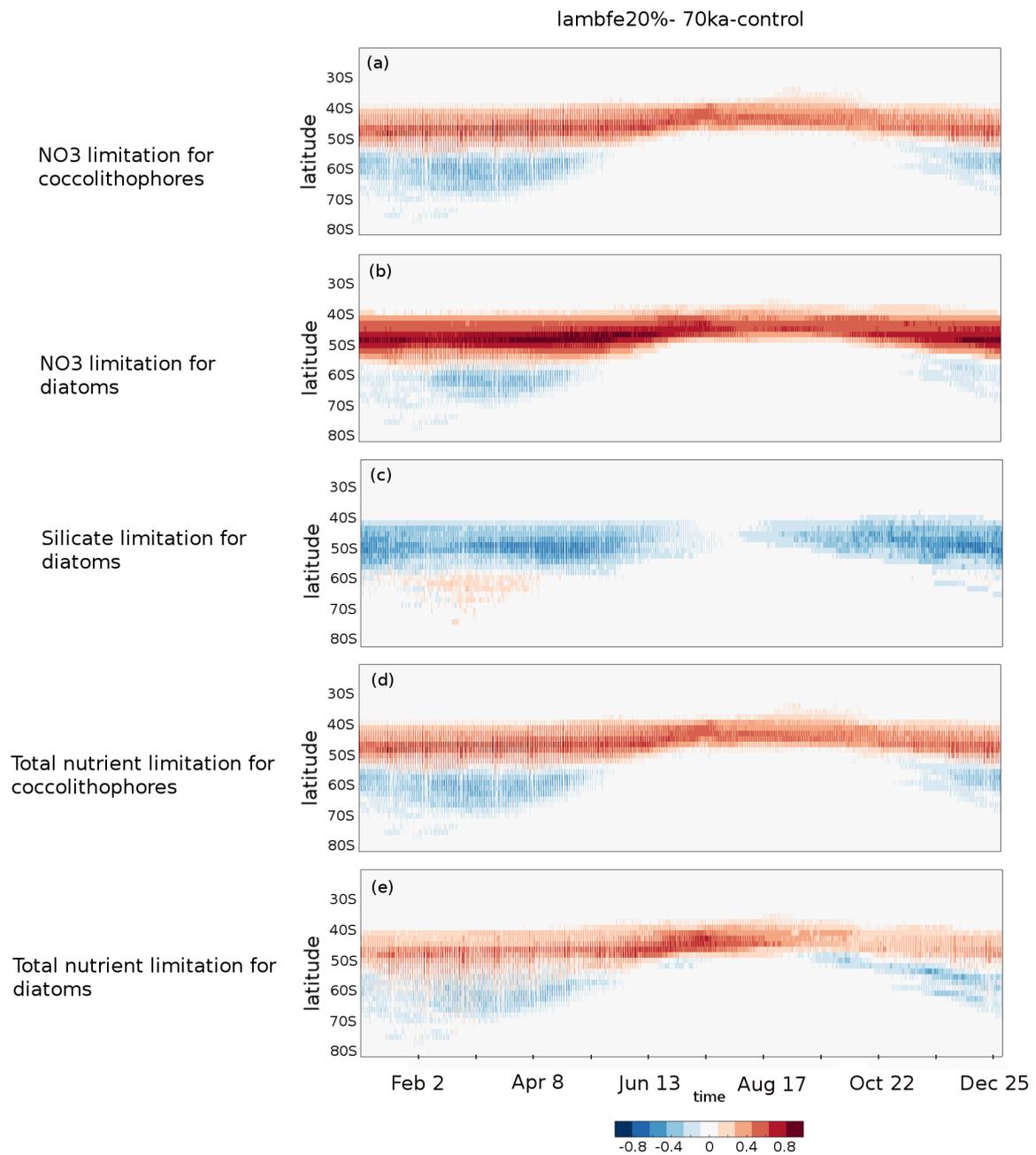


Fig.R3: Hovmöller diagrams of the lambfe20% minus 70ka-control anomaly in the proportion of ocean grid cells per latitude band for which (a) nitrate is limiting coccolithophore growth, (b) nitrate is limiting diatom growth, (c) silicate is limiting diatom growth, (d) either of the macronutrients is limiting coccolithophore growth and (e) either of the macronutrients is limiting diatom growth.

We now include this information as the following text and as Figures A9 and A10 respectively.

Lines 244-253

However, as the Southern Ocean iron flux increases, the overall iron fertilisation efficiency reduces. While export production increases south of 47°S, thus using nutrients more efficiently (Figure A8c) and reducing the nutrient advection north of the SAF (Figure A8b), nitrate limitation increases in the sub-Antarctic zone (Figure A9b, d and Figure A10a, b), leading to a decrease in export production. For example, in experiment $\lambda_{\text{bfe}}20\%$, a 67% decrease in nitrate concentration is simulated between 40°S and 47°S (Figure A8b). At the same time, silicate limitation decreases in the sub-Antarctic zone (Figure 9e and Figure A10c) due to a southward shift of both coccolithophores and diatoms and a decrease in diatoms between 40°S and 55°S (Figure A11). This further enhances silica availability in this region, consequently leading to a decrease in silicate limitation. Therefore, the total biological pump efficiency, represented here by changes in P^* (Figure 4c) and Southern Ocean EP to NPP ratio (Figure A8a), saturate at high iron values due to nitrate limitation north of 50°S in the Southern Ocean. The global P^* in $\lambda_{\text{bfe}}20\%$ and in $\lambda_{\text{bfe}}50\%$ -47S (Figure 4c) equal 0.63 and 0.65 respectively, suggesting a maximum efficiency of 65% in our experimental set-up.

Minor comments

L174-175: It is interesting result that even though the two iron deposition patterns are very different, the effect on CO₂ lowering is almost the same for the two patterns. Please add an explanation as to why the Weddell Sea convection would result in smaller changes in CO₂ for the different iron deposition patterns.

We thank the reviewer for this suggestion. Deep convection in the Weddell Sea makes this region slightly more efficient at drawing down atmospheric CO₂. We have added the following sentences:

Lines 214-219:

The glcfe mask is however slightly more efficient in drawing down atmospheric CO₂. The iron flux into the South Atlantic sector is higher in the glcfe mask compared to the λ_{bfe} mask, increasing iron concentrations near one of our major convection sites in the Weddell Sea. Bottom water formation in this region leads to greater mixing with deeper layers, replenishing surface nutrient concentrations and resulting in higher export production (Marinov et al., 2006). Global P^* is ~1.5% higher in our glcfe experiments than in our λ_{bfe} experiments resulting in a slightly larger CO₂ drawdown.

We are also making this clearer in the discussion.

Lines 348-351:

The experiments using the glcfe mask are slightly more efficient in drawing down CO₂. One of the major Antarctic Bottom Water formation sites is located in the Weddell Sea in our simulations, making the South Atlantic sector a more efficient region for carbon sequestration. Higher iron dust input in the Weddell Sea in the glcfe experiments thus leads to greater CO₂ drawdown compared to the λ_{bfe} experiments.

L286-287 Where is this information described in the method? I couldn't figure it out, so please let me know.

This information is described in Section 2.2, 1st paragraph.