Reviewer #1

In this paper, Willeit et al detail the implementation of the carbon cycle in the new CLIMBER-X model. They explain the choices made in the atmosphere, ocean, land, and sediments and present results for the modern and historical periods, comparing with existing data. CLIMBER-X is a very promising model. Its rapidity is an asset, as well as the inclusion of many processes relevant for long-time scales, making it a very comprehensive model and a very good alternative to box models to study changes over periods longer than a few thousand years and up to a million years, a deed that more complex models are not capable of.
The paper is well organised and the model description and results well presented. However, the result section remains very descriptive, and it would greatly improve the paper to have more explanation and discussion on differences between model and data, and their potential causes. The simplifications and low resolution of CLIMBER-X are necessary to make it very efficient, but it is also important to have an idea of the limitations, their causes, and the possibilities for future improvements.

We would like to thank the reviewer for the constructive comments and suggestions on our paper. Below we provide a point-by-point response to the individual comments.

l. 29. There is a typo problem in the reference to "Raymo M.E. and Ruddiman W.F., 1992", it should read: "Raymo and Ruddiman, 1992"

Fixed.

Figure 1 (and Figure 3). For the molecules, could you put the numbers of atoms in subscript, such as for CO2,O3... -> CO_2, O_3...

Done.

l.111-112. Why have you modified the stochiometric ratio?

We have slightly increased the stochimetric Fe:C ratio to align with higher values used in other models. The effect of the larger Fe:C ratio is a stronger iron limitation of primary production, as more iron is needed to fix the same amount of carbon. Following the suggestion by reviewer #2 we have added further details on the iron cycle in the model to an Appendix.

l. 127-128. Could you specify the variables involved for photosynthesis

Photosysnthesis depends on absorbed shortwave radiation, air temperature, vapor pressure deficit between leaf and ambient air, atmospheric CO2 and soil moisture. We have added this information to the paper.

l.142. in "The rubisco-limited photosynthesis rate the version of PALADYN model": is there a missing "in"? -> The rubisco-limited photosynthesis rate in the version of PALADYN model

Fixed.

l. 278-280. what is the impact of the simplification?

The impact of organic carbon fluxes with associated nutrients from land to the ocean and organic carbon burial in sediments represent an additional level of complication with relatively little observational constraints. We therefore decided to leave this for a separate study.

Section4.1. When discussing the global values of Table 1 or 2 it would be useful to give the numbers in the text.

Where appropriate, we added some numbers in the discussion when referring to the Tables 1 and 2.

Table 1. The legend could be slightly expanded, e.g. Global values of the main ocean biogeochemical variables for the present-day.

Done. Thanks for the suggestion.

l. 299. which models from CMIP6 are included?

The following CMIP6 models are included for ocean biogeochemistry: CESM2, IPSL-CM6A-LR, MRI-ESM2-0, MIROC-ES2L, MPI-ESM1-2-LR, UKESM1-0-LL and CanESM5.
For the land carbon cycle, the following models are used: ACCESS-ESM1-5, BCC-CSM2-MR, CanESM5, CNRM-ESM2-1, GFDL-ESM4, IPSL-CM6A-LR, MIROC-ES2L, MPI-ESM1-2-LR, MRI-ESM2-0, NorESM2-LM, UKESM1-0-LL.
We added this to the revised paper.

l. 314-315. Why is the NPP in the Southern Ocean lower in climber-X ?

NPP in the Southern Ocean is lower in CLIMBER-X than in MPI-ESM, but the MPI-ESM seems to be an outlier in this respect, possibly because of biases in climate, which have little to do with the HAMOCC ocean carbon cycle model. We will have a closer look at the physical climate biases in MPI-ESM and CLIMBER-X in the Southern Ocean.

Figure 6. The zonal profiles are presumably global, are there differences between basins?

We now make it clear in the caption that what is plotted are ‘global zonal means’.
Obviously, we would expect some differences between different basins, but we think that global zonal means are sufficient for the purpose of a general comparison between different models.

Figure 7. Since P is not limiting anywhere, could it be removed from the colorbar?

We removed P from the colorbar.

Figure 8. a,b,c,d are missing. Dust deposition is high everywhere in Africa in CLIMBER-X, especially in the southern part of Africa contrary to other models where the values are lower in the southern part compared to the northern part of Africa: why?

We added a,b,c,d to the figure panels. Meanwhile, we improved performance of our dust module: the dust emission pattern changed substantially after the introduction of a topographic erodibility factor for dust emissions following Ginoux et al., 2001. The dust deposition fields are now generally in better agreement with other models and with observations with a notable improvement also over southern Africa.

Figure 9. You could change the x and y labels, e.g. “modelled dust deposition” or “dust deposition in the model”, and for the y axis: “observed dust deposition” or “dust deposition in observations”.

We changed the axes labels as suggested. We also fixed an error which resulted in the x- and y-axis labels being exchanged.

l.334-l.335 what is the reference for the CMIP6 surface iron concentration? Could it be added to Figure 10?

The comparison is referring to Fig. 11d, but a reference to the figure was missing in the text. We fixed that.

l. 351-353 and Table 1. The surface silicate values are much higher than in the observation: why?

A HAMOCC retuning, and in particular an increase in the Si/C uptake ratio in diatoms, substantially improved the simulated silicate values in general and especially at the surface.

l.364-366. There are large biases in the δ13C distribution: why?

The negative biases at 500-1500m depth are associated with the "nutrient trapping" problem (Aumont et al., 1999, Dietze and Loeptien, 2013) that is often seen in ESMs. This problem is characterised by high concentrations of remineralised nutrients and carbon and, therefore, low d13C (Liu et al. 2021). The positive biases are likely to result from too strong ventilation in the model. We added this discussion to the revised manuscript.

l. 368-369. How are the winds in the model? Are they indeed underestimated? If the winds were higher and the mixing enhanced, would it not change also the nutrient distribution, which seems relatively good?
What is the explanation for the biases in the Southern Ocean for δ13C and Δ14C?

The simulated average winds are not underestimated. This is more about non-linearity effects of synoptic variability. A one time mixing down to e.g. 100 m by a wind storm could/would have a large effect for some tracers. We would expect this non-linear effect to be much more important for radiocarbon than for nutrients.
See response to comment above for carbon isotope biases.

l. 371 Why is there too little CaCO3 in the Pacific?

The underestimation of calcite weight fractions in sediments of the eastern South Pacific Ocean is caused by water being undersaturated with respect to calcite in this area. This leads to dissolution of most of the calcite produced at the surface before it can even reach the sediments. The strongly undersaturated water is ultimately a result of deficiencies in the simulated ocean circulation. Some other models show similar deficiencies in the simulated calcite fraction in Pacific sediments (e.g. Kurahashi-Nakamura et al. 2020).

l. 373 (and l.377) The table is referred to as "Tab.1" but before in the text (l.304) it has been referred to as "Table1".

Fixed.

l.374-375 Why is the opal content in sediments overestimated?

After HAMOCC retuning, the global Opal fluxes to the sediment and the burial fluxes are perfectly within the range of recent estimates and the overestimation of opal content in the sediments is somewhat reduced. However, Opal is still too high in some regions. The model still overestimates Opal concentration in the eastern equatorial Pacific, simply as a result of missing CaCO3 in the sediments in that area. Opal sediment content is also overestimated in the northern Atlantic, for reasons that will be explored further. We also updated the observations of sediment content to the more recent dataset from Hayes et al. 2021, which provides an internally consistent analysis of CaCO3, Opal and TOC content in the surface sediment.

Table 2. As for table 1, the legend could be expanded, e.g. Global values for the main variables of the land carbon cycle.

Done. Thanks for the suggestion.

l.385 Table 2 is referred to as "Tab.2", but "Table2" l.383.

Fixed.

l. 390-393. In Table 2, the data for soil carbon indicate a mean value of 4000 GtC , while CLIMBER-X simulates 2187 GtC, this seems like a large difference, could you discuss it?

The simulated total soil carbon in the top soil meter in CLIMBER-X is well in the range of observational estimates, as shown in Table 2, indicating that the mismatch in total soil carbon content originates from un underestimation of carbon in deeper soil layers. One possible explanation for that is that the maximum turnover time scale of soil carbon is set to 5000 years in the model, which will limit the amount of carbon that can be accumulated. Other possible reasons include: (i) a general underestimation of vertical carbon transport by diffusion, particularly into perennially frozen soil layers, (ii) a possible depth dependence of soil carbon turnover due to processes other than temperature and moisture (e.g. Koven et al. 2013), which is not included in the model.
However, it should also be noted that carbon content in deeper soil layers is highly uncertain (e.g. Table 2 in Fan et al. 2020).
We added some of this discussion to the paper.

l.395 Table 2 indicate that the carbon stock in permafrost has a mean value of 1300 Gtc, but CLIMBER-X simulated only 861 GtC: why is there so little carbon in permafrost? Is the permafrost area not large enough or the carbon storage too small? Are there missing processes? Or is it due to climate biases?

This is due to an underestimation of carbon in deep soil layers, related to what discussed in the response to the point above. As shown in Table 2, the permafrost area is well captured by the model.

L419. Why is the silicate weathering low compared to data while the carbonate weathering is relatively high?

There was a bug in the model. The activation energy for silicates was used for carbonate weathering and viceversa. Since the activation energy for carbonates is lower than that for silicates, this resulted in an overestimation of carbonate and underestimation of silicate weathering fluxes. After the bugfix the weathering fluxes are well within the range of observations.

Section 4.2. Does it make a difference if you simulate the evolution during the historical period in the closed or open configurations? Presumably the impact of long-term processes on such a short period should be very limited but have you tried to simulate both to test this?

For the historical period it does not make any difference whether the closed or open carbon cycle are used. As seen e.g. from Fig. 32, the differences become tangible on millennial time scales.

Conclusions. Could you discuss the biases, their potential causes, and what could be done to improve the model?
Biases is the simulated distribution of ocean biogeochemical tracers exist and can mostly be related to deficiencies in the simulated ocean circulation changes, which can at least partly be attributed to

relatively coarse ocean model resolution and the frictional-geostrophic approximation employed in the 3D GOLDSTEIN ocean model. On land, the carbon in soil layers below 1 m is underestimated, particularly in the permafrost zone, with possible implications for the land carbon cycle response to global warming.
We added these points to the conclusion.
Additionally, following also a suggestion by Reviewer #2, we added a discussion on possible future directions for model development and improvements.

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