Response to egusphere-2023-2525 RC1

Below is our point-by-point response to RC1. Referee #1's comments are in *gray italic*. Our responses are in black. Expected manuscript revisions are indicated in blue.

General comments:

The paper of Pasquier et al. investigates the future changes of the ocean's biological and preformed carbon pumps by 2090s under two emission scenarios (RCP4.5 and RCP8.5) using a simple model biogeochemistry model and steady-state ocean circulation transport matrix models. They present a new partitioning of preformed DIC to separate the contributions of different pathways of preformed DIC to the ocean carbon storage and outgassing. Using this data-constrained model approach, they found that biological production declines only modestly in the future, while organic matter export declines more significantly due to the reductions in both biological production and export ratio.

The paper is well-written with clear figures and presents interesting results on the biogeochemical cycling and biological carbon pump. I only have specific minor comments and questions detailed below:

We thank Referee #1 for their positive general comments.

- *The authors highlight the fact that the model results are to some extent imprinted by unrealistic circulation features of the ACCESS1.3 model, especially in the Southern Ocean and the deep ocean. The sensitivity of the results to the choice of this peculiar model should be more emphasize.*

We agree that these features have important effects on the ocean carbon cycle, as we point out throughout the manuscript. Without direct comparison with other circulation models it is difficult to quantify the sensitivity. While deep convection that reaches to the bottom in the Southern Ocean is unrealistic, this turns out to be the ACCESS1.3 mechanism for forming AABW, and ACCESS1.3 reduces AABW formation in the future. Reduced AABW formation in the future is a feature that is robust in the sense that it is seen in a number of models and it is also supported by recent observations (de Lavergne et al., 2014). We therefore expect the large-scale changes we document not to be particularly sensitive to the fact that AABW is formed through unrealistic means. In response, we will add to the Discussion something along the following lines:

> While the ACCESS1.3 model has unrealistically deep convection in the Southern Ocean, this deep convection forms much of the model's AABW (Bi et al., 2013), and the future reduction in AABW seen here is robust across different models and also expected from recent observations (de Lavergne et al., 2014). We therefore do not expect our results to be particularly sensitive to this unrealistic model feature.

- *This study does not account for the potential changes in the oceanic circulation and stratification due to melting of ice sheets, which could alter the ventilation and storage of carbon in the deep ocean. If this were the case, would it result in different behavior of the biological production or organic matter export?*

Referee #1 is correct that ACCESS1.3 does not model meltwater input from terrestrial ice sheets (as is the case for most climate models, as far as we are aware). We agree that melting ice sheets will have significant effects on biological production and organic-matter export through major changes in the global circulation (Li et al., 2023; Purich et al., 2018). While we cannot give a definitive answer, we would expect the effect from ice-sheet meltwater to exacerbate the reduction in future Southern Ocean ventilation (this was the case for meltwater experiments using the ACCESS-ESM1.5 model in the SSP5-8.5 scenario; (Purich & England, 2023)). In response, we will add to the Discussion something along the lines of:

> We note that while the parent ACCESS model includes effects from sea-ice melting on the ocean circulation, it does not include melting terrestrial ice sheets. If meltwater from ice sheets were included, we would expect a stronger reduction in Southern Ocean ventilation (Purich et al., 2018, 2023; Li et al., 2023). This could in turn strengthen the already dominating role of the circulation in driving changes in the biological and preformed carbon pumps discussed here.

- *Why focusing on the RCP4.5 and RCP8.5 scenarios? This has to be justified.*

We chose the RCP8.5 scenario simply because, of the commonly studied and available future scenarios, it provides the strongest perturbation of the ocean state and hence a very clear signal for us to quantify. Adding the more likely intermediate RCP4.5 scenario allowed us to quantify sensitivity to future scenario by additionally studying a more realistic perturbation. In response, we plan to add the following to Section 2.1 (Ocean Circulation Models):

> We use the Representative Concentration Pathway RCP8.5 (which represents the worst-case scenario for future global warming; Meinshausen et al., 2011) because it provides the strongest perturbation, along with the more likely, intermediate RCP4.5 to assess the sensitivity of our results to climate-change scenario.

- *What are the implications of prescribed pCO2 concentrations for the simulation? It would have been interesting to account for the feedbacks between the ocean carbon cycle and the atmospheric pCO2 concentration, which may affect the future evolution of the preformed DIC.*

The implications for our simulations are that changing the prescribed atmospheric $p\mathrm{CO_2}$ has a negligible effect on everything except the preformed DIC pipes. While we agree that the feedbacks on atmospheric $p\mathrm{CO_2}$ are important (and has been the subject of previous work by the authors, e.g., Holzer et al. (2021)), they are out of the scope of our study.

If the total (i.e., ocean + atmosphere) carbon inventory were prescribed at its 2090s levels — instead of prescribing atmospheric $p\mathrm{CO_2}$ — then most of the carbon would ultimately end up in the ocean because of the buffer factor, resulting in an atmospheric $p\mathrm{CO_2}$ close to its preindustrial value. Furthermore, the prescribed atmospheric $p\mathrm{CO_2}$ does not affect anything other than the mean preformed DIC concentration. For example, we found that prescribing pCO_2 = 360 µatm (the mean 1990s value, which differs from the preindustrial 270 µatm used here) for our preindustrial state merely shifts DIC concentrations up by the same amount at every location. This uniform shift in DIC would have little effect on our results because no process in the ocean interior depends on the global mean DIC concentrations. This is demonstrated by the following unpublished figure of global-mean tracer profiles (see the yellow and green lines, for which we used the preindustrial circulation but with different pCO_2 values):

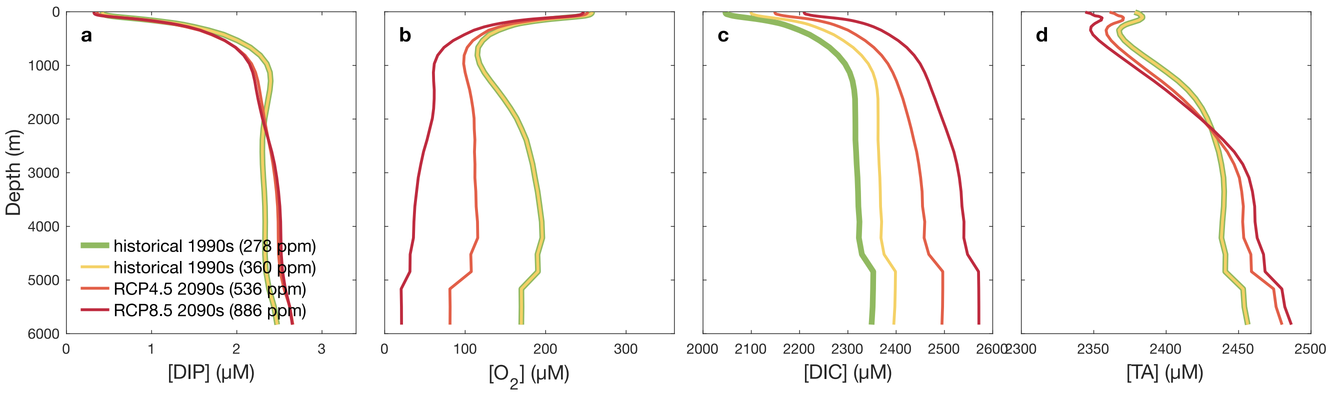

Figure 1: Global mean depth profiles of (a) PO_4, (b) dissolved O_2, (c) DIC, and (d) total alkalinity for the preindustrial state (green and yellow lines) and future states (orange and red lines). Note how the green and yellow lines only differ for DIC (panel c).

In response, we will add something along these lines in the Discussion:

> Note that the changes in prescribed atmospheric pCO_2 dominate the changes in air–sea exchange and strongly affect the flowrates of preformed DIC through ingassing and degassing. Hence, the flowrates of the preformed DIC pipes in Fig. 6 would be significantly different if we had prescribed the total (i.e., oceanic plus atmospheric) carbon inventory instead of only the atmospheric carbon inventory.

- *I found the description of the preformed carbon pump and how it differs from the solubility pump a bit confusing. I think it could be clarified.*

We will clarify the distinction in the Introduction to read something similar to (addition in bold):

> To comprehensively track all carbon through the ocean, we quantify future change in terms of the biological carbon pump and in terms of what we call the preformed carbon pump. A quantification of the preformed pump is made possible by a novel partition of preformed DIC according to its sources and sinks. The preformed pump can be regarded as the solubility pump, although the latter term is often used specifically for the subduction of DIC driven by solubility gradients (e.g., Volk and Hoffert, 1985). **The preformed pump defined here allows us to track all preformed DIC back to its source when**

> **atmospheric CO2 entered the ocean, when organic matter was remineralized in the surface ocean, or when aphotically regenerated DIC resurfaced. In addition, we track preformed DIC forward to its sinks, when it will degas back to the atmosphere or be utilized biologically.** In this way we quantify the timescales and flow rates (the "plumbing") of not just the biological pump but also of the preformed pump, as well as the interaction between these pumps and the atmosphere and how these change in the future under idealized steady-state scenarios.

- *As explained by the authors, the effect of iron on phytoplankton growth is not included in this study to avoid complexity. How would it change the presented results if it was taken into account? (i.e. does it have an important role?)*

It is difficult to answer this question quantitatively without explicitly modelling the iron cycle, which is out of the scope here. However, our PCO2 model captures the global patterns of iron limitation in the late 20th-century ocean because the model was optimized against observed nutrient concentrations (Pasquier et al., 2023), which are partly controlled by the iron cycle. In addition, we expect that future changes in the global iron supply will not play a significant role in the carbon cycle (Tagliabue et al., 2014). Iron deposition and its effect on biological production are predicted to be order 10% by 2100 for RCP8.5 with strong spatial variations and compensations (Drenkard et al., 2023; Liu et al., 2024). For example, Liu et al. (2023) did not report any biological-pump effect from changes in the iron cycle (even though the CESMv1 model used includes iron). Thus, while the iron cycle could change dramatically on very long timescales, it is reasonable to assume that its effects would be dominated by the large effects from circulation changes as considered here in our steady-state analysis. No change expected.

Other comments:

L6: "experiences only modest declines". Precise how much.
We will add "8–12 %".

L8: the latter being driven
"being" will be added.

L19: In recent decades,
Comma will be added.

L30: …pump, preindustrial atmospheric pCO2 concentrations
Comma after "pump" will be added and "p" will be added to read "pCO_2".

L55: remove the brackets of the sentence. Same at L77-78, L90-91, L128-129, L132, L258-259, L320-321, L375-376, L452-453 and in the caption of Figure 4.
We agree that too many parentheses reduces readability. However, we think that some of our parenthetical sentences should remain parenthetical to make it easy for the reader to identify details that could be skipped on a first reading. We will defer to the Editor, but the changes we expect to apply are:

- L55: OK
- L77-78: OK
- L90-91: OK

- L128-129: no change
- L132: OK
- L258-259: OK
- L320-321: OK
- L375-376: no change
- L452-453: OK
- caption of Figure 4: OK

L66-71: this paragraph has to be removed from the introduction since it is about the results of the study.
We agree that this paragraph can be removed, and we will do so in the revisions. We would like to note, however, that this type of "upshot paragraph" is fairly commonplace and often gives a useful preview of essence of the paper. Whether to include an upshot paragraph or not is mostly a matter of style. In this instance, we agree that it is not necessary.

L80: atmospheric pCO2. Same at L93.
L80 is correct as we are talking about the CO_2 mixing ratio. No change expected.
L93 is also correct. However, as suggested by Referee #1, we will change "atmospheric CO_2 concentrations" to "atmospheric pCO_2" here.

L105-106: precise the reference used to choose the parameters of the PCO2 model
The choice of parameters in the PCO2 model was described in detail in our previous study (Pasquier et al., 2023). We will add the reference in the manuscript.

L112: …which in steady state obeys:
No punctuation here is not incorrect and a matter of house style, which we leave for the copy editor to decide. No change expected (unless required by copy editor).

L133: the ocean through pCO2 air-sea exchange
Partial pressures are not exchanged, CO_2 molecules are. No change expected

L138: Note that in our model, carbon
Comma will be added.

L156: "the exact same concentrations as traditionally defined preformed DIC". This has to be precised. What are these concentrations? How are they chosen?
Note that the traditionally-defined preformed concentrations are described in the previous sentence. For clarity, we will change to "as obtained from the traditional propagation approach".

L178: what are the main mechanisms
This sentence is intended as a signpost to guide the reader by indicating what comes next, including a description of these main mechanisms. No change expected.

L183: remove merely
OK.

L186: "the more sluggish circulation". Precise the sentence with value for the circulation.
There is no unique metric for circulation sluggishness. The point here is that biological production declines together with the nutrient supply, and that this decline is expected given that the circulation is slower in our future states than in the preindustrial. In this paragraph we report the nutrient decline in the euphotic zone and then discuss its drivers. Adding a metric of the circulation change here would distract from the main point. Such a metric would need to be explained and motivated, e.g., justified through its relation with mean euphotic nutrient concentrations, which is so much detail that it would derail our argument. Having said this, to give you an idea of how much the deep circulation slows down, the mean age and mean reexposure time change by up to 600 and

1200 years for the RCP4.5- and RCP8.5-based states, respectively (see Fig. C3 in this manuscript or the workd of Holzer et al. (2020)). No change expected.

L186: decline by 12 and 19 % for the two scenarios compared to the preindustrial
For readability, we avoided repeating "compared to the preindustrial state" every time when this is clear from context, which we think is the case here. The two-sentence lead paragraph of Section 3.1 includes "We now examine how each of these components change from their preindustrial values". No change expected.

L187-188: "due to the slower future circulation and decreased ventilation". Please give values.
As for first L186 point above, it would be distracting to dive into circulation/ventilation metrics at this stage of the manuscript. No change expected.

L191: for RCP4.5 and RCP8.5 respectively (compared to the preindustrial)
As for point above, we also avoided repeating "respectively" over and over, particularly when unambiguous from the context, as we think is the case here. No change expected.

L191: "although the North Atlantic contains a patch of prominent cooling". Does it have a local effect on nutrient and carbon uptake rates?
Yes, because the nutrient and carbon uptake rates are temperature dependent (Eq. (2)). However, this effect is not widespread enough to impact the global-scale response. No change expected.

L204: RCP4.5 and RCP8.5 respectively
Will add "respectively".

L220-221: in the RCP4.5 and RCP8.5 scenarios respectively, compared to preindustrial. Same in L253.
As for L186 point above, that the changes mentioned are relative to the preindustrial state is obvious from the context. No change expected L220–221. However, for L253, we will add that Table 1 also lists the "corresponding preindustrial-to-future changes" in the preceding sentence.

L230: "do not suffice". Replace by are not enough.
This is correct common-language English. No change expected.

Table 1: Add to the caption "...for preindustrial, RCP4.5 and RCP8.5 scenarios. Variations relative to the preindustrial are also shown".
OK.

L271: remove a priori
OK.

L275: remove such
OK.

L302: and how they change in the future
We will replace "these" with "they".

L303: remove the [t]
OK.

Figure 6: make the dashed rectangle in the left corner more visible for the reader.
OK.

L326: To better understand the transport pathways of preformed DIC, we quantify the amount able to enter
OK.

L328: (not shown in Fig. 6) revealed that regardless of source-sink pair, more
OK.

L357: Italic font may be used for emphasis and used sparingly. Remove the italic style of the word less. Same in L361, 364, 365.

The emphasis usage in this paragraph is important because it brings attention to the subtle and surprising differences between pump strength and pump efficiency as we quantify them here. Italic font is used for emphasis for 5 words out of roughly 15,000 for the whole article. No change expected.

L437-439: remove the sentence to explain the SSP scenarios since it is not useful.

We respectfully disagree that explaining how RCPs match SSPs is not useful, but we agree that this passage is too verbose. We will rephrase succinctly as "(which nominally match RCP4.5 and RCP8.5; Riahi et al., 2017, Arias et al., 2021)".

L461: remove below

OK.

L462: Liu et al. (2023)

We think this is correct usage but will defer to the editor. The "Liu et al." citation without the year is done through the `\citeauthor` command in LaTeX, which is suggested in the publisher's LaTeX template:

```
%% LITERATURE CITATIONS
%%
%% command & example result
%% citet{jones90}| & Jones et al. (1990)
%% citep{jones90}| & (Jones et al., 1990)
%% citep{jones90,jones93}| & (Jones et al., 1990, 1993)
%% citep[p. 32]{jones90}| & (Jones et al., 1990, p. 32)
%% citep[e.g.,][]{jones90}| & (e.g., Jones et al., 1990)
%% citep[e.g.,][p. 32]{jones90}| & (e.g., Jones et al., 1990, p. 32)
%% citeauthor{jones90}| & Jones et al.
%% citeyear{jones90}| & 1990
```

This avoids unnecessarily repeating the year here, which is unambiguous given that Liu et al. (2023) was referenced at the start of the paragraph and that there is only one reference for Liu et al. No change expected unless other Liu et al. references are added.

L484: remove brought to light here

This is appropriate English for what was done in this work. No change expected.

L491: this allows for the first time

This is correct English. No change expected.

L496: with declines of ~10 %, even for RCP8.5. Remove the italic style as well.

Will remove "merely" and add the comma after "10 %". This paragraph contains no italic style.

L500: RCP8.5-based steady-state scenarios respectively, in comparison to preindustrial

Will add "respectively" here but will add "compared to the preindustrial" to the previous bullet point instead.

References: sort the references of DeVries in chronological order.

References are automatically sorted alphabetically by the publisher's LaTeX template. No change expected.

References (including those already cited in the manuscript)

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