## Legend:

Text: Reviewer's comments

Text: My responses

Text: Tracked Changes

Open Access Paper (submitted to EGU): https://editor.copernicus.org/index.php?_mdl=msover_md&_jrl=11&_lcm=oc108lcm109w&_acm=get_comm_sup_file&_ms=106043&c=233471&salt=1224728252505037330

Supplementary to Paper: https://bg.copernicus.org/preprints/bg-2022-178/bg-2022-178-supplement.pdf

Revised Paper: Revised_manuscript.pdf

Tracked Changes: Tracked_Changes.pdf

## RC2

The paper investigates extremes in NBP based on CESM2 simulations. It uses a rather rough spatial resolution - the 26 SREX regions - and monthly timesteps. No comparison to observations are used (taken for granted that CESM2 historical runs represent "reality" faithfully) and considers only a single scenario - SSP5-8.5. These two are severe limitations for the paper; in particular, extreme events are likely to be very sensitive on both model and scenario choice. Only at the end is an opening for multi-model and scenario runs, but they are strongly recommended already for this paper.

Response: We computed the anomalies of NBP at every grid cell using the monthly time series data (see lines 100-101). The extremes were computed based on the global NBP anomalies (see lines 88-90). The attribution of NBP extremes to climate drivers was also performed at every grid cell (see lines 136-137). Results were aggregated and presented for 26 SREX regions for regional analysis to compare across regions.

Discussions on the merits of using a single model and multimodel ensemble:

Predictive understanding of climate, specifically in the context of carbon cycle, can benefit potentially in different ways through analysis of multiple Earth system model (ESM) simulations vs. a deep dive into the simulations from a single model. Multi-model statistics tend to provide a better predictive understanding of trends and patterns in climate statistics including variability and predictability. However, aggregate multi-model statistics tend to lose physical consistency and often preclude our ability to investigate model processes and parameterizations and suggest ways to improve them. In this paper, we chose to use one of the established ESMs, specifically CESM2, to better understand the predictive ability and strength and weakness of the climate-carbon feedbacks of this community ESM. Furthermore, out of the current generation (Coupled Model Intercomparison Project phase 6: CMIP6) of ESMs, only two models, CESM2 (which we used here) and CNRM-ESM2-1, produced all the simulation outputs (including “fFireAll”: “Carbon Mass Flux into Atmosphere Due to $CO_2$ Emission from Fire Including All Sources”) that can be used for attribution studies in this paper, but even out of those two, only CESM2 currently produces a comprehensive set of simulations outputs and better represents a wider range of feedback processes when compared with observations. We wanted to investigate the science of one model and investigate in detail the anomalies, climate-carbon feedbacks across space and time, understand the mechanisms embedded in this model, and what are the possible implications of our findings. Investigating one model in detail also helped us identify some of the model artifacts. For example, we saw that the magnitude of extremes in NBP and interannual variability in NBP increased drastically during the period 2000-15. We reached out to the modeling group and found that during this period the LULCC forcing was changed from decadal to annual, which likely increased the carbon-climate variability during 2000-15.

For the variables that we analyzed in this study, CESM2 is always ranked among the top 3 ESM based on the ILAMB benchmarking scores for the historical period, see Figure 5.22 of Chapter 5: Global Carbon and other Biogeochemical Cycle and Feedbacks, IPCC Sixth Assessment Report Working Group 1 (Canadell et al. 2021).

We investigated climate-carbon feedback in detail for the SSP585 pathway because the literature suggests (Schwalm et al. 2020, Abadie et al. 2020, Trugman et al. 2018, Park et al. 2015) that this pathway is possibly the best match to midcentury under the current and stated policies and with (likely) plausible levels of $CO_2$ emissions in 2100.

Based on the reviewers' comments we have expanded the caveats section to include these limitations (see below or Tracked Changes: ln 400-403). In the future, we will test the multi-model variability and their physical consistency. In the next study, we plan to use multi-model and multi-scenario analysis and address the issues raised by the reviewer.

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This study analyzed climate-driven NBP extremes using one Earth
system model, CESM2, from 1850 to 2100. Using only CESM2 simulations
helped us to delve deeper into the climate-carbon feedbacks across
different periods and spatial resolutions, as well as to identify
model artifacts. However, the current study lacks comparison to
observations, other Shared Socioeconomic Pathways, and other Earth
System Models.
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The authors do a good job in preparing the input, i.e. the calculation of anomalies, by taking out the annual cycle using SSA. The reviewer isn't that happy with the decision to define every SSA component with a dominant period > 10 years as "nonlinear trend". This is arbitrary and contrary to our knowledge of long-term cycles in observations, e.g. of Sea Surface Temperatures.

Response: Thank you for acknowledging the data preparation methodology. The trends in this study were defined as the sum of all signals from SSA with a return period of 10 years and higher at every gridcell. Therefore, detrending removes all periods that are greater or equal to 120 months. We chose periods larger than 10 years for defining trends because we wanted ENSO, which has a return period of 3 to 7 years, to be part of anomalies. The trends are non-linear for most grid cells because the relationships between photosynthesis and elevated $CO_2$ and temperature are not linear. Sharma et. al. 2022 shows the trends of GPP (Figure 2). Although we did not perform statistical tests to check for nonlinearity, we can qualitatively say that the trends in the carbon cycle are nonlinear. Zscheischler et al. (2013, 2014) used SSA to calculate anomalies and defined non-linear trends as the sum of all signals from SSA with a return period of 30 years and higher. We defined trends as larger than 10 years consistent with existing literature.

Another issue is while it is true that responses to climate drivers may vary over short time scales ("daily to monthly", l. 55) and CMIP6 simulations are available at daily scales, it is suprising that the authors nevertheless use monthly data only, depriving them from any conclusions on these shorter scales.

Response: While the reviewer is correct that some of the atmospheric variables like temperature and precipitation are available at daily temporal resolution. The land component variables like GPP, NBP, and Fire (fFireAll), that we used in our study, are available only at monthly time resolution (source: https://esgf-node.llnl.gov/projects/cmip6/).

The explanation of compound events and in particular the concept of mutually inclusive / exclusive is confusing. It should be rephrased and in particular simplified.

Response: We have revised the description (see below) of the exclusive and inclusive climate drivers in the revised manuscript to better explain their meaning [Tracked Changes: lines 289-293].

Mutually inclusive climate drivers represent the simultaneous occurrence of various climatic conditions that drive extreme events in NBP. Mutually exclusive climate drivers are those climatic conditions that do not occur at the same time to cause an extreme event. For example, if an extreme event in NBP is driven by both hot and dry conditions, the mutually exclusive climate driver is only hot & dry and the mutually inclusive drivers are hot, dry, and hot & dry.

Some specific comments:

l. 194: change LULUCC forcing from decadal to annual and back to decadal: do you mean in the model? If so, the net carbon uptake change would just be an artefact of the model setup, which would be embarrassing since no proper conclusions (also for the other 25 year periods) could be drawn.

Response: Yes, it is an artifact of the model setup. We saw an increased magnitude of NBP extremes and interannual during the time period 2000-24. It is most likely due to changes in the LULCC forcing from decadal to annual for the period 2000-15. This increased frequency of LULCC forcing likely led to high variability in NBP. However, the impact of change in LULCC forcing was not as significant for mean NBP changes (Figure S3). Hence, the findings that we have presented are valuable for evaluating the changes in the extremes in NBP over time and across regions. We have revised the paper to clarify this doubt [Tracked Changes: lines 210-213].

The large magnitude of net carbon uptake changes during the period 2000-24 was likely due to the change in LULCC forcing from decadal to annual during 2000-2015 and then back to decadal from 2015 onward. The increased temporal resolution of LULCC forcing possibly caused higher climate variability due to biogeophysical feedbacks and subsequently led to increased carbon cycle variability and extremes. Since we focused on NBP extremes, which are tails of PDF of anomalies (or interannual variability) of NBP, the magnitude of carbon cycle extremes was large during this period. However, the impact of LULCC forcing was not as significant on mean NBP changes (Figure S3).

l. 207: "global anomalies": are you  sure -  the NBP TCEs are surely based on each SREX regions separately? It wouldn't make sense to put thresholds for anomalies worldwide, since some regions would have anomalies all the time, and others never.

Response: Yes, the thresholds were calculated using the global anomalies in NBP. We wanted to quantify the NBP extremes that are significant globally. Moreover, we wanted to perform a comparative analysis of the global NBP extremes across various SREX regions. However, you are correct that in current study some regions will show more extremes than others because of larger NBP and interannual variability. We have revised the manuscript to clarify this ([Tracked Changes: lines 96-97; 98-100] and see below).

We wanted to quantify the NBP extremes that are significant globally and compare the distribution of global NBP extremes across various regions. The Intergovernmental Panel on Climate Change (IPCC) (Seneviratne et al., 2012) defines extremes of a variable as the subset of values in the tails of the probability distribution function (PDF) of anomalies. Based on the global PDF of NBP anomalies, we selected a threshold value of q, such that total positive and negative extremes constitute 5% of all NBP anomalies.

l. 249: "Hot temperatures that persist for long periods induce heatwaves" - isn't that the very same? Remove the tautology in that case.

Response: Thank you for pointing it out. We have changed it in the revised manuscript [Tracked Changes: line 265] and shown below.

Hot temperatures ~~that persist for long periods induce heatwaves, which~~ over long periods tend to reduce ecosystem production and enhanced terrestrial respiration . . .

l. 264: "Reduction of fuel load by changing vegetation composition...": who does change the composition? In the model? The SSP5-8.5 is the "business as usual" scenarion where no (major) changes (like e.g. forest restructuring) is foreseen. Also, not every change in vegetation composition reduces fuel load. What do you imply here?

Response: We made general qualitative observations that could explain the reason for the decline in the number of SREX regions dominated by fire. However, we have not systematically analyzed LULCC in this current study. Therefore, we deleted this sentence from the revised paper. [Tracked Changes: lines 280-281]

l. 312: enhancing stomatal closure and ecosystem respiration": this is a contradiction. It is possible that plants' response to increased CO2 offer is a partial closing of the stomata, leading to sink saturation, but at the same time, this REDUCES respiration, i.e. the opposite.

Response: Yes, the increased atmospheric concentration of $CO_2$ leads to stomatal closure and reduction in autotrophic respiration. While droughts decrease both vegetation productivity and terrestrial respiration, hot temperatures decrease vegetation productivity and increase terrestrial respiration due to a large increase in heterotrophic respirations (Pan et al. 2020). In models, stomatal closure and ecosystem respiration (sum of autotrophic and heterotrophic respiration) are not linked directly. In Figures S9 and S10 we show the rise in the autotrophic and heterotrophic respirations over time in the tropics and high latitudes.

There are more detailed comments and suggestions to changes in the attached pdf, please consider these as well.

Preferably, the paper should be enlarged in scope by including additional models and scenarios, leading to a major revision. If this is not an option, the other changes required are more of "minor" character.

Response: While including other models does add value it will be a larger task and warrant a new study approach. We think the findings of our paper significantly contribute to increasing our understanding of NBP extremes and their climate drivers over time. In our next study, we will include multi-model and multi-observation comparisons of extremes in carbon fluxes.

Additional Comments are also addressed (link) and the manuscript is revised accordingly.

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