Response to Reviewer Comments on "Reconstructions and predictions of the global carbon budget with an emission-driven Earth System Model"

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We thank the Reviewers for their time and comments towards improving our manuscript. Please find our point-by-point response (normal font) to all review comments (*italics*) below.

Reviewer #1: Wei Li

The authors assimilated physical data products into the MPI-ESM and used a CO_2 emission (rather than CO_2 concentrations) driven approach to reproduce the interannual variations of each carbon fluxes in the global carbon budget. The results show that the MPI-ESM prediction system has the ability to predict the global carbon budget for the next year. This study provides a novel approach to advance the carbon flux prediction under the global carbon project. I think this manuscript is well written, and the message is very clear and well supported by the figures. This manuscript was submitted to another journal previously, and I was one of the reviewers. I was very surprised why it was not accepted by that journal after two rounds of revisions. At that time, I raised some concerns about the novelty and details of LUC simulations and CO_2 concentrations. But I notice that the authors already addressed my previous concerns in this version submitted to ESD. Therefore, I would recommend publication of this manuscript.

R: We thank the Reviewer for the insightful review and for his previous constructive comments that helped improve our manuscript. We are so delighted that the novelty and contribution of our reconstruction and prediction work to the global carbon budgeting are well accepted.

Reviewer #2: Vivek Arora

General comments

The authors present a forecast system for the global carbon cycle based on the seasonal to decadal forecasting system of the MPI-ESM that requires initializing the physical variables in the model based on observations. The manuscript reads well and

the science is sound. However, since the manuscript covers two different aspects of Earth system modelling (the global carbon cycle and seasonal to decadal forecasting) the authors need to make their terminology and descriptions easier to understand for both communities. As a land carbon cycle person myself, there were several aspects of seasonal to decadal forecasting that I was unable to completely understand.

R: We thank the Reviewer for his insightful and constructive comments. The review comments are mainly on clarification of the prediction procedure and how the simulations and analyses are done. In the attempt to make the terminology and descriptions of initialized predictions easier to understand, we have added a schematic as shown in Fig. 1 to explain our simulations in a stepwise manner. We substituted the first figure in previous manuscript with this new figure.

In particular, as a reader, I am unable to completely understand how the simulations are done.

R: We have made a new illustration figure (Fig. 1). This will help readers to understand how the simulations are done. We have done 3 sets of simulations from left to right sequentially, i.e., the uninitialized "free" simulations, an assimilation simulation, and initialized predictions. The uninitialized simulations are run freely in the same way as the Coupled Model Intercomparison Project (CMIP) historical type simulation spanning the period from pre-industrial to the end of this century, i.e., 1850-2099. The assimilation simulation starts from year 1959 of the uninitialized simulation and integrates forward by nudging available observations and data products to capture the actual evolution of the climate and carbon cycle. The initialized predictions start from each year of the reconstruction state from the assimilation simulation and run freely for 5 years to see how long the system keeps the memory from initial conditions.

Are multiple 5-year simulations done starting from each year from 1960-2018, and then the values at the end of the first year of each simulation are used to construct a time series corresponding to a 1-year lead time?

R: Yes, the multiple 5-year simulations are done starting from each year from 1960-2018, but it is not the values at the end of the first year of each simulation, rather the annual mean values are concatenated to time series according to the lead time, as shown with the colored dots in Fig. 1C. For example, the blue dots are concatenated for the lead time of year 1 series. Please note that not every starting year prediction is shown, only starting years at 10-year intervals, and ensemble mean dots are shown to make the illustration clearer. The skill of prediction is evaluated by comparing the concatenated time series of predictions (i.e, hindcasts) with the observations/data products.

In addition, several sentences are unclear and I have suggested rewording them in the annotated PDF attached to this response.I suspect that English may not be the first language of the first author, and I think the manuscript would benefit from the attention of other co-authors. A detailed list of comments can be found in the attached annotated PDF of the manuscript which

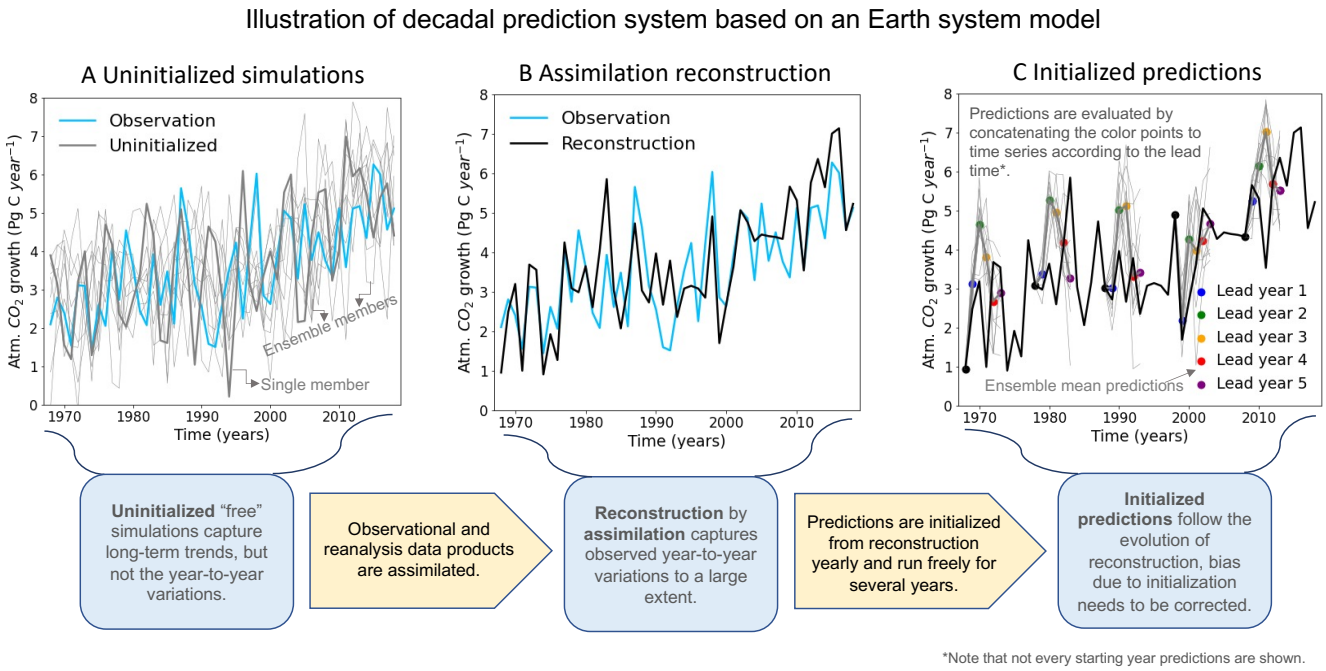

Figure 1. Illustration of a decadal prediction system based on an Earth system model MPI-ESM simulation of the atmospheric CO_2 growth rate. The time series are annual means from model simulations plotted together with observations from the Global Carbon Project. We conduct 3 sets of simulations, from left to right in sequential order: i) uninitialized "free" simulations which are the same as the Coupled Model Intercomparison Project (CMIP) historical type simulations; ii) an assimilation simulation to reconstruct the evolution of climate and carbon cycle towards the real world by nudging observation and reanalysis data during the integration; iii) initialized predictions are started from reconstruction states produced by the assimilation simulation and integrated freely (i.e., no nudging of data) for 5 years. The left panel plot A time series show that the uninitialized simulations capture the long-term trend well, but the year-to-year variations are out of phase to the observations. The middle panel plot B time series shows that the assimilation simulation forces the variations in the uninitialized freely run simulation towards the real world, and results in a reconstruction closer to the observations. The right panel plot C presents the reconstruction together with 5-year long initialized predictions (i.e., hindcasts). To make the illustration more clear, only predictions with starting years at 10 year intervals are shown.

also summarizes my comments so that they can be easily located.I look forward to reading a revised version of this manuscript.

R: Thank you for pointing out the sentences that are unclear, we have reworded them following your suggestions in the annotated PDF. We have also replied to all the review comments in the annotated PDF as listed below. The co-authors have contributed in editing the manuscript, in the meantime, a native speaker colleague has helped read and edit the revised manuscript.

Annotated comments

Page2 L32: "2 PgC/year for some years". What's the average imbalance?

R: The 1959-2018 mean value of BIM is 0.17 PgC/year. We have added this information to the end of the sentence: "Therefore, the global carbon budget is not closed but ends up with a budget imbalance term of up to 2 PgC/year for some years though the climatological mean value is nearly zero of 0.17 PgC/year."

Page2 L39: "predict", predict or project?

R: As illustrated in Meehl et al. (2009), decadal prediction is in between the weather forecasts of initial value problems and the multidecadal to century projections of forced boundary condition problems. The decadal prediction systems aim for predicting climate changes in near future up to 10 years by improving the initial conditions and investigating the added skill due to initialization. Therefore, it is more proper to use "predict" than "project" in this study.

Meehl, G. A., Goddard, L., Murphy, J., Stouffer, R. J., Boer, G., Danabasoglu, G., ... Stockdale, T. (2009). Decadal prediction: can it be skillful?. Bulletin of the American Meteorological Society, 90(10), 1467-1486.

Page2 L42: "predictions", or projections?

R: "predictions" is the correct word. In addition to our response to the last comment above, we would also like to emphasize that prediction in this study is based on dynamical model integration and representation of evolution in physical and biogeochemical processes. It is also distinguishable from the statistic-based projections.

Page2 L47-49: "Prediction systems have proven skill in predicting air-sea and air-land CO_2 fluxes (Ilyina et al., 2021), for the first time, we extend our previously concentration-driven prediction system to an emission-driven system, taking into account the interactive carbon cycle and hence resolving prognostic atmospheric CO_2 and making atmospheric CO_2 predictions." Long sentence needs rewording.

R: We have reworded the sentence as: "Prediction systems have proven their skill in predicting air-sea and air-land CO_2 fluxes (Ilyina et al., 2021). For the first time, we extend our previously concentration-driven prediction system to an emission-driven system. The emission-driven system takes into account the interactive carbon cycle and therefore determines atmospheric CO_2 prognostically and predicts atmospheric CO_2 variations."

Page3 L58-59: "The assimilation simulation states, which are close to the real world, are then used to start our retrospective initialized prediction simulations to predict the changes of the global carbon budget in the next years." Unclear.

R: Both weather and climate predictions endeavour to improve skill by improving the initial conditions to initialize the prediction simulations. The initial conditions are produced by a separate assimilation simulation through assimilating data products into the model so they are as close to the real world as possible. We have reworded this sentence as: "The assimilation simulation's states, which are close to the real world through constraints from observations and data products, are used to start the initialized simulations, which predict the changes of the global carbon budget."

Page3 L60: "are expected to capture internal variability better than freely evolving uninitialized simulations". Is this true? Isn't variability a function of a model rather than its initial state?

R: It is more precise to say "actual evolution" than "internal variability". We have reworded the sentence as: "Initialized predictions are expected to capture the evolution of climate and carbon cycle more realistically than freely evolving uninitialized simulations due to their improved initial conditions from reconstruction."

Page3 L68: "200-km grid spacing". Can you also please note the resolution in degrees?

R: The atmospheric component is on spectral resolution with truncation T63, i.e. 192*96 lon*lat grids, it is about 1.88 deg at equator. We have added this information in the text as: "The atmospheric horizontal resolution has a spectral truncation at T63 (approximately 200 km or 1.88 deg grid spacing at equator) with 47 vertical levels."

Page3 L80-81: "the interaction with the strength in CO_2 uptake/outgassing of the land and ocean" reword - for example in response to the atmosphere-land and atmosphere-ocean CO_2 fluxes.

R: We have reworded it as: "in response to the strength of air-land and air-sea CO_2 fluxes".

Page3 L86-87: "control simulation". Is this a pre-industrial simulation? If yes, please make this clear.

R: Yes, it is pre-industrial control simulation. We have revised this as: "pre-industrial control simulation".

Page3 L88-89: "The initialized ensembles are generated with lagged 1-day initializations from a given branching point of the assimilation simulation." Please reword. This sentence is unclear.

R: We have added the following words to the end of the sentence: "i.e., initialized from October 31st, November 1st...until November 9th."

Page4 Figure1 legend: "Reconstruction". Does this mean "initialized simulation" ?

R: No, reconstruction is from the assimilation simulation by nudging observations and data products. We have replaced Figure 1 with the new illustration figure as presented in the response letter. The new figure is clearer in explaining the procedure and how the simulations are conducted.

Page4 Figure 1 caption: "reconstruction and prediction" Does reconstruction mean initialized, and prediction means freely involving? Please make this clear. Also, it is unclear to me how the thick black line in panel A is made if the initialized simulation is run for 5 years from every year of the 1968-2018 period.

R: Reconstruction is from the assimilation simulation with assimilating observation and data products. The thick black line in panel A is from the continuous assimilation run.

Predictions are simulations that are run freely starting from the reconstruction yearly. The time series of initialized predictions are concatenated according to the lead time, i.e., all the 1st year predictions are concatenated, and so forth for the 2nd to 5th year predictions. This means concatenating the dots shown in the new illustration figure panel C with the same color. For instance, the red curves in Figure 4A are the concatenated predictions at lead time of 1 year.

Page 4 Figure 1 caption: "and results in a reconstruction close to the data." Can you back this up with correlation coefficients?

R: The correlation number is shown in Figure 2D, that is 0.745.

Page 4 last line: "from the". Do you mean "towards the"?

R: Yes, we have revised it as "towards the".

Page 5 L103-104: "global carbon cycle is well represented from the assimilation of physical variables only" I have an idea what this means but please make this more clear.

R: We have reworded this sentence as: "the global carbon cycle is well captured by assimilating only physical variables".

Page 5 L119:"differencing"

R: We have reworded the sentence: "differencing the two simulations results in the..."

Page 5 L125-127: "The time series of initialized simulations at lead time of 1 year (2, 3, 4, and 5 years) combine the 1st year (2nd, 3rd, 4th, and 5th year) predictions from initialized simulations of all the starting years from 1959-2018, therefore, the time series at lead time of 1 year (2, 3, 4, and 5 years) are from 1960-2019." This is still a bit unclear. I am not sure I understand how many simulations are performed and how a combined time series is put together.

R: To make this clearer, we have made a new illustration figure. The time series of predictions are concatenated according to the lead time, i.e, points with the same color in panel C of the illustration figure (Fig. 1). Please note that not every starting year predictions are shown to avoid a crowded figure.

Page 6 L129: "Bias correction is an unavoidable topic for decadal predictions due to initial shock, which varies with lead time." Are you saying you had to do bias correction? If yes, how?

R: Yes. The decadal prediction studies mostly present anomalies with focus on variations by removing the climatological mean and/or trend bias due to model drift caused by the initialization of observations. The anomalies are calculated relative to the respective climatology according to the lead time, the absolute values can be achieved by adding the anomalies to the best estimates from observations (Boer et al. 2016, Meehl et al. 2021). To infer predictions of absolute values of the atmospheric CO_2 concentration, the respective anomalies from the predictions are added to the best estimates of climatology and trend from data, here the observations from NOAA_GML are used. This clarification has been added to the end of this paragraph in the manuscript.

Boer, G. J., Smith, D. M., Cassou, C., Doblas-Reyes, F., Danabasoglu, G., Kirtman, B., ... Eade, R. (2016). The decadal climate prediction project (DCPP) contribution to CMIP6. Geoscientific Model Development, 9(10), 3751-3777.

Meehl, G. A., Richter, J. H., Teng, H., Capotondi, A., Cobb, K., Doblas-Reyes, F., ... Xie, S. P. (2021). Initialized Earth System prediction from subseasonal to decadal timescales. Nature Reviews Earth Environment, 2(5), 340-357.

Page 6 L148: "change in"

R: It is revised.

Page 6 L149-151:"Cumulatively, the CMIP6 CO_2 emission forcing is 8.20 PgC higher than that from the GCB2019, which results in a difference of atmospheric CO_2 of 3.86 ppm (by dividing a factor of 2.124 PgC ppm-1 globally." There is a subtlely here. Not all emissions stay in the atmosphere so you can't calculate the difference in CO_2 due to these emissions by just dividing by 2.12.

R: Thanks to the reviewer for pointing out this. We agree that not all emissions but only about 50% of the emissions stay in the atmosphere. We have revised the sentence as "...which is equivalent to a difference of atmospheric CO_2 of 1.93 ppm assuming that 50% of the emissions stay in the atmosphere (i.e., by dividing 4.10 PgC with a factor of 2.124 PgC ppm^{-1} (Ballantyne et al., 2012))"

Page 8: "but not by" "it implies that" "for LUC emissions"

R: All the above edits are done.

Page 8 L173-174: "By design of the Global Carbon Budget, there is a budget imbalance term because the individual budget terms originate from separate measurements together with stand-alone ocean and land model simulations" Please reword.

R: We have reworded it as: "The annual assessment from the Global Carbon Project has a budget imbalance term. This is because the individual budget terms are from separate measurements together with ocean and land model simulations, which are not linked to each other internally. "

Page 8 L175: "in each sub-models". Unclear.

R: We have rewritten this as: "we assimilate atmosphere and ocean data products within a fully coupled ESM..."

Page 8 L176: "towards the real world" Please reword. We know all models have their biases.

R: We agree that all models have biases. The data assimilation constrains the model towards the real world evolution by nudging observations and data products.

Page 8 L177-178: "it is more consistent to attribute the GCB variations using the assimilation simulation". I get the gist, but please reword.

R: We have reworded the sentence as: "the assimilation simulation based on a fully coupled ESM enables attribution of the GCB variations."

Page 8 L179-180: "ensures the atmospheric CO_2 directly from measurements, so far ESM-based assimilation requires further efforts in improving the constraint of atmospheric CO_2 from observations". Please reword.

R: We have reworded the sentence as: "The current method of the Global Carbon Project's GCBs (Friedlingstein et al., 2019) which uses the directly measured atmospheric CO_2 increment has the advantage of representing the actual evolution of atmospheric CO_2. Our ESM-based assimilation shows a high correlation of 0.75 with the atmospheric CO_2 measurements, but still needs to be improved. Further efforts are required to constrain the atmospheric CO_2 from observations."

Page 8 L184: "075"-> "0.75"

R: It is corrected.

Page 9 Figure3 caption: "in A-D" -> "in panels A and B"

R: It is revised.

Page 13 L211-212: "historical freely evolving run (0.61), which is mainly contributed by the coherent trends of the freely evolving run and the GCB2019". How is the freely evolving run affected by GCB 2019 in any way? It should not be.

R: Here we meant that the coherence between historical free run and the GCB2019 is from the consistent trends, but not the interannual variations. The uninitialized historical free run can capture the long-term trend of climate and carbon cycle changes due to responses to external forcings.

Page 13 L221 L234: "for up to" "for up to"

R: They are revised.

Page 15 Figure 6 caption: "sum of prediction" This is unclear. Can you please clarify what "sum of prediction" means?

R: Here we added the time series of lead time at 1 year and 2 years together to get an combined time series. It is commonly used in the decadal prediction studies to investigate integrated/smoothed variations up to decade with aggregated lead time.

Page 15 L250: "Here we also the surface atmospheric CO_2 concentration". This sentence doesn't read properly.

We have revised it as: "Here we also present the surface atmospheric CO_2 concentration."

Page 15 L254-255: "therefore, it ends up with around 8ppm higher global atmospheric CO_2 concentration in the model simulation than in the observations (see Fig. A4)." I am confused why Figure 7 (D, E,F) look so nice but Figure A4 is 8 ppm higher.

R: The time series showing in Figure A4 are original time series, but those in Figure 7 are bias corrected as stated in the last sentence of Figure 7 caption: "The time series are bias corrected by removing the difference of mean states and linear trend between observation and simulations according to Boer et al. (2016)." The critical/challenging part of decadal predictions is the multi-year variations rather than mean states and linear trends that can be deduced from observations.

Page 15 L257-258: "The time series shown in Fig. 7D-F are bias corrected by removing the difference of mean states and linear trends" If the mean is removed why does the y-axis values start at around 390 ppm?

R: Here the difference of mean states and linear trends between the model simulations and observations is removed, i.e., the mean states and linear trends from observations are retained together with the model simulated multi-year variations.

Page 16 L261-262: "The initialized simulations could represent the observed evolution well even at lead time of 5 years," But this skill comes from simply the increasing CO_2 in response to emissions and more or less correctly simulated sinks.

R: We compare RMSE of the initialized simulations and that of the uninitialized simulations relative to NOAA_GML observations. Both the initialized and uninitialized simulations are bias corrected to be put in the same level for comparison. The increasing of CO_2 in response to emissions should be captured in the uninitialized as well because both the initialized and uninitialized simulations share the same external forcing. Then the improved RMSE in the initialized simulations comparing to the uninitialized simulations are from the initialization. This also indicates improved predictive skill due to initialization in capturing the multi-year variations.

Page 16 L266:"in stead" -> "instead"

R: It is revised.

Page 16 L272-273:"is intervened by the predictability of ENSO in some starting year predictions." Please reword. I am not sure what "intervene" implies here.

R: We have revised this sentence as: "is degraded by the poor predictive skill of ENSO in some starting year predictions."

Page 16 L279: "the" -> "an"

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R: It is revised.

Page 16 L284: "with high correlations (0.75, 0.97, and 0.75) with the GCB2019" At what lead time?

305 R: These are the correlations from reconstruction by assimilation simulation.

Page 16 L284-285: "This enables a closed quantification of the GCB" -> "This enables quantification of the GCB in a closed system"

310 *Page 16 L286-287:"and internally consistent metrics"->"in an internally consistent framework".*

Page 16 L290:"of"->"in" "in"->"for"

Page 17 L302: "shows" -> "exhibits the"

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R: All the above suggested revisions are done.

Page 17: "This will be a powerful tool in supporting the global carbon stocktaking and informing policies that comply with the goals of the Paris Agreement." Please reword and tone down, or make explicit connection to the Paris agreement.

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R: We have revised the sentence as: "This will be a useful tool in supporting the global carbon stocktaking in compliance with the goals of the Paris Agreement."