Ocean biogeochemical reconstructions to estimate historical ocean CO2 uptake

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Below we provide point-by-point answers to reviewers comments, together with indications of what was changed in the new version of the paper and where to locate these changes. Reviewers comments are in bold and are followed by an "Answer" and a "Changes" sections.

Reviewer #1

<u>Comment:</u> **The manuscript "Ocean biogeochemical reconstructions to estimate historical ocean CO2 uptake" by Bernardello et al is a very useful comparison of different methods of estimating ocean carbon uptake from ocean-only models forced by reanalysis versus also including 3D temperature and salinity data assimilation with direct relevance to the current gap between ocean inverse estimates and "OBGC" or "OMIP" estimates used by the Global Carbon Project. My major criticism is that the authors include only analysis of AMOC and MLD changes and ignore impacts on the thermocline structure, pCO2, and anthropogenic CO2 (GLODAP) observational constraints and impact on ideal age and transient tracers. It is not enough to casually correlate the AMOC increase to the anthropogenic CO2 increase in the data assimilation: the authors should at least look at the pattern differences in CO2 uptake between the various model runs to see where the extra CO2 is accumulating. Below I provide specific places where I think such a quick analysis would substantively improve the manuscript.**

<u>Answer:</u> We would like to thank reviewer #1 for this constructive criticism of the paper. We agree that our analysis fell short of explaining the reasons for the observed changes in CO2 uptake and in general ocean biogeochemistry. We welcome the reviewer's suggestions to provide such an analysis and below we respond point by point explaining how we have addressed the issues raised.

<u>Changes:</u> We have introduced 7 new figures representing changes in the meridional overturning circulation, changes in the ideal age tracer distribution, changes in the anthropogenic carbon accumulation in the interior of the ocean and a comparison between model's estimates of anthropogenic carbon distribution and the observation-based estimate provided by GLODAP. These new figures are described and discussed in the text. Details are given below in response to reviewer #1's specific comments.

<u>Comment:</u> **19-20 - In the sentence "This becomes particularly important in the context of a future decline of global CO2 emissions and the UN Framework Convention on Climate Change stocktaking activities" it is not clear why "a future decline of global CO2 emissions" makes carbon uptake more important than**

under scenarios of future increase. The authors may be intending to call out the 2015 Paris Agreement that seeks climate stability/sustainability and net zero emissions at particular temperature thresholds, but the connection should be explicit.

Answer: We agree that this sentence was not clear at all. We meant that, in a context of declining CO2 emissions, the relative importance of variability in ocean CO2 uptake (induced by natural climate variability) increases with respect to the net uptake of the anthropogenic fraction of CO2. This means that being able to quantify the natural variability becomes relatively more important for the detection and attribution of a changing trend in ocean CO2 uptake, when CO2 emissions decline. We modified the text to make this point clear.

Changes: We have modified the text in the introduction to better explain this point (see lines 19-22).

Comment: 139 – remove "we"

Answer: We have made extensive use of the active form throughout the paper. After careful consideration, we decided that changing to passive form would decrease the readability of the text.

Changes: We haven't substantially changed the use of the active form.

Comment: 209-210 – To answer the question "it is hard to pinpoint a single cause for the improvements we see in biogeochemical variables when we apply data assimilation of temperature and salinity." The classical means of doing so is to look at changes to ideal age and transient tracers like CFC's and SF6. My expectation is that the OMIP version of the model is overly stratified and that the thermocline/warm water sphere is deeper in the assimilation case. While the assimilation increasing AMOC certainly goes in the right direction, I expect it is the enhancement of the shallow gyre circulation of AMOC (rather than the deeper, thermohaline aspect) that is driving the improvement as it applies to all the gyres, not just the North Atlantic. It should be easy to see where the changes in DIC accumulate – whether it is just in the Atlantic below 1000 m (in support of the thermohaline mechanism), or throughout the ocean above 1000 m (in support of the general thermocline ventilation mechanism). These two comparisons should be very easy for the authors to conduct.

Answer: Unfortunately we didn't include CFCs and SF6 in these runs but we do have the ideal age tracer. We have used this tracer to look into the changes in ventilation that occur when applying data assimilation, as suggested. At the same time, we compared simulations to see where the most marked changes in anthropogenic DIC distribution happen within the water column in different regions. Results of this analysis, point to a general deeper penetration of anthropogenic DIC, up to 3000m, in the Atlantic as well as a deeper penetration of DIC in the Southern Ocean at depths compatible with an enhanced formation of Antarctic Intermediate Waters. In the Pacific ocean the accumulation of DIC is shallower, mainly above 1000m depth.

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Changes: We have introduced figures 6 and 7 representing the meridional overturning circulation for the Atlantic, Pacific and Southern oceans. These are described in the result section at lines 183-189 and in the discussion at lines 264-267 and 273-281.

We have introduced figure 8 representing changes in the distribution of the ideal age tracer when applying data assimilation with respect to the omip simulations. This figure is described in the results section at lines 191-196 and in the discussion at lines 264-267.

We have introduced figures 10 and 11 representing changes in the accumulation of anthropogenic carbon when applying data assimilation with respect to omip simulations. These figures are described in the results section at lines 206-214 and in the discussion at lines 269-281.

Comment: 228 – furthering the need to look at the patterns of DIC inventory increase above, more detail on the "ameliorated density profile" is necessary here. For example, it would be helpful if the MLD analysis indicated the direction of the improvement – i.e. it looks like the biases being ameliorated were a deep bias in the northern gyre extension regions and a shallow bias in the Southern Ocean… suggesting that it may be increased ventilation in the Southern Ocean that is the most important. Looking at MLD is certainly a big part of the story, but the relation with the overall ventilated thermocline depth is more relevant to net anthropogenic CO2 uptake.

Answer: The reviewer's interpretation of Figure 7 is correct. A deep bias is reduced in the North Atlantic for ERA5 while for JRA55 the bias reduction goes in the opposite direction, towards correcting a shallow bias. In the Southern Ocean a shallow bias is clearly reduced in the Pacific and Atlantic sectors for ERA5, while the changes for JRA55 are less evident. These changes result in a deeper penetration of DICant in the Southern Ocean while in the North Atlantic, because the omip simulations differ substantially one from the other (ERA5-omip and JRA55-omip), when data assimilation is applied important differences are observed between ERA5 and JRA55.

Changes: We have modified the description of the MLD figure (now fig. 9) to better highlight the direction of the bias reductions (Results, at lines 206-212). We have modified the discussion to link the changes in MLD induced by data assimilation with the changes observed in both ventilation and anthropogenic carbon distribution. These changes are in the discussion at lines 269-281.

Comment: 235 – I don't find the degradation in nutrients and chlorophyll surprising at all as this was the foundational problem in the Park et al., 2018 study the authors cite for their decision to reduce nudging near the equator and is consistent with what I suspect is increasing ventilation under data assimilation increasing surface nutrients and chlorophyll from a baseline configuration in which the BGC parameterizations for phytoplankton physiology and nitrogen and iron limitation were tuned to match observations of high nutrient/low chlorophyll patterns.

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<u>Answer:</u> There is no degradation in nutrients. On the contrary, there is an overall improvement in their distribution. This is one of the main results that was showcased in Figure 4. The reason the reviewer suggests for the insensitivity (or degradation) of chlorophyll to these improved nutrient fields coincides with one of the reasons we propose in the paper (e.g. tuning of the BGC model), together with unchanged iron availability.

<u>Changes:</u> We opted for not changing this part of the discussion

<u>Comment:</u> 255 - I disagree with the assertion that "their direct validation is not straightforward" as it seems very straightforward to compare against the surface ocean pCO_2 product of Landschützer et al (2017):

Landschützer, P., Gruber, N., & Bakker, D. (2017). An updated observation-based global monthly gridded sea surface pCO_2 and air-sea CO_2 flux product from 1982 through 2015 and its monthly climatology (NCEI Accession 0160558), edited, NOAA National Centers for Environmental Information.

And anthropogenic CO_2 inventories of GLOPAPv2:

Lauvset, S. K., Lange, N., Tanhua, T., Bittig, H. C., Olsen, A., Kozyr, A., ... & Key, R. M. (2022). GLODAPv2. 2022: the latest version of the global interior ocean biogeochemical data product. Earth System Science Data Discussions, 2022, 1-37.

<u>Answer:</u> With respect to CO_2 fluxes, with this statement we meant that observation-based air-sea CO_2 flux products also suffer from large uncertainties derived from the limited coverage (spatial and temporal) of the original pCO_2 dataset (SOCATv3) and from different techniques of interpolation. As a consequence, these products are used as an additional line of evidence rather than a benchmark in the Global Carbon Budget (e.g. Friedlingstein et al., 2022). We tried to convey this message by including in Figure 1 the single members of both the model estimate and the obs-based products. The spread around the mean is similar for the two estimates. Additionally, in Figure 2 we show a correlation matrix between the 7 obs-based products from GCB2022 (including Landschutzer et al., 2017) and the model estimates from GCB2022 (besides our simulations). For any model, there is a considerable variability in the value of the correlation coefficient while moving across obs-based products (horizontally), pointing to a large variability among these. Analogously to the practice adopted by the GCB exercise, we decided to evaluate the improvements in surface pCO_2 when applying DA by comparing directly the original point values from the SOCATv3 dataset with the correspondent values in the models, co-located in space and time (Hauck et al. 2020). This comparison is presented in Figure 3.

With respect to DIC, GLODAPv2.2022 is the dataset we have used to calculate the reduction in RMSE when applying data assimilation of temperature and salinity (see Table 2 and Fig. 4). Total DIC is the variable we have used for Fig. 4. In a previous release of GLODAPv2 (Lauvset et al., 2016), a mapped estimate of the accumulated anthropogenic carbon in the year 2002 is provided. We will use this estimate as a reference when analyzing the changes in the distribution of DIC between omip and DA simulations. However, similarly to observation-based products for CO_2 fluxes, the

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estimates of anthropogenic DIC distribution suffer from considerable uncertainties linked to the diversity of methods used to infer them (e.g. Khatiwala et al., 2013).

Changes: We have introduced Figures 12 and 13 showing zonal averages for the Atlantic, Pacific and Indian oceans of the differences in anthropogenic carbon distribution between each simulation and the GLODAP estimate. These figures are described in the result section at lines 216-219 and in the discussion at lines 294-299.

References

Friedlingstein, P., O'sullivan, M., Jones, M. W., Andrew, R. M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I. T., Olsen, A., Peters, G. P., et al.: Global carbon budget 2022, Earth System Science Data Discussions, 2022, 1–159, 2022. https://doi.org/10.5194/essd-14-4811-2022

Hauck, J., Zeising, M., Le Quéré, C., Gruber, N., Bakker, D. C., Bopp, L., Chau, T. T. T., Gürses, Ö., Ilyina, T., Landschützer, P., et al.: Consistency and challenges in the ocean carbon sink estimate for the global carbon budget, Frontiers in Marine Science, 7, 571 720, 2020. https://doi.org/10.3389/fmars.2020.571720

Khatiwala, S., Tanhua, T., Mikaloff Fletcher, S., Gerber, M., Doney, S. C., Graven, H. D., Gruber, N., McKinley, G. A., Murata, A., Ríos, A. F., and Sabine, C. L.: Global ocean storage of anthropogenic carbon, Biogeosciences, 10, 2169–2191, https://doi.org/10.5194/bg-10-2169-2013, 2013.

Lauvset, S. K., Key, R. M., Olsen, A., van Heuven, S., Velo, A., Lin, X., Schirnick, C., Kozyr, A., Tanhua, T., Hoppema, M., Jutterström, S., Steinfeldt, R., Jeansson, E., Ishii, M., Perez, F. F., Suzuki, T., and Watelet, S.: A new global interior ocean mapped climatology: the 1° × 1° GLODAP version 2, Earth Syst. Sci. Data, 8, 325–340, https://doi.org/10.5194/essd-8-325-2016, 2016.

Reviewer #2

Comment: **Bernardello et al. provide model-based experiments showing that constraining ocean physics towards observed temperature and salinity results in a better representation of global biogeochemistry. Two sets of simulations are done: the standard GCB approach, which uses prescribing boundary conditions from atmospheric reanalyses, and the additional assimilation of observed ocean physical variables. Thus the paper shows nicely that the estimate of the ocean CO2 uptake can be more reliable if considering the physical changes of the ocean. I find the paper clearly written and very convincing. I only have some minor suggestions on this work.**

Answer: We thank Reviewer#2 for the time dedicated to reviewing our paper and we detail below the changes we introduced to address the suggestions.

Comment: **Although using EN4 gridded data is ok, the authors might be aware of the problems in EN4 data (e.g., some instrumental biases are not corrected, the gridded fields are shifted to the climatology in data-sparse regions, etc.). Good et al. 2013 actually explicitly stated that the data should be used with caution when**

dealing with long-term changes. Thus, it would be worthwhile to have some discussions, at least in the conclusion section, that, potentially, using a better dataset would have further benefits/improvements. A quite comprehensive description of the data issues for ocean temperature can be found in a recent online reprint (https://essd.copernicus.org/preprints/essd-2024-42/).

Answer: Thanks for pointing this out. We have expanded the discussion and conclusion sections to highlight these potential issues with EN4. The choice of EN4 comes from a long analysis and trial/error attempts to obtain a robust reconstruction that could provide initial conditions for near-term climate predictions. Each product comes with its own problems and advantages and we agree that these need to be better highlighted in our case.

Changes: We have introduced a paragraph in the discussion (lines 283-292) to acknowledge potential limitations of using a specific dataset for interior 3D nudging.

Comment: For the discussion of large-scale circulation, only AMOC is mentioned and discussed, however, ocean circulation is not only that and the other parts are also important for carbon uptake. Please expand the discussion related to other circulation systems such as subtropical gyres,, subpolar gyres, or the water mass formation/transformation.

Answer: We addressed this suggestion with the analysis introduced in response to the main criticism of reviewer#1. We agree that we didn't provide enough insight on the changes in general circulation that are brought by data assimilation and we introduced 3 new figures to show the meridional overturning circulation in different regions and the changes in ventilation highlighted by changes in the distribution of the ideal age tracer.

Changes: We have introduced figures 6 and 7 representing the meridional overturning circulation for the Atlantic, Pacific and Southern oceans. These are described in the result section at lines 183-189 and in the discussion at lines 264-267 and 273-281.

We have introduced figure 8 representing changes in the distribution of the ideal age tracer when applying data assimilation with respect to the omip simulations. This figure is described in the results section at lines 191-196 and in the discussion at lines 264-267.

Comment: Salinity is rarely discussed, how the improved representation of salinity can improve the biogeochemical changes? Any insights would be very useful.

Answer: Salinity can play a critical role (even more than temperature) through its contribution to the large scale density gradients and deep water mixing. For example, in the Labrador Sea, vertical stratification is generally controlled by salinity. So, having the correct salinity is critical to improve the MLD. These are indirect impacts on biogeochemistry as they manifest through changes in the physical/dynamical state of the ocean.

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Changes: We have addressed this aspect with the expansion of the analysis and discussion on the changes in circulation and their effect on CO2 uptake and ocean biogeochemistry in general.

Comment: Fig.6: probably other SST observation data can be added to assess how large the observational uncertainty is.

Answer: We agree.

Changes: We have introduced 2 new SST estimates to figure 14.

Comment: Table 1: why a reanalysis data (ORAS5) is used for SSS? It likely suffers from spurious shifts due to salinity observation system changes over time (i.e., around 2005, from a ship-based system to an Argo-based system).

Answer: The main reason for this choice is that it allows us to make sure that both the SST and SSS fields are physically consistent, which can't be guaranteed when using objective analyses such as EN4. We have discussed this point together with the expanded discussion on the limitations of EN4.

Changes: We have introduced this discussion together with the considerations about using EN4, at lines 283-292.