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Interactive comment on "Spatially resolved evaluation of Earth system models with satellite column averaged CO_2" *by* Bettina K. Gier et al.

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Response to Anonymous Referee #1

We thank the reviewer for the helpful comments. We have revised the manuscript according to all review comments we have received. A pointwise reply is given below, with the original comments in **bold** and our answers in red.

This is a concise analysis of the current CMIP6-generation emission-driven Earth System Models' ability to reproduce satellite-observed variability characteristics of column-average atmospheric carbon dioxide concentrations (XCO_2). The manuscript provides a comparison with the previous generation of models

and demonstrates improvement over time as a modeling community. The manuscript also demonstrates that geographic and temporal sampling biases in the satellite observations contribute to an observed negative trend in the amplitude of the seasonal cycle of XCO_2. This manuscript is an important documentation of the models' ability to simulate atmospheric CO_2 and could be suitable for publication after addressing some of the concerns outlined below.

We thank Referee #1 for the constructive comments which helped to improve the manuscript.

Major Comments:
1. The spatial sampling issues comparing models to satellite obs are addressed in this manuscript, but the temporal issues are only partially addressed. It is not clear what role the presence of cloud cover plays in the results. Satellite observations of column-average CO_2 occur over locations with low cloud cover (line 120). One could imagine that some processes – such as stomatal conductance – could vary significantly on cloudy vs. cloud-free days. The model monthly averages however include all model timesteps and are not impacted by the presence of clouds. Some quantitative assessment of this effect is needed to interpret the results of this study. Perhaps reconstructing some monthly averages using a daily or sub-daily cloud mask could help understand whether or not this has a large influence on the comparison between models and satellite observations.

Only monthly frequency CO_2 data is currently available on the ESGF and therefore an analysis as proposed here is not possible at the current time. While it is true that studies have found cloud cover to have an impact on photosynthesis, the response can be fundamentally different for various ecosystems (Still et al., 2009). Cheng et al. (2016) found that "the diffuse light effect from clouds is not as strong of

a driver of regional or global ecosystem productivity in temperate ecosystems during the midday as previously suggested in other studies". The satellite data we use is measured at 13:00 local time, which falls into this midday period. Moreover, we would expect a larger effect from the diurnal cycle than the cloud cover with the satellite data measure at 13:00, while the model monthly means are computed using both day and night data. While both of these effects may change the absolute values, their scale should not vary much throughout the years, so that they have no effect on relative changes on growth rate and seasonal cycle amplitude.
We have added this point as a caveat in section 5.3.2. and in the Conclusions as part of the discussion of limitations and future directions.

2. What are the baseline trends in the control simulations for the physical climate and carbon cycle processes that influence atmospheric CO_2? Was there an attempt to detrend the models? Why or why not?

We have looked at various variables for a few sample models in the control simulations, and found no significant trend in the physical processes. For CO_2 the trend in the control simulations is negligible compared to the interannual variability, as discussed e.g. by Dunne et al. (2020) for GFDL-ESM4. Therefore, the models have not been detrended. A detailed analysis including all the processes which influence atmospheric CO_2 which you are suggesting here on a per model basis is a study on its own and beyond the scope of this paper.

3. Were multiple model ensemble members from each model considered? The manuscript seems to suggest that only one ensemble member from each model was considered. This point should be clarified and all available ensemble members should be analyzed to get as comprehensive a picture as possible regarding the models' intrinsic variability given the nature of this study and the relatively short time period of analysis.

In CMIP5 only one model performed the future scenario simulations with more than one ensemble member, and therefore we have chosen not to include these. For CMIP6 there are various models with several ensemble members. We have extended Figure 3 (the timeseries) both with additional panels depicting the computed monthly growth rate and detrended seasonal cycle, as well as including all the ensemble members for CMIP6 in it. The multi-model mean shown in this plot only includes the first member for each model. A deeper analysis shows that while there are small differences in the growth rate for different ensembles members, the SCA and its patterns on the map plots are very similar. The inclusion of more ensemble members does not impact the existing analysis and we have therefore elected to only include the first ensemble member for each model in all analysis beyond Figure 3, which gives a good overview of the models intrinsic variability. Using an ensemble mean would average out much of the interannual variability found in each individual member.
We have made this clearer by ending section 2.2 on the model simulations with "For CMIP5, only one model had more than one ensemble member performing the emission driven RCP 8.5 simulation and thus only one ensemble member for each model has been used. In CMIP6, several models have three or more ensemble members. We consider all of them in Figure 3 for the timeseries to show the models' intrinsic variability, but then proceed the analysis with only the first ensemble member for each model, as they perform similarly to each other for the analysis in this paper, and using an ensemble mean would reduce the interannual variability found in each individual member."

4. The conclusions section would benefit from a longer discussion regarding the limitations of the study and future directions. Can the authors make any further recommendations regarding improvements that are needed on either the observational or modeling side to make this comparison better?

We have added a paragraph devoted to the discussion on the limitations and future directions:
"There are several ways to improve on this analysis in the future. With more available future scenario simulations, the analysis can be extended for a longer time series, making use of longer observational timeseries, such as the one introduced in Reuter et al. (2020). Higher temporal resolution of the models would enable studies on the effect of the diurnal cycle of CO_2 on the monthly mean and also allow for the construction of a co-located time series with the Level 2 satellite data. This could help highlight some of the causes of model biases by being able to pinpoint time and space where they occur more precisely. Model biases may also result from the CMIP experimental design, such as requiring the climate state to be in equilibrium in 1850 while the real world may not have been (Bronselaer et al., 2017), or the parametrizations of biological and physical processes not allowing the system to change rapidly enough (Hoffman et al., 2014). Along with a longer time series, newer satellites, such as OCO-2 or the planned Sentinel 7 bring higher resolutions and more data, potentially helping to fill in the gaps and reduce the impact of the sampling we discussed in Section 5.3.2."

Minor Comments:
Line 21: Replace "slightly" with a more quantitative value
Replaced "slightly" with the multi-model mean bias for the growth rate.

Line 40: Unequivocal warming of what? Troposphere?
Changed to "unequivocal warming of the climate system" which was used in the IPCC report used as reference.

Lines 46-48: This sentence has some grammatical issues
Following a suggestion by referee #2 to shorten this part of the introduction, this sentence has been removed.

Line 57: What is meant by "seems to be"
Changed sentence to "Although models do not agree unanimously, the dominant effects are a positive trend in SCA due to the CO_2 fertilization combined with a negative trend due to climate warming."

Line 119: The observational record is already relatively short from a climate perspective. Discarding 2 years seems like a lot. Consider adding in the years if simulations are now available.
While we have been able to add additional models to the analysis, scenario simulations are still not available for all models discussed in this study and have therefore not been included.

Lines 131-133: Consider expanding the discussions as to why these sites were selected
The discussion has been reworded to make the selection process clearer, with stronger critera being mentioned first. "Measurement sites at locations with no available satellite data were excluded from the analysis, which ruled out the four baseline observatories in Mauna Loa, Samoa, as well as the South Pole and Point Barrow sites. Furthermore, sites which did not collect data during the period from 2003–2014 were discarded. From the remaining sites, a sample of five sites was chosen which had the best coverage of different latitudes, and when latitudes were similar, different longitudes were selected for increased spatial coverage. The selected sites are listed in Table 1."

Line 205-206: Consider mentioning these offsets sooner in the paragraph to improve readability.
Swapped this and the previous sentence.

References: Please add data DOIs for all CMIP6 datasets downloaded and analyzed from the ESGF archive.

Data citations with DOIs have been added as the last entry in Table 2 under “References”.

Figure Comments:
Figure 3: Is there a way to incorporate linear trend information into this figure?
As mentioned above, we have added additional panels to this figure, showing the growth rate and the detrended seasonal cycle. As the growth rate symbolizes the trend and the mean value with interannual variability is given in Figure 4, we believe this is enough. Adding regression lines and further linear trend information to the time series panel would clutter the figure.

Figures 6a & 6b: Consistent color scale ranges are needed for comparison
Implemented consistent color scale for both CMIP ensembles. We have also changed the color scale to the non-divergent newly implemented one used for the top panels of Figure 6 (formerly 7) for consistency.

Figures 7a and 8a: A non-diverging color scale for the top panels could make it easier to contrast against the information contained in the bottom panels
Changed the color scale to a non-divergent one for the top panels in Figure 6 (formerly 7).

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