August 7, 2018

Dr. Fortunat Joos
Associate Editor
Biogeosciences

Dear Dr. Joos,

Thank you for the August 7th correspondence regarding the revised manuscript entitled "The impact of spatiotemporal variability in atmospheric CO_2 concentration on global terrestrial carbon fluxes" (bg-2018-187).

Please find our response letters to the reviewers and the revised manuscript. As suggested, we attach both versions of the manuscript: the track-change version and the clean version of the revised manuscript. We appreciate the helpful comments from the anonymous reviewers to improve this manuscript.

Again, thank you for considering the study for publication in Biogeosciences.

Sincerely,
Eunjee Lee

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Response letter to RC1

Dear Reviewer,

Thank you for the May 22nd correspondence. We appreciate the helpful comments. In responding to them, we feel we have greatly improved the manuscript.

We have carefully noted your comments and suggestions. Please find our responses to the comments and suggestions below, prefixed with an arrow sign (=>). The figures and the table in the letter are labeled and numbered with "L". The page and line numbers noted refer to the revised manuscript, if not noted otherwise.

Sincerely,

Eunjee Lee, Sc.D.
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General comments

Lee et al. have studied the effect of different atmospheric co2 concentration forcing datasets on GPP and NBP of a global vegetation model, Catchment-CN. Their control case has 3-hourly temporal resolution, and then they make different cases with coarser temporal evolution, and finally also by omitting spatial resolution, in order to see what role these different resolutions play. They evaluate these different runs at global scale, and also regional assessment is done, based on TransCom regions.

The text is well written. It's more like a sensitivity study, than a new frontier exploration. The main motivations seem to be assessing how much sense the new CMIP6 run recommendations make and challenging results from a study by Liu et al. and as such I consider its publication to be justified, as the work and analysis seem to be sound and the topic is important.

However, there are some points in the manuscript that I think need further work. E.g. I found the comparison to FACE experiments problematic, as the methodology used was not clearly explained and also, it is not really something that is highly relevant for this study (that addresses short term / small changes in atmospheric co2 concentration). Also the different test cases were not that clearly motivated. I therefore recommend publication with major revisions and I hope the authors would address the following points.

=> Again, thank you for the valuable comments and suggestions. Please find our responses to your major and minor comments below.

Major comments

p. 2, l. 13: It is not clear for me, what is meant by that quantification of drivers in the models would help to improve them. The forcing makes the models to behave exactly like they have been coded. Could you clarify your point a bit?

=> The reviewer is right that models respond to the meteorological forcing as they are designed. There can be biases, however, from the assumptions associated with the way that meteorological forcings are used to drive models. Some of them are made during a model development for convenience (e.g., applying globally averaged annual CO_2 instead of the spatially varying, 3-hourly CO_2), or some others are inevitable with limitations in the forcing data itself, such as lack of forcing variables. For example, a meteorological forcing does not provide direct and diffuse radiations but total radiation only, and an assumption to partition the total radiation into direct and diffuse radiations is necessary to compute modeled photosynthesis. Thus, quantification of drivers can help identify what parts of model processes and assumptions are responsible for causing the biases, and in turn, help improve the model. The sentence was revised for clarity (also see Page 2, Lines 12-14 of the revised manuscript).

[Previous]
Such quantification promotes essential understanding regarding what controls these fluxes, understanding that should, in turn, lead to improved models of terrestrial carbon processes.

[Revised]
Such quantification helps identify model processes and assumptions that are responsible for the uncertainty. It indeed promotes essential understanding regarding what controls these fluxes, understanding that should, in turn, lead to improved models of terrestrial carbon processes.

p. 3, l. 20: What do you mean by 'flux sensitivities'?
=> For clarify, the part was revised as follows (also see Page 3, Lines 21-23 of the revised manuscript).

[Previous]
We first evaluate the ability of the model to reproduce observationally-informed carbon flux estimates and flux sensitivities.

[Revised]
We first evaluate the ability of the model to reproduce observationally-informed carbon flux estimates. This evaluation includes a test of our model's response to artificially enriched CO2 – an imposed surplus of 200ppm, mimicking the surplus applied in an established field experiment.

Section 2.1. You should also mention, how the fires are treated in the model. Now their role is mentioned on p. 9, l. 8 and shown in one equation, and raises questions.
=> The fire was adopted as modeled in the CLM4 (Oleson et al., 2010). The flux is controlled by the amount of fuel (i.e., carbon pool) and the status of soil moisture. The fractional burned areas are computed at each time step (90 minutes using the Catchment-CN in this study) and the fire flux is estimated from the combusted fraction of the carbon pools. The description was added in Page 5, Line 28 in the revised manuscript.

p. 7, l. 29-30: I'm not sure I interpret your tests correctly. Why did you not study, how much annually changing co2 concentration (without spatial information) changes the results compared to your control? Because that test actually is the difference between the current way of doing

simulations and the control case here, and I'd consider that to be important. Or is this difference clearly seen in your results? If so, maybe you could clarify your message.
=> We agree with the reviewer. To address this important point, we modified the experimental design and performed a few additional simulations (maCO2, magCO2, and magtCO2; the additional simulations are highlighted in red in Figure L1 for the reviewer's convenience). The magCO2 case uses the "annually changing CO_2 concentration (without spatial information)", which is a popular and conventional way to prescribe the atmospheric CO_2 in many other LSM and TBM modeling studies. Please see the Section 3.4, and Tables 1 and 2 in the revised manuscript for further details.

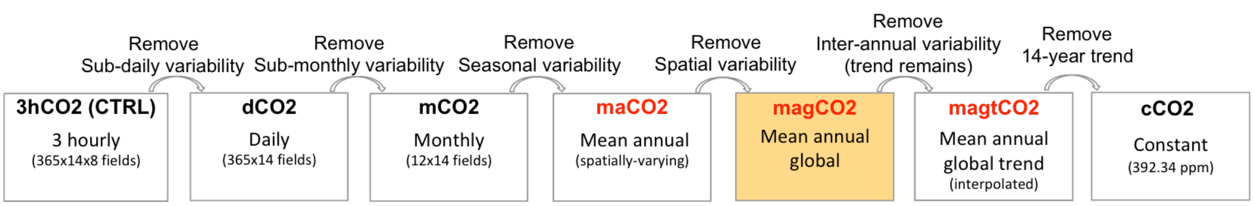

Figure L1: Revised schematic figure of the experimental design (revised Figure 1). The magCO2 indicates the common CO_2 forcing, "annually changing global CO_2". The additional simulations are highlighted in red for the reviewer's convenience.

Section 3.1.: Do you have knowledge, how CLM4 is going in this respect? If you have same latitudinal pattern, then it would be due to CN-dyanmics, if it's different, then it would be due to other features. Just a thought, that it might be interesting addition, in case you have that information available.
=> We implemented the CN dynamics from CLM4 into Catchment-CN, but did not run the original CLM4 because they are different models. Bonan et al. (2011) reported the pattern of CLM4 zonal GPP averaged over 1982-2004 (red curve in their Figure 5a – please see Figure L2a).

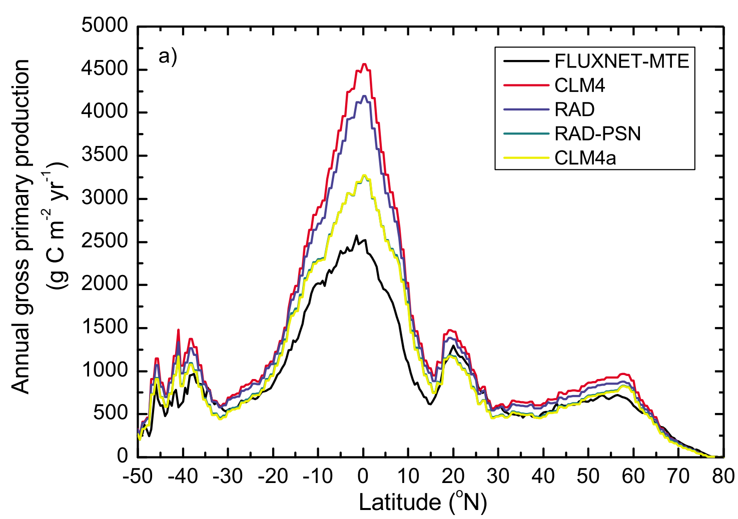

Figure L2a. Figure 5a in Bonan et al. (2011) study.

The zonal GPP of Catchment-CN in this study (averaged over 2002-2011) shows reduction the overestimated GPP in the tropics and agrees better with the MTE-GPP (please see Figure L2b). This is mainly attributable to the different meteorology, and the implementation of CN dynamics is minor. Please see our response to the referee's comment on p. 8, l. 19-27 below for further details. Also, please note that because we did not run the original CLM4 model, we choose not to modify the manuscript itself regarding this point.

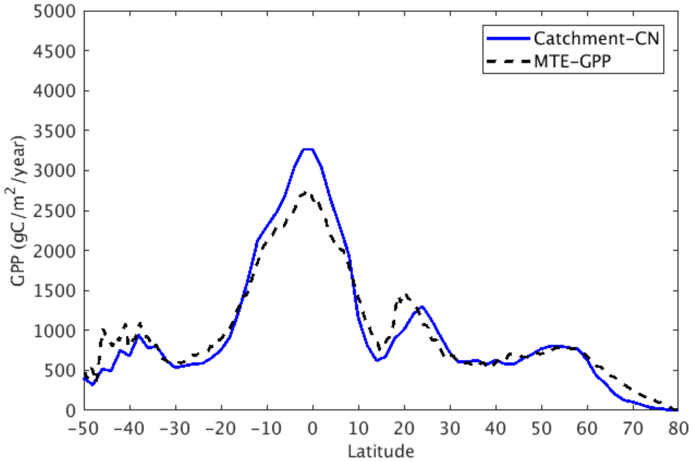

Figure L2b. Annual zonal mean GPP of Catchment-CN (2002-2011)

p. 8, 16-18: And how much is the contribution from Sahel in Catchment-CN in that latitude? You could explain this difference in a bit more detail, it seems quite big GPP for Sahel region. How about comparing the results with the same land mask, would that be possible?

=> As suggested, we regridded the Catchment-CN landmask to match to the MTE-GPP landmask and applied the same mask. Previously, the Catchment-CN land mask (Figure L3a) included them as land grids with non-zero values, while the MTE-GPP land mask excluded a majority of the values from the Sahel region. The revised land mask is shown in Figure L3b below.

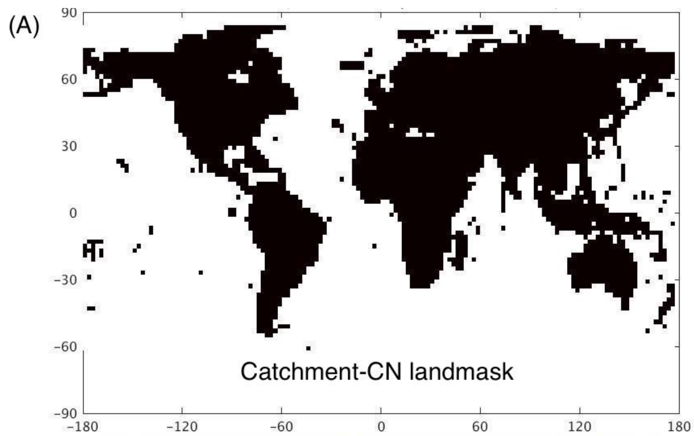

Figure L3a. Landmask of Catchment-CN (previous)

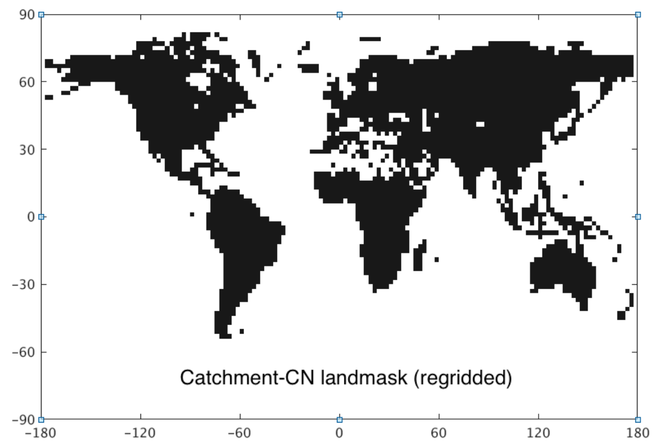

Figure L3b. Landmask of Catchment-CN (regridded)

By applying the revised landmask to the Catchment-CN (Figure L3b), the zonal GPP of Catchment-CN (Figure L3d) shows a better agreement to the MTE-GPP, confirming that a majority of the zonal GPP difference around the 20N results from the choice of land mask. The GPP estimates and Figure 2 in Section 3.1 were revised accordingly.

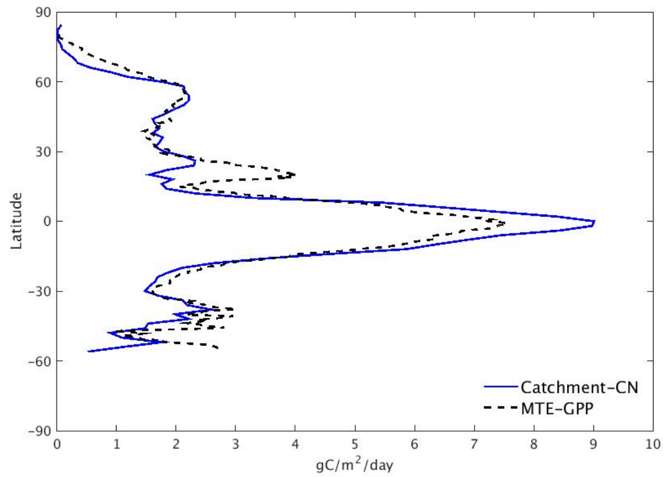

Figure L3c. Zonal GPP (previous Figure 2c)

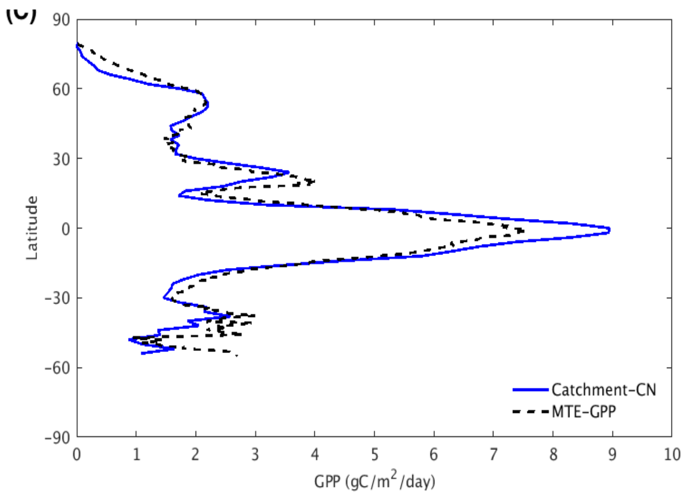

Figure L3d. Zonal GPP with regridded landmask (revised Figure 2c).

p. 8, l. 19-27: Could you make a table, where you compare your modelling results for the actual time periods of your references here? If I understand correctly, you had over 30 PgC difference in global GPP when adapting CLM to Catchment-CN. Is that really right? Because these revisions for CLM4.5 were then not adapted to Catchment-CN, or were they? If my first interpretation was right, could you comment, why you had such a change in your adaptation.

=> As briefly mentioned above, a majority of over 30 PgC/yr GPP difference results from the choice of meteorology. The GPP change associated with the model implementation is minor.

Bonan et al. (2011) reported the NCAR CLM4's GPP value as 165 PgC/yr (averaged over 1982-2004) when their model was forced with the NCAR/NCEP reanalysis meteorology. We tested a case to force Catchment-CN with a very similar metorology (i.e., Princeton meteorology: Sheffield et al., 2006) that is based on the same NCEP reanalysis as in NCAR CLM4 meteorology. Averaged over the same time period (1982-2004), the model mean GPP was estimated to be 162 PgC/yr.

This indicates that model implementation is attributable to only a few PgC/yr difference. Being forced with very similar environmental variables, GPP values from both models (CLM4 and Catchment-CN) fall into a similar range.

On the other hand, by applying the MERRA-2 meteorology to the Catchment-CN model, the GPP difference is much larger (35 PgC/year, from 162 PgC/yr to 127 PgC/yr), explaining the majority of GPP difference between Bonan et al. (2011) study and this study. Therefore, it is the choice of meteorology (MERRA-2) that results in a better agreement of Catchment-CN GPP to the MTE-GPP. Our finding on the role of the metorology in estimating the carbon fluxes is also consistent with a previous study by Poulter et al. (2011).

Please see the summary in Table L1. Also, the explanation was included in Page 9, Lines 4-5 of the revised manuscript.

	Catchment-CN with MERRA-2 meteorology (This study)	Catchment-CN with Princeton meteorology	Bonan et al. (2011)
Meteorology	MERRA-2	Sheffield et al. (2006)	NCEP/NCAR reanalysis
Model	Catchment-CN	Catchment-CN	CLM4
Average over	1982-2004	1982-2004	1982-2004
CO2	Increasing CO_2 with diurnal variability applied	Increasing CO_2 with diurnal variability applied	Spatially uniform, annually increasing CO_2
GPP	127 PgC/yr	162 PgC/yr	165 PgC/yr

Table L1. Effects of meteorology vs. model implementation. The spin-up process of the Catchment-CN with the Princeton meteorology was done separately from the case using MERRA-2: both reaching to an equilibrium for year 1850 with the choice of the meteorology and then conducting a transient CO_2 simulation from 1850 onward.

As a side note, among the environmental variables, we found that the total amount of input radiation and the partitioning ratio of direct vs. diffused photosynthetically active radiation (PAR) are attributable to GPP estimation. The radiation change alone explains at least half of the GPP change.

Regarding implementation of CLM 4.5 into Catchment-CN, the effort is being made and the version of the model was not available at the time when this study was conducted.

Section 3.2.: For the supplement plot I'd add GPP with MTE-GPP for the different seasons as a function of latitude also. This would highlight more, if the low northern hemisphere summer values are caused by respiration or gpp.

=> The suggested plots for DJF, MAM, JJA and SON are now included in the supplementary information (Figure S1). Together with the new figure 2d (annual cycles of Catchment-CN GPP vs. MTE-GPP), the overall lower summer carbon sink in part can be explained by the lower model GPP in July and August. The smaller regional sink of the Catchment-CN in the Northern Hemisphere during JJA (Figure S2c) also possibly results from GPP (Figure S1c).

p. 9, l. 8: Why not make a subplot to Fig. 3, where you show annual cycles of GPP, respirations and fire? Now the seasonality of GPP is not really visible anywhere.
=> As mentioned above, we included the GPP seasonality in Figure 2d that compares Catchment-CN GPP to MTE-GPP. The suggested figure showing annual cycles of model carbon components (GPP, respirations, fire, and NBP) is included in the supporting information (Figure S3).

Section 3.3.: I find the way that FACE experiments have been used to “evaluate” the model performance a bit problematic, but maybe this is just a matter of more in-depth explanation by the authors. The authors claim here, that the NPP response for enhanced CO2 concentration is similar than with other models. But this is after several years of experiments, when other factors, such as nitrogen cycle come into play. If I’ve understood right, in this study the aim was to see how Catchment-CN responses to different CO2 fields and therefore I’d suspect the response of the model to CO2 responses in short time scales is relevant. E.g. Zaehle et al. (2014) mention that the NPP response of CLM4 (which is the basis of the Catchment-CN biochemistry) is too low after the first year. It would be this response that is more relevant considering the aim of this study.
=> We agree with the reviewer that the model’s response to CO_2 enrichment in a shorter time scale is more relevant to the purpose of this study. In the revised manuscript, we now report the first-year NPP response of the Catchment-CN to the 200ppm enrichment and compare it to the observed and other models’ initial responses in Zaehle et al. (2014) (numbers from their Figure 5). Please see Page 10, Lines 16-21 of the revised manuscript.

The comparison to FACE experiments is not properly described. Did you do site level runs, or did you just do a global model run with increased CO2 concentration and then take data from the corresponding catchment? And when did you increase the CO2 concentration? Beginning of 2001, which is the time of your simulation, or already on the last years of the spinup, when the actual FACE experiment starts at the sites? That makes a difference in the light of N cycle, that you have on your model.
=> We performed a global-scale simulation (i.e., global CO_2 enrichment treatment) and compared the NPP from the closest tile to the two forest FACE experiment sites. The immediate CO_2 jump (step-wise increase by 200ppm) was applied at the beginning of year 2001, not the actual FACE experiment starting years (1996 for the Duke site and 1998 for the ORNL site). We applied MERRA-2 meteorology instead of the site-level meteorology. We have now clarified these points in the revised manuscript (Page 10, Lines 23-24).

While admitting potential bias from these caveats, we argue that reporting the first-year NPP can suit our purpose to evaluate the model’s degree of response to an excessive CO_2 enriched treatment. Our initial NPP increase (18 % for Duke site and 15 % for ORNL site) is found to be lower than observed responses but still greater than the original CLM4 NPP increase, and also is comparable to other model values. Please see our revised Section 3.3 for further details.

Also, the p. 13, l. 12-14 comment is only partly true, as in this longer time scale you are using in your evaluation also includes N cycle feedbacks. For the short time scales (& without step- wise large CO2 enhancement) it is true and actually for your aim also. I'd guess it's more a matter of how the stomates respond to increasing co2, i.e., much shorter time scale phenomena, that is important to your results, than what you're showing here.
=> Considering that this comment is a part of Section 3.3., we assumed that the argument is located on Page 10, Lines 12-14 of the original submission (if not, please correct us). We agree with the reviewer that the statement does not represent the focus of this study. To avoid confusion, we deleted the sentence in the revised manuscript.

p. 11, l. 14: What do you mean by this sentence? Usually in all modelling experiments annually varying co2 concentration would be used, it is not clear why this section 3.4.3. is relevant.
p. 11, Section 3.4.3: It is not clear for me, what was the motivation behind this test. Could the reason be explained somewhere more clearly?
=> With the revised experimental design (including the case forced with annual varying CO_2), the section is revised. Please see the Section 3.4 in the revised manuscript.

Fig. 8.: The largest changes in regions seem to be in R5, where perhaps the actual GPP is not that big. Could you also say something, where the highest changes are in absolute GPP values. And these are now changes in respect to the control and not the preceding test simulation?
=> The southern boundary of the TransCom region R5 (i.e., the equator; see the map in Figure 8L) includes a part of the African rainforest with high GPP (for spatial pattern, please also see Figure 3a). The southern part is where the GPP change associated with the CO_2 diurnal variability appears strongly (Figure 4b). In addition, as shown in the regridded land mask in the above (Figure L3b), the majority of the Saharan desert was excluded in the R5 GPP calculation. Therefore, in fact, the GPP value of R5 is not substantially smaller than any other regional values but is comparable to them (please see Figure L4 below).

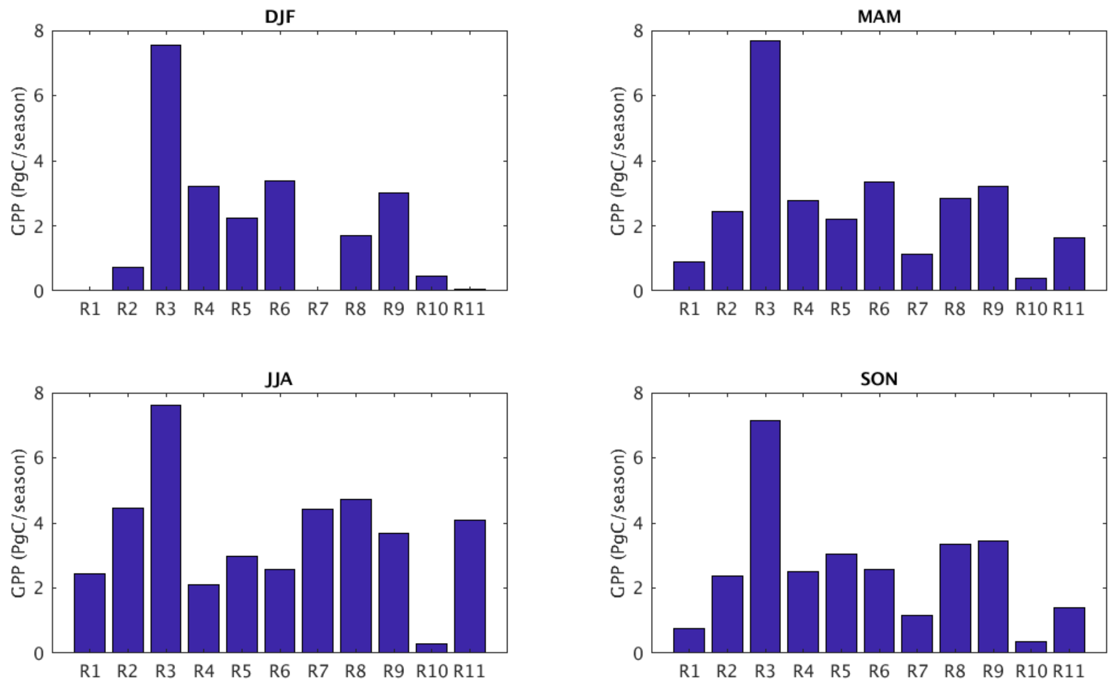

Figure L4. Histograms of regional GPP (PgC/season) for DJF, MAM, JJA and SON

To the last part of the comment, each GPP change (%) is to the preceding test simulation (this figure highlights the effect of each variability). A clarification was made in the legend of the revised Figure 8.

p. 14, l. 10: Can you explain this sentence about the 'rectifier effect' a bit more.
=> For clarity, we revised this part as (also see Page 14, Lines 29-30 of the revised manuscript):

[Previous]
They suggest that the diurnal 'rectifier effect' in a DGVM-based NBP…

[Revised]
They suggest that the diurnal 'rectifier effect', the substantial CO_2 covariations that are introduced with daily variations in photosynthesis and boundary layer turbulence, in a DGVM-based NBP…

p. 14, l. 12-14: But unfortunately the current DGCMs have larger problems, having exactly right co2 concentration won't solve them. . .
=> We agree with the reviewer that there are other issues that the DGVM carbon fluxes are more greatly affected. We highlighted in the abstract "the magnitudes of the sensitivities found

here are minor". Also for clarity, we revised the sentence as below (also see Page 14, Lines 32-34 of the revised manuscript).

[Previous]
Furthermore, they suggest that if the land surface carbon dynamics component of a modeling system is not coupled to the atmosphere with a sub-daily time step, the evolution of land carbon (e.g., in a climate change study) will not be realistic.

[Revised]
Furthermore, they suggest that if the land-carbon component of an Earth modeling system is not coupled to its atmospheric component with a sub-daily time step (e.g., in a climate change study), the bias can be carried into the evolution of regional and seasonal land carbon dynamics , albeit the global effect may be minor.

p. 14, l. 15-20: Yes, this is quite basic knowledge, but usually this is connected to large CO2 changes (e.g. FACE experiments) or extreme events. It would be interesting to hear some further motivation, why you consider that your current model runs (where the changes in co2 conc are nevertheless quite modest) promising tool to be used in this direction.
=> We revised this part as (also see Page 15, Lines 1-3 of the revised manuscript):

[Previous]
Finally, increasing CO_2 has been shown in field experiments (McCarthy et al., 2010; Norby and Zak, 2011) to foster biomass production (Huntingford et al., 2013). Under a CO_2-enriched environment, plants obtain CO_2 through the open stomata more efficiently and thereby lose less water to the atmosphere, allowing them to be more productive in dry regions or seasons. This process can alter the seasonality of the water cycle (Lemodant et al., 2016) as well as estimates of the plants' productivity in water-limiting areas (Swann et al., 2016). While our results in fact indicate, on their surface, a negligible impact of spatio-temporal CO_2 variability on water cycle variations (not shown), more careful analysis of the data may reveal some interesting connections.

[Revised]
Finally, our results indicate indicate a negligible impact of spatio-temporal CO_2 variability on water cycle variations through their impacts on stomatal conductance and thus evapotranspiration (not shown). The interaction between the water and carbon cycles in this study is thus limited; more careful analysis in a fully coupled modeling system, however, may reveal some interesting connections.

Overall, this is a bit off from the scope of this study, but one also starts to wonder, what kind of influence the atmospheric transport model will have on LSM results. In this study CT results are used, so they are result of inversion, but would the authors consider it worthwhile mentioning, based on their results, what kind of errors are to be expected, when doing e.g. a coupled run with land and atmosphere models.

=> In a coupled system, if the land carbon cycle is not directly coupled to the atmosphere (in other words, only water and energy cycles are coupled), the land component would need a prescribed atmospheric CO_2 from somewhere such as CarbonTracker. If the AGCM is not from the same model family (for example, TM5 for the CarbonTracker), the transport model error can be carried in the evolution of the modeled land carbon flux from the inconsistency. To avoid this, one can use a CO_2 dataset that uses a transport model from a same model family to the choice of AGCM.

As this study is a sensitivity study applying the CarbonTracker (i.e., using a single transport model) to an LSM, our findings on the *relative* importance of variabilities (not the absolute model GPP values) would not be influenced by the error associated with the choice of the transport model. However, the choice of inversion (for example, CarbonTracker vs. MACC) as an input to an offline LSM would make the *absolute* GPP values as shown in Liu et al. (2016).

Minor comments

Many of the figures are having only unit instead of the variable name on the axis. I recommend adding the name, so that it's not necessary always to check that from the caption.
=> The figures were revised as suggested.

Table 1: Could you also have delta between the different tests and CTR?
=> As suggested, we included a supplementary table (Table S2) showing GPP and NBP changes compared to the control simulation (3hCO2). Also, we included another table (Table 2) showing the changes to the magCO2 (i.e., annually increasing global CO2; the common CO_2 forcing).

Fig. 2: a & b) You're having the model output and MTE-GPP shown on different spatial resolutions. For a visual comparison, I'd show them on the same resolution.
=> As suggested by the reviewer, Figure 2b (MTE-GPP) was regridded into the same spatial resolution of the Catchment-CN model output (2 degree x 2.5 degree). Please note that 2 degree x 2.5 degree is for the visualization purpose only.

l.1: It would be interesting to know, how many PFTs you have available.
=> Total 19 PFTs were used in Catchment-CN model, as the text in section 2.1 now states. The details are listed in the supplementary table (Table S1).

p. 4, l. 12: You could list the environmental variables effecting your photosynthesis calculation. Now the temperature dependence of Vcmax is not mentioned (that I'd suspect to be included).
=> We listed the names of environemtal variables from the forcing in Page 4, Line 8.

[Previous]
Atmospheric CO_2 concentrations directly affect leaf photosynthesis (A)..

[Revised]
The environmental variables (temperature, precipitation, radiation, humidity, wind and atmospheric CO_2 concentrations) directly affect leaf photosynthesis (A)..

And the temperature dependence of Vcmax is now mentioned in Page 4, Line 19.

"V_{cmax} is the maximum rate of carboxylation (μmol CO_2 m^{-2} s^{-1}) that varies according to the leaf temperature, soil water and daylength."

Also, a sentence in the experimental design was revised for clarity (Page 7, Lines 23-25).

"We performed a series of six experiments covering the period 2001-2014 (applying the same meteorology except for the atmospheric CO_2 concentrations and using the same 2001 initial conditions as the control)"

p. 4, l. 20: Do you mean canopy temperature by the vegetation temperature? So, it's not air temperature, but you resolve for canopy temperature, right?
=> The reviewer is right that it means the canopy temperature. In the NCAR CLM4 tech note (Oleson et al., 2010), the variable T_v is referred as either vegetation temperature or leaf temperature. We chose leaf temperature to replace vegetation temperature in the revised manuscript (Page 4, Line 21).

p. 5, l. 13: You could mention the range of m.
=> The values of m are included in the main text. In Page 5, Line 12, it was revised as:
"where m is a parameter dependent upon plant functional type (m = 5 for C4 grass, 6 for needleleaf trees, and 9 for all other types)"

The m values are from Table 8.1 in CLM4 tech note (Oleson et al., 2010).

p. 5, l. 21: And how is GPP tied to the photosynthesis? How do you upscale the photosynthesis for larger scale? And do you have considerations for photorespiration, or was that considered already earlier?
=> Leaf photosynthesis and GPP refer to the same variable in essence, but in different units. In the model calculation, leaf photosynthesis is expressed in units of μmol CO_2 m^{-2} s^{-1} and GPP in units of gC m^{-2} s^{-1}. We estimated a grid-level photosynthesis (GPP) by taking a weighted average by each tile that contains the information of PFT-fractional photosynthesis. This is now mentioned in Page 5, Lines 16-18.

"A grid-level GPP is tied directly to the computed photosynthesis by taking a tile-based (i.e., catchment delineated) area weighted average of A".

We do not consider photorespiration in our model calculations. As mentioned in the manuscript, the carbon modules of the Catchment-CN model are from the NCAR CLM4, and there is no variable that takes account of "photorespiration" in their CLM4 technote (Oleson et al., 2010).

p. 5, l. 27: You already mention this on p. 4, l. 3.
=> Thanks for pointing it out. The abovementioned sentence in the previous page (i.e., in the first paragraph of Section 2.1.) was deleted to avoid redundancy. We kept the sentence at the last paragraph of Section 2.1.

p. 7, l. 29: typo, averaging...
=> Corrected.

p. 8, l. 4-6: Why are you having this sentence here? I'd find a more logical place for it to be in the Methods and model description.
=> As suggested, we moved the sentence to the model description (Page 4, Lines 6-7).

p. 9, l. 11: What does "dominating temperate or boreal forests" mean?
=> For clarity, the part "where the dominating temperate or boreal forests show strong seasonality" was deleted.

p. 9, l. 23: Why are you talking about fields?
=> We replaced the word "fields" with "plots" (e.g., as referred to describe the Duke FACE experiment) in the revised manuscript.

p. 10, l. 12: "perhaps not a surprise" doesn't sound very scientific argumentation, I recommend rephrasing
=> The sentence was deleted in the revised manuscript.

Section 3.4: Why not add the experiment names to the section names? It would make it easier to follow.
=> The experiment names were included in the revised manuscript.

p. 11, l. 11: typo, interannual
=> Corrected.

Fig. 8. In my version the longitudes are in middle of the map, it might look better that they were along axis (if they need to be shown here).
=> The figures were revised.

Fig. S3: Was this the concentration at the lowest atmospheric level? Maybe could be mentioned in the caption
=> The reviewer is right that it is the surface-level atmospheric CO_2 concentration. The caption (now Figure S4) was revised.

References:
Bonan, G. B., Lawrence, P. J., Oleson, K. W., Levis, S., Jung, M., Reichstein, M., Lawrence, D. M. and Swenson, S. C.: Improving canopy processes in the Community Land Model version 4 (CLM4) using global flux fields empirically inferred from FLUXNET data, Journal of Geophysical Research, 116(G2), doi:10.1029/2010JG001593, 2011.

Liu, S., Zhuang, Q., Chen, M. and Gu, L.: Quantifying spatially and temporally explicit CO2 fertilization effects on global terrestrial ecosystem carbon dynamics, Ecosphere, 7(7), e01391, doi:10.1002/ecs2.1391, 2016.

Oleson, K. W., D. M. Lawrence, G. B. Bonan, M. G. Flanner, E. Kluzek, P. J. Lawrence, S. Levis, S. C. Swenson, P. E. Thornton et al.: Technical Description of version 4.0 of the Community Land Model (CLM), http://www.cesm.ucar.edu/models/cesm1.1/clm/CLM4_Tech_Note.pdf, 2010.

Poulter, B., Frank, D. C., Hodson, E. L. and Zimmermann, N. E.: Impacts of land cover and climate data selection on understanding terrestrial carbon dynamics and the CO2 airborne fraction, Biogeosciences, 8(8), 2027–2036, doi:10.5194/bg-8-2027-2011, 2011.

Sheffield, J., Goteti, G. and Wood, E. F.: Development of a 50-Year High-Resolution Global Dataset of Meteorological Forcings for Land Surface Modeling, Journal of Climate, 19(13), 3088–3111, doi:10.1175/JCLI3790.1, 2006.

Zaehle, S., Medlyn, B. E., De Kauwe, M. G., Walker, A. P., Dietze, M. C., Hickler, T., Luo, Y., Wang, Y.-P., El-Masri, B., Thornton, P., Jain, A., Wang, S., Warlind, D., Weng, E., Parton, W., Iversen, C. M., Gallet-Budynek, A., McCarthy, H., Finzi, A., Hanson, P. J., Prentice, I. C., Oren, R. and Norby, R. J.: Evaluation of 11 terrestrial carbon-nitrogen cycle models against observations from two temperate Free-Air CO_2 Enrichment studies, New Phytologist, 202(3), 803–822, doi:10.1111/nph.12697, 2014.

Response letter to RC2

Dear Reviewer,

Thank you for the June 6th correspondence. We appreciate the helpful comments. In responding to them, we feel we have greatly improved the manuscript.

We have carefully addressed your comments and suggestions. Please find below our responses to them, prefixed with an arrow sign (=>). The figures in the letter are labeled and numbered with "L". The page and line numbers refer to the revised manuscript, if not noted otherwise.

Sincerely,

Eunjee Lee, Sc.D.
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The authors have produced a generally clear and well written paper that describes a set of model simulations that are designed to investigate the importance of spatio- temporal resolution of CO_2 forcing for global terrestrial carbon cycle models. They find that increased CO_2 forcing resolution has little impact on global aggregate GPP and NBP, but may be important in some regions and seasons.

Overall the paper represents a valuable contribution to the field. However I do have some concerns, or some suggestions that could increase clarity. My main concern is the design of the experiments; where variability in space or time is reduced, from 3hourly spatially varying CO_2 to 390ppm CO_2 that do not vary in time or space. In this line of variability reduction, the middle step includes removing interannual variability (trend + annual anomalies around the trend). I think the paper could be more clear if it ends with what models are commonly forced with, global, annual CO_2 concentrations that changes between years. Subsequent reductions in variability could be reported also, but those are less interesting.
=> Thanks for the comment. We agree with the reviewer and have accordingly modified the experimental design (please see Figure L1 below).

We performed a few additional simulations (maCO2, magCO2, and magtCO2; the additional simulations are highlighted in red in the Figure L1 for the convenience). The magCO2 uses the "annually changing co2 concentration (without spatial information)", which is a popular and conventional way to prescribe atmospheric CO_2 in many other LSM and TBM modeling studies. We split the interannual variability into two (i.e., annual anomalies and the trend) as suggested by the reviewer. The magtCO2 case removes the high frequency component of the interannual variability but keeps the longer-term trend.

The differences in GPP and NBP produced in each experiment relative to that produced in the magCO2 experiment (i.e., the one that applies the commonly utilized approach) are shown in Table 2. The results section (section 3.4) was also revised with the modified experimental design. Please see the revised manuscript for further details.

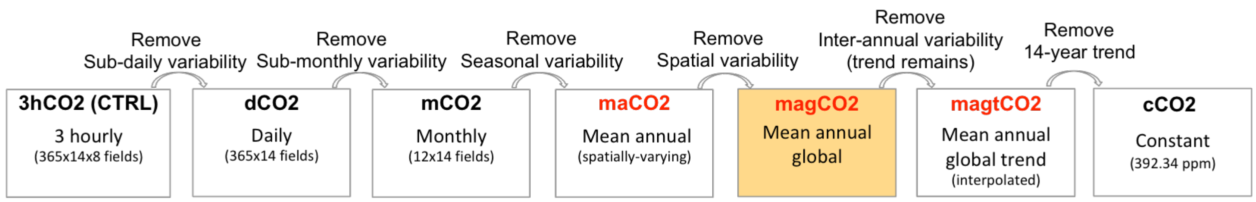

Figure L1: Revised schematic figure of the experimental design (revised Figure 1 in the manuscript). Three additional simulations are highlighted in red for the reviewer's convenience.

Page 7, line 23: it is not clear if global averages of CO_2 are preserved or not through the reductions. Interpolation of monthly means may change the sum of daily values (or 3 hourly). A clarification on this would be good.
=> In removing diurnal variations (from 3hCO2 to dCO2), there was no interpolation applied but simple daily mean values were used for every time step for a given model day. For 3hCO2 and dCO2, the global averages of CO_2 are conserved.

In removing daily variations (from dCO2 to mCO2), the interpolation to the monthly means results in a slight increase of the global average of CO_2 but the increase is very small (0.0009 %). Thus we consider the difference negligible. It was clarified in the revised manuscript (Page 7, Lines 31-32).

Minor comments:

Page 1, line 30, and continuing on page 2: sentence is unclear.
=> The part was revised as below (also see Page 1, Line 30 through Page 2, Lines 1-3 of the revised manuscript).

[Previous]
Studies disagree on portioning of the land carbon sink between the tropics and the extratropics, for example, tropical ecosystems as carbon sinks (Stephens et al., 2007; Lewis et al., 2009; Schimel et al., 2015; Houghton et al., 2015) or sources (Baccini et al., 2017).

[Revised]
For example, studies disagree on the partitioning of the land carbon sink between the tropics and the extratropics. Some studies consider tropical ecosystems to be carbon sinks (Stephens et al., 2007; Lewis et al., 2009; Schimel et al., 2015) and others consider them to be carbon sources (Baccini et al., 2017; Houghton et al., 2018).

Page 5, line 24 and throughout the paper: NBP is usually positive for a sink.
=> As suggested, the sign of the NBP now follows the convention (i.e., positive NBP means a carbon sink) in the revised manuscript. The signs of the NBP values in Figure 2, Equation 6 and in the text were revised accordingly.

Page 6, line 31: recycled instead of multiple loops? e.g. "with recycled 1981-2015 MERRA-2 forcing data"
=> For clarify, the part was revised as "consisting of repeated cycles of the 1981-2015 MERRA-2 dataset" (Page 7, Line 5).

Page 7, line 3: omit "simply"
=> The word was deleted.

Page 7 line 20: "every land surface element" is not clear
=> It was revised as "every tile" (Page 7, Line 27 of the revised manuscript). Please note that the tile structure was introduced and explained earlier in Page 5, Lines 16-18.

Page 8, line 17-18: Why not use the same mask for both datasets? Regridding may be needed.
=> We agree with the reviewer. In the revised manuscript, a regridded land mask (Figure L2b shown below) was used for a better match to the MTE-GPP landmask. The numbers and Figure 2 were revised using the revised landmask. As a result, the zonal GPP in Figure 2c in the revised manuscript shows a better agreement.

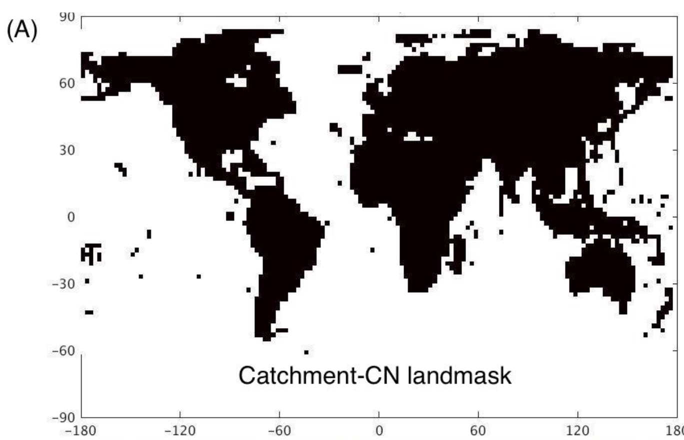

Figure L2a. Landmask of Catchment-CN (previous)

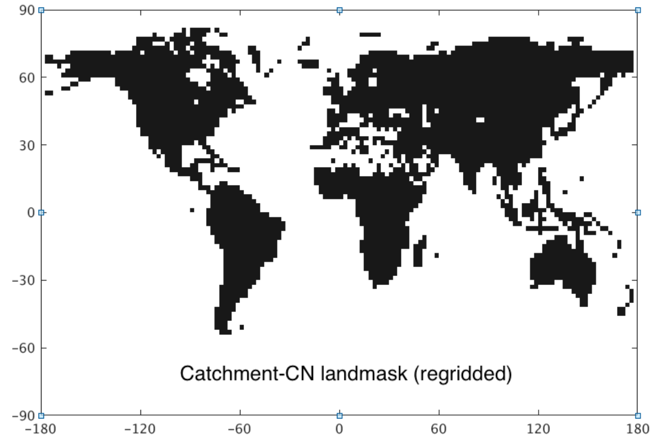

Figure L2b. Landmask of Catchment-CN (regridded)

Page 9, first paragraph: Why zonal GPP evaluation and seasonal NBP evaluation?
=> A new figure showing seasonal GPP evaluation (Figure 2d) is included in the revised manuscript. We also included zonal GPP evaluations for DJF, MAM, JJA and SON (Figure S1) in the supporting information. Please see Sections 3.1 and 3.2 for further details in the revised manuscript.

Page 9, last row, "this turns out" could perhaps be expressed better.
=> We revised it as "These results are at the low end of the observations…". Please see Page 10, Line 20 in the revised manuscript.

Page 10, line 12 " by the way, is perhaps not a surprise" could also be expressed better.
=> The sentence was deleted in the revised manuscript.

General; synoptic and daily are both used for the same reduction of variability, I recommend using one of to be consist
=> The word "synoptic" is replaced with "day-to-day" in the revised manuscript. Please note that there is one exception where the word "synoptic" remains (Page 11, Line 18) when it is used to describe the horizontal scale of weather, not to refer the temporal variability of CO_2.

Track-change manuscript

The impact of spatiotemporal variability in atmospheric CO_2 concentration on global terrestrial carbon fluxes

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Abstract. Land carbon fluxes, e.g., gross primary production (GPP) and net biome production (NBP), are controlled in part by the responses of terrestrial ecosystems to atmospheric conditions near the Earth's surface. The Coupled Model Intercomparison Project Phase 6 (CMIP6) has recently proposed increased spatial and temporal resolutions for the surface CO_2 concentrations used to calculate GPP, and yet a comprehensive evaluation of the consequences of this increased resolution for carbon cycle dynamics is missing. Here, using global offline simulations with a terrestrial biosphere model, the sensitivity of terrestrial carbon cycle fluxes to multiple facets of the spatiotemporal variability of atmospheric CO_2 is quantified. Globally, the spatial variability of CO_2 is found to increase the mean global GPP by a maximum of 0.05~~2~~ PgC $year^{-1}$, as more vegetated land areas benefit from higher CO_2 concentrations induced by the inter-hemispheric~~ce~~ gradient. The temporal variability of CO_2, however, compensates for this increase, acting to reduce overall global GPP; in particular, consideration of the diurnal variability of atmospheric CO_2 reduces multi-year mean global annual GPP by 0.5 PgC $year^{-1}$ and net land carbon uptake by 0.1 PgC $year^{-1}$. The relative contributions of the different facets of CO_2 variability to GPP are found to vary regionally and seasonally, with the seasonal variation in atmospheric CO_2, for example, having a notable impact on GPP in boreal regions during fall. Overall, in terms of estimating global GPP, the magnitudes of the sensitivities found here are minor, indicating that the common practice of applying spatially-uniform and annually increasing CO_2 (without higher frequency temporal variability) in offline studies is a reasonable approach – the small errors induced by ignoring CO_2 variability are undoubtedly swamped by other uncertainties in the offline calculations. Still, for certain regional- and seasonal-scale GPP estimations, the proper treatment of spatiotemporal CO_2 variability appears important.

1 Introduction

Quantifying the sources and sinks of carbon at the land surface is key to an accurate carbon balance and to the overall assessment of where anthropogenically released fossilized carbon ends up in the Earth system. While current estimates suggest that the land absorbs the equivalent of about a quarter of anthropogenic CO_2 emissions (IPCC, 2014), the uncertainty in the global carbon budget associated with terrestrial ecosystem processes is large (Le Quéré et al., 2016). For example, s~~S~~tudies disagree on the paortitioning of the land carbon sink between the tropics and the extratropics. So~~,~~ me studies~~, for example,~~ consider tropical ecosystems ~~as~~ to be carbon sinks (Stephens et al., 2007; Lewis et al., 2009; Schimel et al., 2015~~; Houghton et al., 2015~~) ~~or~~ and others consider them to be carbon sources (Baccini et al., 2017; Houghton et al., 2018). A substantial interannual variability is found in the tropical carbon balance, primarily in response to climate-driven variations (Baker et al., 2006; Cleveland et al., 2015; Fu et al., 2017); indeed, tropical ecosystems represent a large fraction of the uncertainty in estimates of the total land carbon sink and its future trajectory (Pan et al., 2011; Wang et al., 2014). Carbon fluxes in boreal ecosystems also remain highly uncertain and are likely to be strongly influenced by changes in climate and the length of growing season. Warming over Northern lands may lead to an increase in vegetation productivity (Xu et al., 2013) and to a greater amplitude of seasonal CO_2 exchange (Forkel et al., 2016) via climate-induced changes in phenological seasonal cycles (e.g., earlier vegetation "green-up"~~s~~).

Because terrestrial carbon dynamics are greatly influenced by atmospheric forcing ~~from the atmosphere~~ (e.g., air temperature, precipitation, radiation, humidity, CO_2 concentration), quantifying the sensitivity of surface carbon fluxes to variations in atmospheric drivers is critical to obtaining accurate flux estimates. Such quantification helps identify model processes and assumptions that are responsible for the uncertainty. It indeed~~, and~~ promotes essential understanding regarding what controls these fluxes, understanding that should, in turn, lead to improved models of terrestrial carbon processes. Only with accurate models can we obtain reasonably accurate projections of climate under different emission scenarios.

While the impacts of some aspects of atmospheric variability, such as that of temperature and precipitation, on global land carbon fluxes have been explored extensively (e.g., Beer et al., 2010; Poulter et al., 2014; Ahlström et al., 2015), the impact of atmospheric CO_2 variability on the fluxes is relatively understudied and is in fact generally ignored in recent flux estimation exercises. In most land surface models (LSMs) or terrestrial biosphere models (TBMs) simulations, the atmospheric CO_2 applied is annually and/or spatially uniform (e.g., TRENDY project, Sitch et al., 2015) or allowed to vary only on a monthly and/or zonal basis (e.g., Multi-scale Terrestrial Model Intercomparison Project (MsTMIP), Huntzinger et al., 2013; Wei et al., 2014; Ito et al., 2016). Potential time variations in the carbon fluxes associated with the diurnal and ~~synoptic~~ ~~daily~~day-to-day variability, if monthly CO_2 is applied, and also with the seasonal variability, if annual CO_2 is applied, are not represented in these modeling studies. Likewise, the regional flux response to spatial variations in CO_2 is only partially represented with the latitudinal CO_2 driver and not at all with the spatially uniform CO_2 driver.

Such simplifications neglect lessons from decades of in-situ measurements showing that CO_2 concentrations vary widely on different time and space scales. During the growing season, daytime (nighttime) CO_2 at the canopy level can be significantly smaller (larger) than the daily mean CO_2 due to the diurnal cycle of photosynthesis. Summertime measurements, for example, at an 11-m tower in northern Wisconsin indicate that the atmospheric CO_2 concentration fluctuates by approximately 70 ppm over the course of a day, from 350 ppm ~~at daytime~~during the day to 420 ppm at night (Yi et al., 2000); indeed, the day/night difference is comparable to the global atmospheric CO_2 growth of the last few decades (~63 ppm since 1980). In addition to large diurnal variations, many stations observe strong seasonal variations in CO_2 concentrations; for example, such variations are as large as 30 ppm at the Hegyhátsál monitoring site in western Hungary (e.g., Haszpra et al., 2008).

Spatial variations in CO_2 are also known to be significant. ~~The covariance between flux processes and atmospheric transport, for example, results in a phenomenon called the 'rectifier effect' wherein substantial spatial variations are introduced into simulated CO_2 fields, even when an annually balanced biosphere flux is assumed (Denning et al., 1995; 1999).~~ Concentrations of CO_2 contain large spatial gradients with higher annual mean values found in the Northern Hemisphere than in the Southern Hemisphere due to the higher level of fossil fuel ~~burning~~ emissions (Tans et al., 1989). Higher annual mean concentrations are evident over land masses, particularly those with large anthropogenic emissions. In addition, t~~T~~he covariance between flux processes and atmospheric transport~~, for example,~~ results in a phenomenon called the 'rectifier effect' wherein substantial spatial variations are introduced into simulated CO_2 fields, even when an annually balanced biosphere flux is assumed (Denning et al., 1995; 1999).

In light of such known variations, the Coupled Model Intercomparison Project (CMIP6) is now encouraging modeling groups to force their 'offline' models with CO_2 concentrations that vary in space and time (Eyring et al., 2016). Ostensibly this makes sense, given that relevant datasets on temporal and spatial CO_2 variations are available for use (Meinshausen et al., 2017). Nevertheless, it seems appropriate at the outset of such efforts to quantify the potential usefulness of this added complexity. It is still arguably unknown how much the uncertainty in estimated terrestrial carbon fluxes will decrease through the explicit consideration of CO_2 variations.

In a recent study, Liu et al. (2016) begin to address this issue – they use a TBM to show that the explicit consideration of the seasonal variation of CO_2 in modeling studies can lower the estimated terrestrial GPP by 0.4 PgC year^{-1} globally, and they also show that the consideration of the spatial variability of CO_2 can increase mean global GPP estimates by 2.1 PgC year^{-1}. There are, however, additional facets of CO_2 variability that are worth exploring. In particular, diurnal variations in CO_2 are known to be large (e.g., ~70 ppm in the central US and ~50 ppm in central Europe), and it is worth determining if, in ignoring these particular variations, process-based models produce significant errors in carbon flux estimation.

In this paper we provide an analysis of carbon flux sensitivity to spatial and temporal variations in atmospheric CO_2 that is duly comprehensive. We employ in this study a particular process-based terrestrial biosphere model, the Catchment-CN model of NASA's Global Modeling and Assimilation Office (GMAO). We first evaluate the ability of the model to reproduce observationally-informed carbon flux estimates. This evaluation includes a test of ~~and flux sensitivities. Then we test the degree of~~ our model's response to ~~an~~ artificially enriched ~~excessive~~ CO_2 ~~enriched treatment –~~ ~~(~~an imposed surplus of~~jump to~~ 200ppm, mimicking the surplus applied in an established field experiment~~ surplus), comparing it to the observed responses.~~ ~~Then~~~~Finally~~Then, in a carefully designed suite of simulation experiments, we quantify the sensitivity of monthly simulated GPP and NBP to different temporal and spatial scales of atmospheric CO_2 variability. The paper concludes with some discussion on the implications of the results for future carbon cycle research.

2 Methods

2.1 Catchment-CN model

The NASA Catchment-CN model (Koster et al., 2014) is a hybrid of two existing models: the NASA Catchment model (Koster et al., 2000) and the NCAR-Community Land Model version 4 (CLM4) (Oleson et al., 2010). The hybrid utilizes the code from the Catchment model that performs water and energy ~~cycle~~ budget calculations. The carbon and nitrogen dynamics from CLM4 provides to the hybrid all of the carbon reservoir and carbon flux calculations as well as photosynthesis-based estimates of canopy conductance for use in the Catchment model's energy balance equations. Unlike most land surface models, the surface element for Catchment-CN is the hydrological catchment (with a typical spatial dimension of about 20km); model equations further provide a separation of each catchment into three separate dynamic hydrological regimes, each with its own set of energy balance calculations. There are 19 available ~~up to four~~ Plant Functional Types (PFTs) (Table S1), and up to four PFTs are allowed in each of ~~the~~ three static sub-areas loosely tied to the three hydrological regimes. The model used a 10-minute time step for the energy and water balance calculations and a 90-minute time step for the carbon calculations. ~~. Note that~~ T~~t~~his model's ability to capture the observed sensitivity of phenological variables to moisture variations was demonstrated in~~by~~ Koster et al. (2014). ~~Note that land-use and land-cover change are not represented in this version of the Catchment-CN model.~~

~~For this study, the Catchment-CN model is driven with atmospheric fields from NASA's Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalysis (Gelaro et al., 2017, and also available at http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/). Since MERRA-2 fields are provided on a 0.5°×0.625° resolution grid, the forcing values for a given Catchment-CN tile are taken from the MERRA-2 grid cell whose center is closest to the tile's centroid. Precipitation forcing is the same as that used in the production of the Soil Moisture Active Passive (SMAP) level 4 product (Reichle et al., 2016); this precipitation is scaled to agree with rain gauge observations where available. All of our analysis is performed on tile-based (i.e., catchment delineated) fluxes, which efficiently excludes coastal water and lake water and thus allows for an accurate estimation of the aggregated land-based global carbon fluxes.~~

The environmental variables (temperature, precipitation, radiation, humidity, wind and atmospheric CO_2 concentrations) ~~Atmospheric CO_2 concentrations~~ directly affect leaf photosynthesis (A) in Catchment-CN (as in NCAR-CLM 4 (Oleson et al., 2010); see also Farquhar et al. (1980) and Collatz et al. (1991) for the C3 plants model, and Collatz et al. (1992) for the C4 plants model), which is predicted to be the minimum value (Eq. (1)) of Rubisco-limited photosynthesis (ω_c, Eq. (2~~1~~)), light-limited photosynthesis (ω_j, Eq. (3~~2~~)) and export-limited photosynthesis (ω_e, Eq. (4~~3~~)):

$$A = min\left(\omega_c, \omega_j, \omega_e\right) \qquad (1)$$

$$\omega_c = \begin{cases} \frac{V_{cmax}(c_i - \Gamma_*)}{c_i + K_c(1 + \frac{o_i}{K_0})} & \text{for } C_3 \text{ plants} \\ V_{cmax} & \text{for } C_4 \text{ plants} \end{cases}, \qquad (2~~1~~)$$

$$\omega_j = \begin{cases} \frac{(c_i - \Gamma_*)4.6\,\phi\alpha}{c_i + 2\Gamma_*} & \text{for } C_3 \text{ plants} \\ 4.6\,\phi\alpha & \text{for } C_4 \text{ plants} \end{cases}, \qquad (3~~2~~)$$

$$\omega_e = \begin{cases} 0.5\,V_{cmax} & \text{for } C_3 \text{ plants} \\ 4000\,V_{cmax}\,\frac{c_i}{P_{atm}} & \text{for } C_4 \text{ plants} \end{cases}, \qquad (4~~3~~)$$

where c_i is the internal leaf CO_2 partial pressure (Pa) and o_i is the O_2 partial pressure (Pa). K_c and K_o are the Michaelis-Menten ~~constants~~ parameters (Pa) for CO_2 and O_2, respectively, and vary according to the ~~vegetation~~ leaf temperature. Γ_* is the CO_2 compensation point (Pa), α is quantum efficiency, ϕ is absorbed Photosynthetically Active Radiation (APAR) (W m^{-2}), and V_{cmax} is the maximum rate of carboxylation (μmol CO_2 m^{-2} s^{-1}), which ~~that~~ varies according to the leaf temperature, soil water and daylength. Photosynthesis calculations of the type represented by Eq. (1)-(4~~3~~) are common in process-based land surface models (LSMs), including, for example, the Joint UK Land Environment Simulator (JULES) model (Walters et al., 2014) and the ORganizing Carbon and Hydrology In Dynamic Ecosystems Environment (ORCHIDEE) model (Krinner et al., 2005).

Leaf photosynthesis (μmol CO_2 m^{-2} s^{-1}; denoted as A) can also be expressed in terms of the diffusion gradient and stomatal conductance for CO_2 between the ambient atmosphere, the leaf surface and the internal leaf:

$$A = \frac{c_a - c_i}{(1.37\,r_b + 1.65 r_s)P_{atm}} \quad \text{(between atmosphere and internal leaf)}, \qquad (5~~4~~a)$$

$$= \frac{c_a - c_s}{(1.37 r_b)P_{atm}} \quad \text{(between atmosphere and leaf surface)}, \qquad (5~~4~~b)$$

$$= \frac{c_s - c_i}{(1.65\,r_s)P_{atm}} \quad \text{(between leaf surface and internal leaf)}, \qquad (5~~4~~c)$$

where r_b is boundary layer resistance and r_s is leaf stomatal resistance (~~μmol~~ m^{-2} s^{-1} μmol^{-1}), and where c_a is the CO_2 partial pressure of ambient atmosphere and c_s is the pressure at leaf surface ~~.~~ (Note that Eq 5a is a consequence of the others, Eq. 5b and Eq. 5c).

Using the Ball-Berry model of stomatal conductance (Ball et al., 1987; Collatz et al., 1991), r_s is expressed as a function of A, c_s, and vapor pressures (e_s, the vapor pressure at the leaf surface, and e_i, the saturation vapor pressure inside the leaf):

$$\frac{1}{r_s} = m\,\frac{A}{c_s}\frac{e_s}{e_i}P_{atm} + b, \qquad (6~~5~~)$$

where m is a parameter dependent upon plant functional type (m = 5 for C4 grass, 6 for needleleaf trees, and 9 for all other types), and b is the minimum stomatal conductance (20000 μmol m^{-2} s^{-1}). Assuming the initial value of c_i to be 0.7 c_a~~times~~ (for C3 plants) or 0.4 ~~t~~ c_a ~~imes~~ (for C4 plants) ~~the ambient CO_2 concentration~~, the Catchment-CN model simultaneously computes the leaf photosynthesis (A) from Eq.(1)-(4~~3~~). This value of A is then used to estimate c_s in Eq. (5~~4~~b) and r_s in Eq.

(65), as well as c_i in Eq. (54c), which is inserted back into Eq. (21)-(43) for another calculation of A. The iteration cycle proceeds three times to obtain the final value of A. A grid-level GPP is tied directly to the computed photosynthesis by taking a tile-based (i.e., delineated catchment) area weighted average of A.

NBP was is calculated as:

$$\mathrm{NBP} = -\mathrm{GPP} - + R_a - + R_h - + F, \qquad (76)$$

where the GPP is tied directly to the computed photosynthesis, R_a is the autotrophic respiration (through plant growth and maintenance), R_h is the heteorotrophic respiration (through litter and soil decomposition), and F is fire carbon flux. Positive (negative) NBP values mean that the land surface is a carbon sinkource (sourceink). The respiration terms R_a and R_h were calculated as in the NCAR-CLM4, except for a modification to R_h, imposed here, that prohibits decomposition if the soil water is frozen. With this modification, the Catchment-CN's NBP showed a better agreement to with atmospheric inversion estimates in the Northern high latitude regions during December through February. The fire term (F) is controlled by the amount of available fuel and the status of soil moisture. Note that our study did not consider carbon flux changes associated with land use (e.g., deforestation).

2.2 Datasets for model evaluation and comparison

Given that no direct measurements of GPP exist at the global scale (Anav et al., 2015), we evaluate the GPP values produced in our control simulation against GPP estimates from the data-derived FLUXNET Model Tree Ensembles (MTE) GPP project (hereafter referred to as MTE-GPP) (https://www.bgc-jena.mpg.de/geodb/projects/Home.php). This global-scale, monthly, gridded dataset effectively consists of upscaled observations from the eddy-covariance towers of the FLUXNET network; the upscaling utilizes the the MTE approach with inputs of: (i) meteorological data, (ii) the fraction of absorbed photosynthetically active radiation (fPAR) derived from the Global Inventory Modeling and Mapping Studies (GIMMS) normalized difference vegetation index (NDVI), and (iii) land cover information (i.e., vegetation type) (Jung et al., 2009; 2011). The flux partitioning method utilized was from Lasslop et al. (2010). This dataset is widely used for performance evaluation of TBMs including CLM (e.g., Bonan et al., 2011).

The net carbon fluxes (i.e., NBP) of the Catchment-CN model were evaluated against estimates from three atmospheric inversions: Monitoring Atmospheric Composition and Climate (MACC) v14r2 (Chevallier et al., 2011; http://macc.copernicus-atmosphere.eu/), CarbonTracker 2015 (Peters et al., 2007, with updates documented at http://carbontracker.noaa.gov), and Jena-CarboScope v3.8 (Rödenbeck et al., 2003; http://www.bgc-jena.mpg.de/CarboScope/). The atmospheric inversion methods use atmospheric CO_2 concentration measurements in conjunction with an atmospheric transport model to provide a range of estimates of net carbon fluxes between the atmosphere and biosphere. The net carbon fluxes of the Catchment-CN model were also compared with fluxes estimated by the diagnostic Carnegie Ames Stanford Approach (CASA)-Global Fire Emission Database (GFED, version 3) (Ott et al., 2015; van der Werf et al., 2010). CASA-GFED3 is widely-used dataset that is heavily constrained by satellite observations, including GIMMS fAPAR, as well as by MERRA-2 meteorology. The mean NBP of the 11 years (2004-2014) overlapping our control simulation were evaluated.

2.3 Experimental design

In all simulations examined in this study, the Catchment-CN model is driven with atmospheric fields from NASA's Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalysis (Gelaro et al., 2017, and also available at http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/). Since MERRA-2 fields are provided on a 0.5°×0.625° resolution grid, the forcing values for a given Catchment-CN tile are taken from the MERRA-2 grid cell whose center is closest to the tile's centroid. Precipitation forcing is the same as that used in the production of the Soil Moisture Active Passive (SMAP) level 4 product (Reichle et al., 2016); this precipitation is scaled to agree with rain gauge observations where available. Our control case imposes a maximum level of CO_2 variability. In the control simulation, the model is forced with time varying (at 3-hourly resolution) and spatially varying (at 3° longitude × 2° latitude resolution) global fields of CO_2 concentration over the period 2001-2014. The surface CO_2 fields are extracted from the NOAA CarbonTracker database (Peters et al., 2007) for this period (CT2015, http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/molefractions.php, accessed in August 2016). ~~For this study, the Catchment-CN model is driven with atmospheric fields from NASA's Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalysis (Gelaro et al., 2017, and also available at http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/). Since MERRA-2 fields are provided on a 0.5°×0.625° resolution grid, the forcing values for a given Catchment-CN tile are taken from the MERRA-2 grid cell whose center is closest to the tile's centroid. Precipitation forcing is the same as that used in the production of the Soil Moisture Active Passive (SMAP) level 4 product (Reichle et al., 2016); this precipitation is scaled to agree with rain gauge observations where available. All of our analysis is performed on tile-based (i.e., catchment delineated) fluxes, which efficiently excludes coastal water and lake water and thus allows for an accurate estimation of the aggregated land-based global carbon fluxes.~~

We achieved reasonable initial land carbon states for January 1, 2001 using a two-step approach. First, starting with carbon prognostic states already equilibrated over multiple millennia with a somewhat different modeling/forcing combination (including the use of present-day CO_2 concentrations), the Catchment-CN model was run for at least 2,000 additional simulation years under a spatially and temporally uniform CO_2 concentration of 280 ppm to mimic the pre-industrial era (i.e., before 1850), with meteorological forcing ~~extracted from multiple loops over the~~~~with~~consisting of repeated ~~re~~cycled~~s~~ of the 1981-2015 MERRA-2 dataset. In the second step, the period from 1850 to 2000 was simulated using CO_2 concentrations that varied diurnally, seasonally, and spatially and that grew linearly in time to match the observed CO_2 conditions (see below)~~and that varied diurnally, seasonally, and spatially~~. The meteorological forcing applied during this time was also the cycled 1981-2015 MERRA-2 forcing and thus was also not tied to true year-specific forcing (except for within the final 1981-2000 period);

such meteorological information is ~~simply~~ unavailable for the earlier part of the industrial period, and in any case, the main point of the exercise was to allow the carbon reservoirs in the land surface to respond to the gradual increase in CO_2 concentrations. The resulting status of the land ecosystem on January 1, 2001 was used as the initial condition for the control simulation and for all experiments.

The CO_2 concentration fields used during the 1850-2000 spin-up period were constructed as follows. First, the 3-hourly, spatially varying CarbonTracker CO_2 fields were averaged over 2001-2014 and over each month into a climatological 3-hourly diurnal cycle for each of the 12 months of the year (i.e., 96 fields – eight 3-hourly fields for each month at each grid location). The 12 diurnal cycles were then assigned to the middle of each month, and linear interpolation to each day-of-year produced 365 climatological diurnal cycles of CO_2 concentration. We applied these daily diurnal cycles in each year of 1850-2000 after scaling them with a year-specific scaling factor that forced the annual, global mean CO_2 concentration to increase linearly in time from 280ppm in 1850 to 311ppm in 1950 and then from this value to 375.5ppm in 2000 (to approximate the growth in CO_2 seen in the historical record; see http://www.eea.europa.eu/data-and-maps/figures/atmospheric-concentration-of-co2-ppm-1). All of the interpolation was performed in the time dimension only; the global spatial variation contained within the CarbonTracker data was retained.

The strategy behind our experiments is described in Fig. 1. We performed a series of ~~five~~ six experiments covering the period 2001-2014 (applying the same meteorology except for the atmospheric CO_2 concentrations and using the same 2001 initial conditions as the control), with each experiment removing, in turn, one facet of the spatio-temporal variability of atmospheric CO_2 concentration. In the first experiment (referred to as dCO2), the 3-hourly CO_2 diurnal cycle was averaged into a single daily value at every ~~land surface element~~tile, and these daily-averaged values were then used to force the Catchment-CN model. Comparing the results of this experiment to those of the control thus illustrates the impact of ignoring diurnal CO_2 variability on the modeled carbon fluxes. In the second experiment (mCO2), ~~synoptic~~~~daily-scale~~day-to-day variability in CO_2 was removed – the daily CO_2 concentrations used in dCO2 were averaged into monthly values, which were then linearly interpolated (as in the spin-up procedure) into a temporally smoothed version of the daily fields. Note that through the interpolation, the global average of CO_2 is conserved in essence. ~~Note that the daily fields used for mCO2 still retain the interannual variability of CO_2 inherent in the CarbonTracker data; this interannual variability was removed in the third experiment (mmCO2), in which the daily fields were derived from the climatological monthly values of CO_2 inherent in the 14 years of CarbonTracker data.~~ In the ~~fourth~~ third experiment (maCO2), seasonality in CO_2 was removed – the ~~multi-year,~~ annual average CO_2 from CarbonTracker above a surface element was applied to that element. Note that the ~~daily~~annual fields used for maCO2 still retain the ~~interannual~~spatial variability of CO_2 inherent in the CarbonTracker data; this spatial~~interannual~~ variability was removed in the ~~third~~fourth experiment (mag~~m~~CO2), in which the ~~daily~~globally uniform but yearly varying~~,~~ mean annual CO_2 fields were used. T~~T~~his experiment (magCO2) ~~) that is annually increasing global CO_2~~ replicates the commonly used CO_2 forcing fields applied in many other land modelling experiments. ~~fields were derived from the climatological monthly values of CO_2 inherent in the 14 years of CarbonTracker data.~~Finally, in the fifth ~~(magtCO2)~~ and sixth experiment~~s~~ ~~(eCO2)~~, different facets of the ~~all spatial~~interannual variability in CO_2 were~~as~~ removed. In the fifth experiment (magtCO2), year-to-year variations in globally averaged CO_2 were removed while retaining the overall mean trend; this was achieved by regressing the 14 annual mean values used in magCO2 against the year index and then using the resulting regression line to assign the annual values. ~~consecutively: removing anomalies by linearly interpolating 14 annual mean CO2 (magtCO2) and then lastly~~In the sixth experiment (cC02), ~~removing~~ the long ~~er~~-term trend was also removed by averaging the 14 annual values into a single number – in cCO2, ~~over the global land, 14 years, resulting in~~ a constant CO_2 concentration (392.34~~0~~ ppm) was applied everywhere, every 10 minutes.

All of our analyse~~i~~s were~~as~~ performed on tile-based fluxes. This~~,~~ ~~which~~ efficiently exclude~~s~~s coastal water and lake water impacts and thus allows for an accurate estimation of the aggregated land-based global carbon fluxes. ~~The resulting carbon fluxes were averaged to monthly values for our analyses.~~ We computed mean global GPP ~~(in units of PgC year^{-1})~~ by multiplying tile-based fluxes (in units of gC/m^2/s) by the associated tile area and then aggregating the areal totals over global land (excluding Greenland and Antarctica).~~.~~ ~~The resulting carbon fluxes were averaged to monthly values for our analyses.~~The mean global NBP was estimated in the same way.

3 Results

We evaluate in sections 3.1 and 3.2 the ability of the control simulation to produce reasonable GPP and NBP fluxes, and we examine in section 3.3 the model's ~~ability to reproduce observed sensitivities~~initial response ~~to variations in atmospheric~~to~~a~~ CO_2 ~~.~~enrichment ~~treatement~~. With this overview of model performance in hand, we analyze in section 3.4 the results of the experiments outlined in Fig. 1~~. Note that this model's ability to capture the observed sensitivity of phenological variables to moisture variations was demonstrated by Koster et al. (2014).~~

3.1 Evaluation of simulated GPP against the MTE-GPP dataset

The spatial pattern of the mean annual GPP simulated by the Catchment-CN in the control simulation (i.e., the case forced with spatially varying, 3-hourly atmospheric CO_2 fields) is broadly consistent with the MTE-GPP data over the period of 2002-2011 (Figs. 2a and 2b). ~~Catchment-CN tends to produce higher GPP in the tropics.~~ The generally higher values seen in the tropics for Catchment-CN are not surprising given that higher values were also found for CLM4 (Bonan et al., 2011), the parent model of Catchment-CN's carbon code. Also ~~-~~n~~N~~ote that because the MTE-GPP dataset is more reliable in regions with denser observations, and because measurement stations in the tropics are limited, MTE-GPP estimates in the tropics are subject to particular uncertainty (Anav et al., 2015). Outside the tropics, the model produces higher GPP values in southeastern China, southeastern Brazil and the North American boreal region but slightly lower values in western Europe. ~~The generally higher values for Catchment-CN are not surprising given that higher values were also found for CLM4 (Bonan et al., 2011), the parent model of Catchment-CN's carbon code.~~ The zonal means of the simulated GPP data and the MTE-GPP product in fact agree ~~reasonably~~ well (Fig. 2c), ~~and~~though the seasonal mean of the simulated GPP is slightly more evenly distributed throughoutover the a year than the MTE-GPP (Fig. 2d). . At 20N, however, despite its greater regional GPP in southern China, the zonal mean of the Catchment-CN GPP is smaller than that for MTE-GPP, presumably due to disparate land masks; the Catchment-CN model includes low GPP values in the Sahel, whereas MTE-GPP excludes this region The zonal means of the Catchment-CN GPP for each season also agree reasonably well with the MTE-GPP product (Fig. S1).–.

Averaged over the full simulation period (2001-2014), the Catchment-CN model predicts a mean global GPP of 130.6127.5 PgC year^{-1}. This value is essentially in the range, though at the high end, of estimates from MTE-GPP: 119 ±6 PgC year^{-1} for the period 1982-2008 (Jung et al., 2011) and, 123 PgC per year^{-1} for the period 1998-2005 (Beer et al., 2010), and 130 PgC year^{-1} for the period 2001-2010 (Slevin et al., 2017). The Catchment-CN's GPP estimate also lies within the range of mean global GPP predicted by other process-based LSMs or TBMs. CLM4, from which the Catchment-CN model's carbon modules were procured, produces an estimate of 165 PgC year^{-1}, – (Bonan et al., 2011). We found that a majority of GPP difference between the Catchment-CN of this study and the original CLM4 is attributable to the choice of meteorological forcing. Aand a version of the CLM model with revised treatments (which were adopted later in CLM 4.5) of canopy radiation, leaf photosynthesis, stomatal conductance, and canopy scaling produces a value of 130 PgC year^{-1} for the period of 1982-2004 (Bonan et al., 2011). The JULES model (Slevin et al., 2017) produces a value of 140 PgC year^{-1} for 2001-2010.

3.2 Evaluation of simulated NBP against multiple datasets

The mean global net carbon fluxes from our control simulation were compared with the CASA-GFED3 model estimates (which, in fact, serve as a prior to CarbonTracker (CarbonTracker Documentation CT2015 Release, 2016)) as well as against the three aforementioned atmospheric inversion estimates (MACC v14r2, CarbonTracker 2015, and Jena CarboScope v3.8). In Fig. 3, the phase of the climatological NBP from the Catchment-CN model (solid blue) agrees well with that of the inversions (dotted curves). These datasets agree, for example, on the time during spring at which the land shifts from being a carbon source to a carbon sink. The CASA-GFED3 model (solid red) shows a delay in the shift, a feature noted in previous studies (e.g., Ott et al., 2015).

The annual NBP from Catchment-CN (+-0.536 PgC year^{-1}) indicates that the land is a carbon sink, though the value is smaller than the mean of the sinks estimated by the three atmospheric inversions (-+3.2 PgC year^{-1}). The reason for the smaller value is unclear; we note only that the sink strength produced by the model reflects the net effect of a multitude of physical processes (underlying GPP, respirations, and fire) in the model, processes that can interact with each other in complex ways.

The seasonal and zonal dependence of the Catchment-CN NBP is, in any case, within the spread of the inversions and the CASA-GFED3 model (Fig. S2). The boreal summer (JJA) global carbon sink of Catchment-CN is approximately three quarters of the inversion estimates (Fig. 3) and is relatively weak in the Northern boreal ecosystem, where the dominating temperate or boreal forests show strong seasonality (Fig. S2c). This weaker summer global carbon sink is caused, in part, by the underestimated summer GPP (Fig. 2d) and perhaps also by the the respiration values produced (Fig. S3). During DJF, the model NBP agrees with the inversions and the CASA-GFED3 model estimates in the Northern Hemisphere, but it mostly follows the MACC v14r2 inversion in the Southern Hemisphere tropics where the inversions show disagreement in sign (Fig.

S2a). The spring and autumn NBP from the Catchment-CN lie within the range of the inversion estimates (MAM in Fig. S2b; SON in Fig. S2d).

3.3 Sensitivity of Catchment-CN Fluxes to enrichment of CO_2

Our analysis in section 3.4 will focus on how simulated GPP responds to various facets of the spatio-temporal character of the imposed atmospheric CO_2 forcing. It is thus particularly appropriate to evaluate the realism of the model's sensitivity to CO_2 variations.

The Large-Scale Free-air CO_2 Enrichment (FACE) experiments provide valuable data for such an evaluation. In these experiments, CO_2 iwas released into the air and advected by natural wind over the vegetation within experimental fieldsplots; the resulting CO_2 concentrations were increased by about 200ppm above ambient conditions. Net Primary Productivity (NPP) observations over the FACE plots these fields were compared to those over control fields plots that lacked thewith no CO_2 increase (e.g., Ainsworth and Long, 2004; Norby et al., 2005; Norby and Zak, 2011). Here we focus on two particular temperate forest FACE experiments: Duke FACE (35.58°N, 79.5°W) (Hendrey et al., 1999) and Oak Ridge National Laboratory (ORNL) FACE (35.54°N, 84.20°W) (Norby et al., 2001), well-documented field experiments that have been used in previous model-data comparison studies (e.g., Hickler et al., 2008; Piao et al., 2013; Zaehle et al., 2014; Walker et al., 2014). To mimic these FACE field experiments, we performed a supplemental numerical experiment with the Catchment-CN model (beyond the experiments outlined in section 2.3): the control simulation was repeated but with the atmospheric CO_2 forcing increased artificially by 200 ppm. In this supplemental experiment, the CO_2 enriched treatement was applied globally starting on 1 JanuaryJan 1, 2001, though we focus here on the simulated increases in , and Considering the land elements containing the Duke and ORNL FACE sites, and considering only the overlapping years (2001-2007 for Duke and 2001-2008 for ORNL), we computed the increase in simulated NPP (relative to the control simulation, (3hCO2), consideringwithin the land elements containing the Duke and ORNL FACE sites (i.e., the closest tile for each site). Because the original CLM4's NPP increase iswas found in a past study (with a similar experiment) to be low after the first year of the CO_2 enrichment, presumabptuously due to thean insufficient supply of mineralized nitrogen in the model for the plants' increased Nnitrogen demand associated with the CO_2-induced increase in the rate of photosynthesis (Zaehle et al., 2014), we evaluate hered only the first year's simulation of NPP that is more appropriate for the purpose of this comparison.. Note that we started the CO_2 enrichment in our first year NPP is for year 20011 as our global CO_2 enrichment treatment was applied at beginning of year 2001, whereas which is a slightly different year from the the actual FACE experiments began in earlier years starting years (August 1996 for Duke and April 1998 for ORNL).

In this CO_2 enriched supplemental simulation, the Catchment-CN model produces an 186% increase of in its first year NPP during the first year for the Duke site and a 152% increase for the ORNL site. This turns out toOurThese results are at the low end of the observations for the Duke site underestimates the observed responses of (325 ± 9 % (Duke) and underestimate the observed response at the ORNL site (25 ± 117 % (ORNL); the model does not capture the full sensitivity measured in the experiments. Thise underestimation of Catchment-CN's initial response must be kept in mind when interpreting our main results in the following section~~.~~ ~~field. It is possible that the underestimation is due to a nitrogen (N) limitation that down-regulates GPP, as was found for the original CLM4 model (Zaehle et al., 2014); the supply of mineralized nitrogen in the model may be insufficient for the plants' increased N demand associated with the CO_2-induced increase in the rate of photosynthesis~~. For example,~~to:~~ we ~~used~~forced our model with ~~the~~ MERRA-2 meteorology instead of the site meteorology ~~that the land carbon status may be different~~, and we applied the CO_2 stepwise increase ~~was applied in slightly~~in different years compared to the FACE experiment.~~,~~

~~This underestimation must be kept in mind when interpreting our model results below. Note, however, that despite the underestimation~~. In any case,~~,~~ our model results are still relevant to the interpretation and evaluation of the Dynamic Global Vegetation Model (DGVM)-based, bottom-up estimates of GPP and NBP found in the literature. ~~Zaehle et al. (2014) discuss the results of forcing multiple DGVMs with a 200 ppm increase in CO_2, along the lines of our own supplemental experiment.~~ For example, t~~T~~he average increase in NPP across the eleven ~~participating~~ DGVMs participating in a similar experiment ~~in that study~~ was about 2~~1~~6% (ranging from 9% to 35%) for the Duke site and 20~~13~~% (ranging from 7% to 30%) for the ORNL site (Zaehle et al., 2014; in their Figure 5), ~~very much in line~~ somewhat similar to ~~with~~ the increases found with our model. We can infer, then, that the sensitivities uncovered with our model experiments likely also apply to other models, including those providing global GPP and NBP estimates to the scientific community. ~~The agreement in the sensitivities, by the way, is perhaps not a surprise, given that the Catchment-CN model's treatment of the dependence of photosynthesis on atmospheric CO_2 is largely contained within Eq. (1)-(5), a set of equations similar to those used in many DGVMs.~~

3.4 Global-Scale Sensitivity of Carbon Fluxes to Imposed CO_2 Variability

Here we present the results of the experiments outlined in Figure 1, with each facet of variability considered separately.

3.4.1 Diurnal ~~Cycle~~ Variability of CO_2 (dCO2-3hCO2)

Figure 4 compares the results of dCO2 to those of the control simulation, thereby revealing the impact of the CO_2 diurnal cycle on simulated GPP and NBP. Figure 4a shows the time series of global mean GPP differences (dCO2 minus control) over the 14 year period; removing the diurnal variability clearly increases GPP, and the effect is particularly large in boreal summer (0.07 PgC month^{-1} , equivalent to 0.8 PgC year^{-1}). Figure 4b shows that most of the increases are in the tropics and in the far eastern areas of the Northern Hemisphere continents. Almost no region shows a decrease in GPP associated with the removal of the CO_2 diurnal cycle. As indicated in Table 1, removing the CO_2 diurnal cycle leads to an overall increase in global mean GPP of 0.497 PgC year^{-1} and a change in the global mean NBP of -0.100 PgC year^{-1}.

The changes evident in Fig. 4 make sense in the context of the daily variations in atmospheric CO_2 noted in many studies (e.g., Denning et al. 1995, 1999). In nature (and as captured in the control simulation), the nighttime atmospheric CO_2 within the planetary boundary layer is higher than the daily mean value due to the shutdown of photosynthetic activity. Correspondingly, mid-day CO_2 concentrations are lower near the surface due to the plants' photosynthetic uptake of CO_2. In experiment dCO2, applying the daily mean CO_2 concentration at all hours of the day has the effect of imposing a higher CO_2 concentration during daytime, when photosynthesis occurs, and this has the effect of artificially "fertilizing" the surface – the extra CO_2 imposed during daytime makes photosynthesis more productive, increasing GPP. The GPP change in the Tropics accounts for about two thirds of the mean global GPP change, which is not surprising given the region's high productivity over the whole year.

3.4.2 ~~Synoptic-Scale~~ ~~Daily~~Day-to-Day Variability of CO_2 (mCO2-dCO2)

The day-to-day variability of CO_2, as influenced, for example, by synoptic-scale weather and its impacts on atmospheric transport, is removed in experiment mCO2~~,~~ relative to experiment dCO2. Table 1 indicates a negligible impact of this modification on the simulated global GPP and NBP compared to the impact of~~using~~ ~~diurnally~~sub-daily ~~varying~~ CO_2~~.~~ variations. The impacts on the temporal changes in the carbon fluxes and on the spatial distribution of the fluxes are similarly minimal (not shown).

~~3.4.3 Interannual Variability of CO_2~~

~~In experiment mmCO2, the interannual variability of atmospheric CO_2 is removed – the mean (location-specific) seasonal cycle of CO_2 is applied instead. The increases in the global GPP seen early in the simulation (2001-2008) and the decreases seen in the later part (2009-2014) (Fig. 5a, showing results for mmCO2 minus mCO2) reflect the fact that the mmCO2 experiment no longer imposes the observed yearly growth rate of atmospheric CO_2. The 14-year mean GPP increases owing to removal of internannual variation of CO_2 are mostly in the tropics (Fig. 5b), leading to an additional change in global mean GPP of 0.078 PgC year^{-1} (Table 1). While this time-mean change is smaller than that associated with neglecting diurnal variability, the differences at the beginning and end of the period (1.4PgC year^{-1} between year 2001 and year 2014) are comparable to, or even larger than the diurnal variability impact. These larger differences may have relevance to some period-specific model-based GPP estimates in the literature.~~

3.4.3~~4~~ Seasonal Variability of CO_2 (maCO2-mCO2)

The ma~~ga~~CO2 experiment forces the land surface with ~~mean annual~~yearly averaged, but spatially varying, atmospheric CO_2. The resulting increases in GPP (ma~~a~~CO2 minus m~~m~~CO2) in Fig. 5~~6~~a thus ~~are indicative~~reflect the impact of seasonal CO_2 variations. By applying the ~~annual mean~~yearly averaged CO_2 concentration all year long, vegetation outside of the Tropics experiences higher CO_2 concentrations during the spring and summer seasons, when photosynthesis is highest, than ~~they~~ it would have otherwise; in nature photosynthetic drawdown of atmospheric CO_2 acts to reduce warm season CO_2 concentrations below the annual mean. The artificial warm season "fertilization" of the vegetation in the ma~~a~~CO2 case leads to an increase in growing season GPP (Fig. 5~~6~~a).

A comparison of Figs. 4 and 5~~6~~ shows that the influence of seasonal CO_2 variations is smaller than that of diurnal variations, which is consistent with the fact that the amplitude of the CO_2 seasonal cycle is about 10~20ppm while that of the diurnal cycle is about five times larger (up to ~120ppm) in boreal summer (Fig. S4~~3~~). The response of GPP to the seasonal variability of atmospheric CO_2 is highest in the Northern Hemisphere high latitudes (Fig. 56b), for which the distinction between cold season and warm season photosynthesis is largest. The regional- and seasonal-scale impact of this variability is further discussed in Section 3.5.

3.4.45 Spatial Variability of CO_2 (magCO2-maCO2)

Finally, Figure 67 shows the impact of applying in experiment mageCO2 a globally uniform mean annualyearly averaged atmospheric CO_2 rather than a spatially varying distribution (e.g., with the inter-hemisphere gradient). In contrast to the above impacts of reducing temporal variability, the loss of spatial variability of atmospheric CO_2 leads to a global GPP decrease (Fig. 67a, showing results for mageCO2 minus maCO2). This decrease in fact tends to partially offset significantly the global GPP increases seen in the other experiments. Loss of spatial variability of CO_2 results in an overall reduction in global mean GPP (relative to the value from aCO2) of -0.189 052 PgC $year^{-1}$ and a change in the global mean NBP of -0.01239 PgC $year^{-1}$.(Table 1).

Notably, the sign of the GPP change associated with the removal of CO_2 spatial variability is not globally uniform (Fig. 67b). In the absence of the large-scale inter-hemispheric gradient (Fig. S54), the GPP change is mostly negative in the densely vegetated areas of the Northern Hemisphere continents and positive in the Southern Hemisphere. GPP decreases are especially large in Europe, in the eastern US, in eastern China, and in tropical regions (e.g., the southeast Asia, Amazon and Congo rainforests), and these changes are only partially compensated by GPP increases in extratropical Southern Hemisphere land areas such as the South America Atlantic forests and Cerrado. For densely vegetated areas, the pattern of the GPP change correlates well with changes in the imposed atmospheric CO_2 (Fig. S54); the agreement is less evident in areas with sparse vegetation.

3.4.5 Interannual Variability of CO_2 (magtCO2-magCO2 and cCO2-magtCO2)

Finally, in experiments magtCO2 and cCO2, the interannual variability of atmospheric CO_2 is removed in a stepwise manner. First, in magtCO2, year-to-year variations in CO2 are removed while retainingIf the longer-term growth trend. This causes remains (magtCO2), the year-to-year anomalies of atmospheric CO_2 caused little change in global mean GPP and NBP (Table 1). The impacts on the temporal and spatial distribution of the fluxes are also negligiable (not shown).

On the other hand, ifwhen the observed growth ratelong-term trend of atmospheric CO_2 is also removed no loger imposed (cCO2), the increases in the global GPP are seen early in the simulation (2001-2008), and the decreases are seen in the later part (2009-2014) (Fig. 7a, showing results for cCO2 minus magtCO2). In Figure 7b, the removal of the long term trend is seen to affect 14-year mean GPP- mostly increases owing to removal of interannual trend of CO_2 are mostly in the tropics, leading to an additional change in global mean GPP of 0.078 PgC $year^{-1}$ (Table 1). While this time-mean change is smaller than that associated with neglecting diurnal variability, the differences at the beginning and end of the period (1.4PgC $year^{-1}$ between year 2001 and year 2014) are comparable to, or even larger than, the diurnal variability impact. These larger differences may have relevance to some period-specific model-based GPP estimates in the literature.

3.5 Regional- and Seasonal-Scale Sensitivity of Carbon Fluxes to Imposed CO_2 Variability

The Atmospheric Tracer Transport Model Intercomparison Project (TransCom) 03 experiment (Gurney et al., 2000) defined a number of land and ocean source/sink regions of interest for the estimation of uncertainty in atmospheric inversion-based carbon flux estimates. The eleven terrestrial regional boundaries shown in their basis function map (http://transcom.project.asu.edu/transcom03_protocol_basisMap.php) offer a convenient framework for characterizing, in one place, the relative impacts of the different facets of spatio-temporal CO_2 variability on carbon fluxes and how the relative importance of these different facets varies across the globe. Such a characterization is presented here in the form of histograms (Fig. 8); together, the histograms succinctly capture our regional and seasonal findings.

Fig. 8 shows, for example, that ignoring the diurnal variation of atmospheric CO_2 results in the overestimation of GPP in all seasons and in all TransCom regions except for Australia, where it slightly ~~decreases~~ reduces GPP and where the influence of the spatial CO_2 variability is dominant. Spatial CO_2 variability is also found to ~~lead to GPP changes in the Northern Hemisphere temperate regions (North America and Eurasia); here, the GPP reduction induced by ignoring spatial CO_2 variations is large enough to offset the increase induced by ignoring diurnal CO_2 variations (Figs. 8b and 8h). In the tropics and North Africa, spatial CO_2 variability only~~ partially compensates for diurnal variability in the Northern Hemisphere temperate regions (North America and Eurasia, see ~~(~~Figs. 8b and 8h)~~.~~ and in ~~the~~ North Africa (Fig~~s. 8e,~~ 8e ~~and 8i~~).
Seasonal CO_2 variations are found to be particularly important in Northern H~~h~~emisphere high latitude regions; during fall ~~(i.e., SON in Fig. 8a)~~, the GPP change induced by seasonal CO_2 variations is comparable to (and in the same direction as) that caused by diurnal variations (Figs. 8a and 8g). Similarly, seasonal variations have an important impact on GPP in Europe during fall (i.e., SON in Fig. 8k), presumably due to the presence of mixed (boreal and temperate) forests there; this impact is~~,~~ ~~and are~~ large enough to offset the fall GPP reduction induced by ignoring spatial CO_2 variations ~~(i.e., SON in~~ Figs. 8b~~a~~ and 8k). ~~For Europe, the global spatial variation in atmospheric CO_2 is also important (Fig. 8k). Synoptic scale~~~~Daily~~Day-to-day and year-to-year variations ~~and the anomalies of interannual variations~~ in atmospheric CO_2 have little impact anywhere, reaffirming our global scale analysis. ~~whereas~~ The long-term trend in ~~interannual variations~~CO_2, however, ~~show~~ has a relatively large percentage impact ~~(in the mean, i.e., beyond the impact of the trend, as described in Fig. S5a)~~ in the two African regions (Figs. 8e and~~,~~ 8f) – ignoring ~~interannual variations~~this trend in CO_2 in these regions leads to increased GPP. While diurnal CO_2 variations are ~~overall~~ important for all seasons ~~and shown year-long in~~across nearly all ~~of regional GPP estimations~~regions, the interplay among seasonal variations, spatial variations, and ~~the~~long-term trend ~~in the interannual variations~~ appears to be ~~more~~ crucial to certain seasonal and/or regional GPP estimations.

4 Discussion

Overall, our results indicate that ignoring temporal variability in atmospheric CO_2 in the bottom-up estimation of carbon fluxes with a representative offline model can lead to overestimates of global GPP of up to 0.5~~6~~ PgC year^{-1} (see Table 1~~ and Fig. S5a~~). The corresponding estimates of the strength of the land carbon sink may be too high ~~(i.e., estimates of mean global NBP may be to low)~~ by about 0.1 PgC year^{-1}. The most important facets of temporal CO_2 variability are found to be ~~its~~ diurnal variability and the trend in ~~and~~ interannual variability~~ies~~; ignoring them contributes 0.5 PgC year^{-1} and 0.08 PgC year^{-1}, respectively, to the global GPP overestimate. On the other hand, ignoring spatial variability in atmospheric CO_2 reduces the mean global GPP by 0.05~~2~~ PgC year^{-1} (~~Fig. S5a~~Table 1); that is, ignoring this spatial variability contributes to an underestimation of global GPP.

Liu et al. (2016) performed, in essence, a subset of the experiments examined here. In agreement with our findings, they show that the seasonal variation of CO_2 lowers global GPP and that the spatial variation of CO_2 increases it. The authors in fact suggest that ignoring spatial variability in CO_2 largely compensates for ignoring the temporal variability, though they admit that the use of marine background CO_2 concentrations in their baseline simulation, which are lower than the surface-layer CO_2 values seen by plants, may have exaggerated the spatial variability-related GPP reduction. Our more comprehensive set of experiments allows us to examine, in addition, the effects of diurnal and interannual CO_2 variability on global carbon fluxes, which turn out to be more important than the effects of either seasonal or spatial CO_2 variability. Note that the neglect of diurnal variability may partially explain the overestimate (relative to observations-based datasets) noted in the literature regarding tropical GPP simulated by CLM4 (Bonan et al., 2011). Also note that because the Catchment-CN model underestimates the response to CO_2 fertilization seen in the FACE experiments, the impact of diurnal variability at work in nature could be somewhat larger than our estimate here.

Again, the overestimation of the global carbon sink ~~(the negative of NBP)~~ associated with ignoring the temporal variability of atmospheric CO_2 is 0.1 PgC year^{-1} (Table 1~~ and Fig. S5b~~). This, again, is ~~in fact~~ a small deviation relative to estimates of the overall land sink; Le Quéré et al. (2016, their Fig. 2), for example, cite an estimate of ~~-~~3.1 PgC year^{-1} for this sink. This small sensitivity has relevance to the ongoing CMIP6 project. Through our experiments we quantify in effect the expected impacts of the minimum requirement recommended by CMIP6 for historical si~~u~~mulations (Eyring et al., 2016), namely, that of globally uniform annual mean CO_2 with interannual variations, and of the CMIP6 option of including latitudinal and seasonal variations (Meinshausen et al., 2017). The small sensitivities we uncover suggest that these recommendations, while not harmful, will nevertheless have little impact on the global-scale fluxes produced in CMIP6. Note again that the first approach, that of using globally uniform annual mean CO_2 with interannual variations, was effectively used in our magCO2 experiment; as shown in Table 2, the global mean fluxes produced in our other experiments are indeed similar to those produced in magCO2. The land modeling and carbon cycle community need not have been too concerned over the years about the global impacts of CO_2 variability finer than what has commonly been applied in past studies (i.e., annually increasing transient CO_2).

This, however, may be an overstatement. It is worth noting that the bias of 0.1 PgC year^{-1} associated with spatiotemporal CO_2 variability is in fact a significant fraction of the uncertainty in this value (listed by Le Quéré et al. (2016) as ±+/- 0.9 PgC year^{-1}). Also, various model intercomparison studies, (e.g., CMIP6, TRENDY and MsTMIP,) and the Global Carbon Project (GCP) may need to consider the full range of spatio-temporal CO_2 variability when estimating terrestrial productivity and net sink size on regional and seasonal scales (Fig. 8), for which the impacts can be larger. The growing-season NBP bias can be as large as -6% from our analysis (MAM in Fig. S6b5), and the local impact on tropical GPP well exceeds the global impact. It is thus sensible to impose, if at all possible, realistic CO_2 variability in carbon budget analyses.

Our results have some broader implications. They suggest that the diurnal 'rectifier effect'-, the substantial CO_2 covariations that are introduced with daily variations in photosynthesis and boundary layer turbulence, in a DGVM-based NBP may need to be considered in future atmospheric inversion studies that use it as a prior, given that biases in the prior can propagate into errors in the inversion products. Furthermore, they suggest that if the land- surface carbon dynamics component of an Earth modeling system is not coupled to itsthe atmospheric componente with a sub-daily time step (e.g., in a climate change study), the bias can be carried into the evolution of regional- and seasonal- land carbon dynamics (e.g., in a climate change study) will not be realistic, albeit the global effect canmay be minor. Finally, increasing CO_2 has been shown in field experiments (McCarthy et al., 2010; Norby and Zak, 2011) to foster biomass production (Huntingford et al., 2013). Under a CO_2-enriched environment, plants obtain CO_2 through the open stomata more efficiently and thereby lose less water to the atmosphere, allowing them to be more productive in dry regions or seasons. This process can alter the seasonality of the water cycle (Lemodant et al., 2016) as well as estimates of the plants' productivity in water-limiting areas (Swann et al., 2016). While our results in fact indicate, on their surface, a negligible impact of spatio-temporal CO_2 variability on water cycle variations through their impacts on stomatal conductance and thus evapotranspiration the open stomata (not shown),). The interaction between the water and carbon cycles in this study is thus the water-carbon interaction via land-atmosphere feedback that this offline study can infer is limited; however more careful analysis of the datain a fully coupled modeling system, however, may reveal some interesting connections.

5 Conclusions

In summary, the key results from this study are:

1. The carbon flux estimates of the Catchment-CN model generally agree with other statistics-based and model-based estimates. The GPP estimates from our control simulation (which utilized the full complement of atmospheric CO_2 variability contained within the CarbonTracker dataset) validate reasonably well with the MTE-GPP dataset, a widely-used product for model evalution, and our NBP estimates are also consistent to first order with results from the diagnostic CASA-GFED3 model (a bottom-up approach) and the atmospheric inversions (a top-down approach). The agreement supports our use of the Catchment-CN model in the experiments outlined in Fig. 1.

2. Ignoring the various facets of temporal variability in CO_2 leads to increases in the mean global GPP simulated by the process-based model. The diurnal component of the variability is particularly important; ignoring it increases the estimated mean global GPP by 0.5 PgC year^{-1}.
3. Ignoring the spatial variability of atmospheric CO_2, on the other hand, leads to a decrease in mean global GPP, with decreases in the Northern Hemisphere and increases in the Southern Hemisphere. The overall decrease of 0.05~~2~~ PgC year^{-1} is smaller than the increase associated with ignoring temporal variability.
4. For estimating multi-year mean GPP, the effect of neglecting interannual ~~variations~~ ~~anomalies~~variations of atmospheric CO_2 is ~~relatively~~ small. ~~I but the effect of i~~gnoring the ~~interannual~~long-term trend, however, ~~is not~~can have important implications ~~negligible~~; ~~however~~ the differences at the beginning and end of the period (up to 1.4 PgC year^{-1} difference between year 2001 and year 2014 in this study) can be much greater than the effect of ignoring the diurnal CO_2 variation.
5. The impacts of ignoring temporal and spatial variability vary with region. The sensitivity in the Tropics tends to be the largest. The seasonal variability of atmospheric CO_2 plays a particularly important role in the NH boreal regions during fall ~~and winter~~. Spatial variability of CO_2 is important in temperate regions, offsetting the local impacts of temporal variability on GPP.
6. The magnitude of the sensitivities found is small, particularly at the global scale. The proper imposition of realistic CO_2 variability in offline studies will incur only slight modifications to the terrestrial carbon fluxes computed. This said, the imposition of realistic CO_2 variability is straightforward and could have more significant impacts on quantified regional and seasonal fluxes.

The carbon flux estimation sensitivities highlighted herein are, of course, model-dependent. The sensitivities are subject to model-specific assumptions and parameters (see the MsTMIP inter-model comparison study, Ito et al., 2016) and to the selection of the meteorological inputs (Poulter et al., 2011). Still, as noted in section 3.3, the sensitivity of GPP to CO_2 increases in the Catchment-CN model is similar to that in other state-of-the-art models, suggesting that the results herein are broadly applicable and that DGVM-based estimates in the literature of global GPP may be subject to the noted biases, small as they are found to be here.

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References

Ahlström, A., Raupach, M. R., Schurgers, G., Smith, B., Arneth, A., Jung, M., Reichstein, M., Canadell, J. G., Friedlingstein, P., Jain, A. K., Kato, E., Poulter, B., Sitch, S., Stocker, B. D., Viovy, N., Wang, Y. P., Wiltshire, A., Zaehle, S. and Zeng, N.: The dominant role of semi-arid ecosystems in the trend and variability of the land CO2 sink, Science, 348(6237), 895–899, doi:10.1126/science.aaa1668, 2015.

Ainsworth, E. A. and Long, S. P.: What have we learned from 15 years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO2: Tansley review, New Phytologist, 165(2), 351–372, doi:10.1111/j.1469-8137.2004.01224.x, 2004.

Anav, A., Friedlingstein, P., Beer, C., Ciais, P., Harper, A., Jones, C., Murray-Tortarolo, G., Papale, D., Parazoo, N. C., Peylin, P., Piao, S., Sitch, S., Viovy, N., Wiltshire, A. and Zhao, M.: Spatiotemporal patterns of terrestrial gross primary production: A review, Rev. Geophys., 53(3), 2015RG000483, doi:10.1002/2015RG000483, 2015.

Baccini, A., Walker, W., Carvalho, L., Farina, M., Sulla-Menashe, D. and Houghton, R. A.: Tropical forests are a net carbon source based on aboveground measurements of gain and loss, Science, 358(6360), 230–234, doi:10.1126/science.aam5962, 2017.

Baker, D. F., Law, R. M., Gurney, K. R., Rayner, P., Peylin, P., Denning, A. S., Bousquet, P., Bruhwiler, L., Chen, Y.-H., Ciais, P., Fung, I. Y., Heimann, M., John, J., Maki, T., Maksyutov, S., Masarie, K., Prather, M., Pak, B., Taguchi, S. and Zhu, Z.: TransCom 3 inversion intercomparison: Impact of transport model errors on the interannual variability of regional CO_2 fluxes, 1988-2003, Global Biogeochemical Cycles, 20(1), n/a-n/a, doi:10.1029/2004GB002439, 2006.

Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., Rodenbeck, C., Arain, M. A., Baldocchi, D., Bonan, G. B., Bondeau, A., Cescatti, A., Lasslop, G., Lindroth, A., Lomas, M., Luyssaert, S., Margolis, H., Oleson, K. W., Roupsard, O., Veenendaal, E., Viovy, N., Williams, C., Woodward, F. I. and Papale, D.: Terrestrial Gross Carbon Dioxide Uptake: Global Distribution and Covariation with Climate, Science, 329(5993), 834–838, doi:10.1126/science.1184984, 2010.

Bonan, G. B., Lawrence, P. J., Oleson, K. W., Levis, S., Jung, M., Reichstein, M., Lawrence, D. M. and Swenson, S. C.: Improving canopy processes in the Community Land Model version 4 (CLM4) using global flux fields empirically inferred from FLUXNET data, Journal of Geophysical Research, 116(G2), doi:10.1029/2010JG001593, 2011.

CarbonTracker Documentation CT2015 Release, CarbonTracker Team, https://www.esrl.noaa.gov/gmd/ccgg/carbontracker/CT2015_doc.pdf ,2016

Chevallier, F., Deutscher, N. M., Conway, T. J., Ciais, P., Ciattaglia, L., Dohe, S., Fröhlich, M., Gomez-Pelaez, A. J., Griffith, D., Hase, F., Haszpra, L., Krummel, P., Kyrö, E., Labuschagne, C., Langenfelds, R., Machida, T., Maignan, F., Matsueda, H., Morino, I., Notholt, J., Ramonet, M., Sawa, Y., Schmidt, M., Sherlock, V., Steele, P., Strong, K., Sussmann, R., Wennberg, P., Wofsy, S., Worthy, D., Wunch, D. and Zimnoch, M.: Global CO_2 fluxes inferred from surface air-sample measurements and from TCCON retrievals of the CO_2 total column: TWO CO_2 FLUX INVERSIONS, Geophysical Research Letters, 38(24), doi:10.1029/2011GL049899, 2011.

Cleveland, C. C., Taylor, P., Chadwick, K. D., Dahlin, K., Doughty, C. E., Malhi, Y., Smith, W. K., Sullivan, B. W., Wieder, W. R. and Townsend, A. R.: A comparison of plot-based satellite and Earth system model estimates of tropical forest net primary production, Global Biogeochemical Cycles, 29(5), 626–644, doi:10.1002/2014GB005022, 2015.

Collatz, G., Ribas-Carbo, M. and Berry, J.: Coupled Photosynthesis-Stomatal Conductance Model for Leaves of C_4 Plants, Australian Journal of Plant Physiology, 19(5), 519, doi:10.1071/PP9920519, 1992.

Collatz, G. J., Ball, J. T., Grivet, C. and Berry, J. A.: Physiological and environmental regulation of stomatal conductance, photosynthesis and transpiration: a model that includes a laminar boundary layer, Agricultural and Forest Meteorology, 54(2–4), 107–136, doi:10.1016/0168-1923(91)90002-8, 1991.

Denning, A. S., Takahashi, T. and Friedlingstein, P.: KEYNOTE PERSPECTIVE. Can a strong atmospheric CO2 rectifier effect be reconciled with a “reasonable” carbon budget?, Tellus B, 51(2), 249–253, doi:10.1034/j.1600-0889.1999.t01-1-00010.x, 1999.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J. and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geoscientific Model Development, 9(5), 1937–1958, doi:10.5194/gmd-9-1937-2016, 2016.

Farquhar, G. D., von Caemmerer, S. and Berry, J. A.: A biochemical model of photosynthetic CO2 assimilation in leaves of C3 species, Planta, 149(1), 78–90, doi:10.1007/BF00386231, 1980.

Forkel, M., Carvalhais, N., Rödenbeck, C., Keeling, R., Heimann, M., Thonicke, K., Zaehle, S. and Reichstein, M.: Enhanced seasonal CO2 exchange caused by amplified plant productivity in northern ecosystems, Science, 351(6274), 696–699, doi:10.1126/science.aac4971, 2016.

Fu, Z., Dong, J., Zhou, Y., Stoy, P. C. and Niu, S.: Long term trend and interannual variability of land carbon uptake—the attribution and processes, Environmental Research Letters, 12(1), 014018, doi:10.1088/1748-9326/aa5685, 2017.

Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., Randles, C. A., Darmenov, A., Bosilovich, M. G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper, C., Akella, S., Buchard, V., Conaty, A., da Silva, A. M., Gu, W., Kim, G.-K., Koster, R., Lucchesi, R., Merkova, D., Nielsen, J. E., Partyka, G., Pawson, S., Putman, W., Rienecker, M., Schubert, S. D., Sienkiewicz, M. and Zhao, B.: The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), Journal of Climate, 30(14), 5419–5454, doi:10.1175/JCLI-D-16-0758.1, 2017.

Gloor, M., Gatti, L., Brienen, R., Feldpausch, T. R., Phillips, O. L., Miller, J., Ometto, J. P., Rocha, H., Baker, T., de Jong, B., Houghton, R. A., Malhi, Y., Aragão, L. E. O. C., Guyot, J.-L., Zhao, K., Jackson, R., Peylin, P., Sitch, S., Poulter, B., Lomas, M., Zaehle, S., Huntingford, C., Levy, P. and Lloyd, J.: The carbon balance of South America: a review of the status, decadal trends and main determinants, Biogeosciences, 9(12), 5407–5430, doi:10.5194/bg-9-5407-2012, 2012.

Gurney, K., Law, R., Rayner, P. and Denning, A. S.: TransCom 3 Experimental Protocol, Department of Atmopsheric Science, Colorado State University., 2000.

Haszpra, L., Barcza, Z., Hidy, D., Szilágyi, I., Dlugokencky, E. and Tans, P.: Trends and temporal variations of major greenhouse gases at a rural site in Central Europe, Atmospheric Environment, 42(38), 8707–8716, doi:10.1016/j.atmosenv.2008.09.012, 2008.

Hendrey, G. R., Ellsworth, D. S., Lewin, K. F. and Nagy, J.: A free-air enrichment system for exposing tall forest vegetation to elevated atmospheric CO2, Global Change Biology, 5(3), 293–309, doi:10.1046/j.1365-2486.1999.00228.x, 1999.

Hickler, T., Smith, B., Prentice, I. C., MjöFors, K., Miller, P., Arneth, A. and Sykes, M. T.: CO $_2$ fertilization in temperate FACE experiments not representative of boreal and tropical forests, Global Change Biology, 14(7), 1531–1542, doi:10.1111/j.1365-2486.2008.01598.x, 2008.

~~Houghton, R. A., Byers, B. and Nassikas, A. A.: A role for tropical forests in stabilizing atmospheric CO2, Nature Climate Change, 5(12), 1022–1023, doi:10.1038/nclimate2869, 2015.~~Houghton, R. A., Baccini, A. and Walker, W. S.: Where is the residual terrestrial carbon sink?, Global Change Biology, 24(8), 3277–3279, doi:10.1111/gcb.14313, 2018.

Huntzinger, D. N., Schwalm, C., Michalak, A. M., Schaefer, K., King, A. W., Wei, Y., Jacobson, A., Liu, S., Cook, R. B., Post, W. M., Berthier, G., Hayes, D., Huang, M., Ito, A., Lei, H., Lu, C., Mao, J., Peng, C. H., Peng, S., Poulter, B., Riccuito, D., Shi, X., Tian, H., Wang, W., Zeng, N., Zhao, F. and Zhu, Q.: The North American Carbon Program Multi-Scale Synthesis and Terrestrial Model Intercomparison Project – Part 1: Overview and experimental design, Geoscientific Model Development, 6(6), 2121–2133, doi:10.5194/gmd-6-2121-2013, 2013.

IPCC: Climate Change 2014: Synthesis Report . Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland., 2014.

Ito, A., Inatomi, M., Huntzinger, D. N., Schwalm, C., Michalak, A. M., Cook, R., King, A. W., Mao, J., Wei, Y., Post, W. M., Wang, W., Arain, M. A., Huang, S., Hayes, D. J., Ricciuto, D. M., Shi, X., Huang, M., Lei, H., Tian, H., Lu, C., Yang, J., Tao, B., Jain, A., Poulter, B., Peng, S., Ciais, P., Fisher, J. B., Parazoo, N., Schaefer, K., Peng, C., Zeng, N. and Zhao, F.: Decadal trends in the seasonal-cycle amplitude of terrestrial CO2 exchange resulting from the ensemble of terrestrial biosphere models, Tellus B, 68(0), doi:10.3402/tellusb.v68.28968, 2016.

Jung, M., Reichstein, M., Margolis, H. A., Cescatti, A., Richardson, A. D., Arain, M. A., Arneth, A., Bernhofer, C., Bonal, D., Chen, J., Gianelle, D., Gobron, N., Kiely, G., Kutsch, W., Lasslop, G., Law, B. E., Lindroth, A., Merbold, L., Montagnani, L., Moors, E. J., Papale, D., Sottocornola, M., Vaccari, F. and Williams, C.: Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations, Journal of Geophysical Research, 116, doi:10.1029/2010JG001566, 2011.

Koster, R. D., Suarez, M. J., Ducharne, A., Stieglitz, M. and Kumar, P.: A catchment-based approach to modeling land surface processes in a general circulation model: 1. Model structure, Journal of Geophysical Research, 105(D20), 24809, doi:10.1029/2000JD900327, 2000.

Koster, R. D., Walker, G. K., Collatz, G. J. and Thornton, P. E.: Hydroclimatic Controls on the Means and Variability of Vegetation Phenology and Carbon Uptake, Journal of Climate, 27(14), 5632–5652, doi:10.1175/JCLI-D-13-00477.1, 2014.

Larson, V. E. and Volkmer, H.: An idealized model of the one-dimensional carbon dioxide rectifier effect, Tellus B, 60(4), 525–536, doi:10.1111/j.1600-0889.2008.00368.x, 2008.

Le Quéré, C., Andrew, R. M., Canadell, J. G., Sitch, S., Korsbakken, J. I., Peters, G. P., Manning, A. C., Boden, T. A., Tans, P. P., Houghton, R. A., Keeling, R. F., Alin, S., Andrews, O. D., Anthoni, P., Barbero, L., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., Currie, K., Delire, C., Doney, S. C., Friedlingstein, P., Gkritzalis, T., Harris, I., Hauck, J., Haverd, V., Hoppema, M., Klein Goldewijk, K., Jain, A. K., Kato, E., Körtzinger, A., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Lombardozzi, D., Melton, J. R., Metzl, N., Millero, F., Monteiro, P. M. S., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S., O'Brien, K., Olsen, A., Omar, A. M., Ono, T., Pierrot, D., Poulter, B., Rödenbeck, C., Salisbury, J., Schuster, U., Schwinger, J., Séférian, R., Skjelvan, I., Stocker, B. D., Sutton, A. J., Takahashi, T., Tian, H., Tilbrook, B., van der Laan-Luijkx, I. T., van der Werf, G. R., Viovy, N., Walker, A. P., Wiltshire, A. J. and Zaehle, S.: Global Carbon Budget 2016, Earth System Science Data, 8(2), 605–649, doi:10.5194/essd-8-605-2016, 2016.

~~Lemordant, L., Gentine, P., Stéfanon, M., Drobinski, P. and Fatichi, S.: Modification of land-atmosphere interactions by CO2 effects: Implications for summer dryness and heat wave amplitude, Geophysical Research Letters, 43(19), 10,240-10,248, doi:10.1002/2016GL069896, 2016.~~

Lewis, S. L., Lopez-Gonzalez, G., Sonké, B., Affum-Baffoe, K., Baker, T. R., Ojo, L. O., Phillips, O. L., Reitsma, J. M., White, L., Comiskey, J. A., K, M.-N. D., Ewango, C. E. N., Feldpausch, T. R., Hamilton, A. C., Gloor, M., Hart, T., Hladik, A., Lloyd, J., Lovett, J. C., Makana, J.-R., Malhi, Y., Mbago, F. M., Ndangalasi, H. J., Peacock, J., Peh, K. S.-H., Sheil, D., Sunderland, T., Swaine, M. D., Taplin, J., Taylor, D., Thomas, S. C., Votere, R. and Wöll, H.: Increasing carbon storage in intact African tropical forests, Nature, 457(7232), 1003–1006, doi:10.1038/nature07771, 2009.

Liu, S., Zhuang, Q., Chen, M. and Gu, L.: Quantifying spatially and temporally explicit CO2 fertilization effects on global terrestrial ecosystem carbon dynamics, Ecosphere, 7(7), e01391, doi:10.1002/ecs2.1391, 2016.

~~McCarthy, H. R., Oren, R., Johnsen, K. H., Gallet-Budynek, A., Pritchard, S. G., Cook, C. W., LaDeau, S. L., Jackson, R. B. and Finzi, A. C.: Re-assessment of plant carbon dynamics at the Duke free-air CO2 enrichment site: interactions of atmospheric (CO2) with nitrogen and water availability over stand development, New Phytologist, 185(2), 514–528, doi:10.1111/j.1469-8137.2009.03078.x, 2010.~~

Meinshausen, M., Vogel, E., Nauels, A., Lorbacher, K., Meinshausen, N., Etheridge, D. M., Fraser, P. J., Montzka, S. A., Rayner, P. J., Trudinger, C. M., Krummel, P. B., Beyerle, U., Canadell, J. G., Daniel, J. S., Enting, I. G., Law, R. M., Lunder, C. R., O'Doherty, S., Prinn, R. G., Reimann, S., Rubino, M., Velders, G. J. M., Vollmer, M. K., Wang, R. H. J. and Weiss, R.: Historical greenhouse gas concentrations for climate modelling (CMIP6), Geoscientific Model Development, 10(5), 2057–2116, doi:10.5194/gmd-10-2057-2017, 2017.

Norby, R. J. and Zak, D. R.: Ecological Lessons from Free-Air CO2 Enrichment (FACE) Experiments, Annual Review of Ecology, Evolution, and Systematics, 42(1), 181–203, doi:10.1146/annurev-ecolsys-102209-144647, 2011.

Norby, R. J., Todd, D. E., Fults, J. and Johnson, D. W.: Allometric determination of tree growth in a CO2-enriched sweetgum stand, New Phytologist, 150(2), 477–487, doi:10.1046/j.1469-8137.2001.00099.x, 2001.

Norby, R. J., DeLucia, E. H., Gielen, B., Calfapietra, C., Giardina, C. P., King, J. S., Ledford, J., McCarthy, H. R., Moore, D. J. P., Ceulemans, R., De Angelis, P., Finzi, A. C., Karnosky, D. F., Kubiske, M. E., Lukac, M., Pregitzer, K. S., Scarascia-Mugnozza, G. E., Schlesinger, W. H. and Oren, R.: Forest response to elevated CO2 is conserved across a broad range of productivity, Proceedings of the National Academy of Sciences, 102(50), 18052–18056, doi:10.1073/pnas.0509478102, 2005.

Ott, L. E., Pawson, S., Collatz, G. J., Gregg, W. W., Menemenlis, D., Brix, H., Rousseaux, C. S., Bowman, K. W., Liu, J., Eldering, A., Gunson, M. R. and Kawa, S. R.: Assessing the magnitude of CO2 flux uncertainty in atmospheric CO2 records using products from NASA's Carbon Monitoring Flux Pilot Project, Journal of Geophysical Research: Atmospheres, 120(2), 734–765, doi:10.1002/2014JD022411, 2015.

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., Phillips, O. L., Shvidenko, A., Lewis, S. L., Canadell, J. G., Ciais, P., Jackson, R. B., Pacala, S. W., McGuire, A. D., Piao, S., Rautiainen, A., Sitch, S. and Hayes, D.: A Large and Persistent Carbon Sink in the World's Forests, Science, 333(6045), 988–993, doi:10.1126/science.1201609, 2011.

Peters, W., Jacobson, A. R., Sweeney, C., Andrews, A. E., Conway, T. J., Masarie, K., Miller, J. B., Bruhwiler, L. M. P., Petron, G., Hirsch, A. I., Worthy, D. E. J., van der Werf, G. R., Randerson, J. T., Wennberg, P. O., Krol, M. C. and Tans, P. P.: An atmospheric perspective on North American carbon dioxide exchange: CarbonTracker, Proceedings of the National Academy of Sciences, 104(48), 18925–18930, doi:10.1073/pnas.0708986104, 2007.

Piao, S., Sitch, S., Ciais, P., Friedlingstein, P., Peylin, P., Wang, X., Ahlström, A., Anav, A., Canadell, J. G., Cong, N., ~~Huntingford, C., Jung, M., Levis, S., Levy, P. E., Li, J., Lin, X., Lomas, M. R., Lu, M., Luo, Y., Ma, Y., Myneni, R. B., Poulter, B., Sun, Z., Wang, T., Viovy, N., Zaehle, S. and Zeng, N.: Evaluation of terrestrial carbon cycle models for their response to climate variability and to CO_2 trends, Global Change Biology, 19(7), 2117–2132, doi:10.1111/gcb.12187, 2013.~~

Poulter, B., Frank, D. C., Hodson, E. L. and Zimmermann, N. E.: Impacts of land cover and climate data selection on understanding terrestrial carbon dynamics and the CO₂ airborne fraction, Biogeosciences, 8(8), 2027–2036, doi:10.5194/bg-8-2027-2011, 2011.

Poulter, B., Frank, D., Ciais, P., Myneni, R. B., Andela, N., Bi, J., Broquet, G., Canadell, J. G., Chevallier, F., Liu, Y. Y., Running, S. W., Sitch, S. and van der Werf, G. R.: Contribution of semi-arid ecosystems to interannual variability of the global carbon cycle, Nature, 509(7502), 600–603, doi:10.1038/nature13376, 2014.

Reichle, R. H., De Lannoy, G. J. M., Liu, Q., Ardizzone, J. V., Chen, F., Colliander, A., Conaty, A., Crow, W., Jackson, T., Kimbal, J., Koster, R. D. and Smith, E. B.: Soil Moisture Active Passive Mission L4_SM Data Product Assessment (Version 2 Validated Release), NASA Global Modeling and Assimilation Office., 2016.

Rödenbeck, C., Houweling, S., Gloor, M. and Heimann, M.: CO_2 flux history 1982–2001 inferred from atmospheric data using a global inversion of atmospheric transport, Atmospheric Chemistry and Physics, 3(6), 1919–1964, doi:10.5194/acp-3-1919-2003, 2003.

Schimel, D., Stephens, B. B. and Fisher, J. B.: Effect of increasing CO2 on the terrestrial carbon cycle, Proceedings of the National Academy of Sciences, 112(2), 436–441, doi:10.1073/pnas.1407302112, 2015.

Sitch, S., Friedlingstein, P., Gruber, N., Jones, S. D., Murray-Tortarolo, G., Ahlström, A., Doney, S. C., Graven, H., Heinze, C., Huntingford, C., Levis, S., Levy, P. E., Lomas, M., Poulter, B., Viovy, N., Zaehle, S., Zeng, N., Arneth, A., Bonan, G., Bopp, L., Canadell, J. G., Chevallier, F., Ciais, P., Ellis, R., Gloor, M., Peylin, P., Piao, S. L., Le Quéré, C., Smith, B., Zhu, Z. and Myneni, R.: Recent trends and drivers of regional sources and sinks of carbon dioxide, Biogeosciences, 12(3), 653–679, doi:10.5194/bg-12-653-2015, 2015.

Slevin, D., Tett, S. F. B., Exbrayat, J.-F., Bloom, A. A. and Williams, M.: Global evaluation of gross primary productivity in the JULES land surface model v3.4.1, Geoscientific Model Development, 10(7), 2651–2670, doi:10.5194/gmd-10-2651-2017, 2017.

Slevin, D., Tett, S. F. B., Exbrayat, J.-F., Bloom, A. A. and Williams, M.: Global Evaluation of Gross Primary Productivity in the JULES Land Surface Model, Geoscientific Model Development Discussions, 1–31, doi:10.5194/gmd-2016-214, 2016.

Stephens, B. B., Gurney, K. R., Tans, P. P., Sweeney, C., Peters, W., Bruhwiler, L., Ciais, P., Ramonet, M., Bousquet, P., Nakazawa, T., Aoki, S., Machida, T., Inoue, G., Vinnichenko, N., Lloyd, J., Jordan, A., Heimann, M., Shibistova, O., Langenfelds, R. L., Steele, L. P., Francey, R. J. and Denning, A. S.: Weak Northern and Strong Tropical Land Carbon Uptake from Vertical Profiles of Atmospheric CO2, Science, 316(5832), 1732–1735, doi:10.1126/science.1137004, 2007.

Swann, A. L. S., Hoffman, F. M., Koven, C. D. and Randerson, J. T.: Plant responses to increasing CO_2 reduce estimates of climate impacts on drought severity, Proceedings of the National Academy of Sciences, 113(36), 10019–10024, doi:10.1073/pnas.1604581113, 2016.

Tans, P. P., Conway, T. J. and Nakazawa, T.: Latitudinal distribution of the sources and sinks of atmospheric carbon dioxide derived from surface observations and an atmospheric transport model, Journal of Geophysical Research, 94(D4), 5151, doi:10.1029/JD094iD04p05151, 1989.

Walker, A. P., Hanson, P. J., De Kauwe, M. G., Medlyn, B. E., Zaehle, S., Asao, S., Dietze, M., Hickler, T., Huntingford, C., Iversen, C. M., Jain, A., Lomas, M., Luo, Y., McCarthy, H., Parton, W. J., Prentice, I. C., Thornton, P. E., Wang, S., Wang, Y.-P., Warlind, D., Weng, E., Warren, J. M., Woodward, F. I., Oren, R. and Norby, R. J.: Comprehensive ecosystem model-data synthesis using multiple data sets at two temperate forest free-air CO_2 enrichment experiments: Model performance at ambient CO_2 concentration: FACE MODEL-DATA SYNTHESIS, Journal of Geophysical Research: Biogeosciences, 119(5), 937–964, doi:10.1002/2013JG002553, 2014.

Wang, X., Piao, S., Ciais, P., Friedlingstein, P., Myneni, R. B., Cox, P., Heimann, M., Miller, J., Peng, S., Wang, T., Yang, H. and Chen, A.: A two-fold increase of carbon cycle sensitivity to tropical temperature variations, Nature, 506(7487), 212–215, doi:10.1038/nature12915, 2014.

Wei, Y., Liu, S., Huntzinger, D. N., Michalak, A. M., Viovy, N., Post, W. M., Schwalm, C. R., Schaefer, K., Jacobson, A. R., Lu, C., Tian, H., Ricciuto, D. M., Cook, R. B., Mao, J. and Shi, X.: The North American Carbon Program Multi-scale Synthesis and Terrestrial Model Intercomparison Project – Part 2: Environmental driver data, Geoscientific Model Development, 7(6), 2875–2893, doi:10.5194/gmd-7-2875-2014, 2014.

van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y. and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), Atmospheric Chemistry and Physics, 10(23), 11707–11735, doi:10.5194/acp-10-11707-2010, 2010.

Xu, L., Myneni, R. B., Chapin III, F. S., Callaghan, T. V., Pinzon, J. E., Tucker, C. J., Zhu, Z., Bi, J., Ciais, P., T?mmervik, H., Euskirchen, E. S., Forbes, B. C., Piao, S. L., Anderson, B. T., Ganguly, S., Nemani, R. R., Goetz, S. J., Beck, P. S. A., Bunn, A. G., Cao, C. and Stroeve, J. C.: Temperature and vegetation seasonality diminishment over northern lands, Nature Climate Change, doi:10.1038/nclimate1836, 2013.

Yi, C., Davis, K. J., Bakwin, P. S., Berger, B. W. and Marr, L. C.: Influence of advection on measurements of the net ecosystem-atmosphere exchange of CO_2 from a very tall tower, Journal of Geophysical Research: Atmospheres, 105(D8), 9991–9999, doi:10.1029/2000JD900080, 2000.

Zaehle, S., Medlyn, B. E., De Kauwe, M. G., Walker, A. P., Dietze, M. C., Hickler, T., Luo, Y., Wang, Y.-P., El-Masri, B., Thornton, P., Jain, A., Wang, S., Warlind, D., Weng, E., Parton, W., Iversen, C. M., Gallet-Budynek, A., McCarthy, H., Finzi, A., Hanson, P. J., Prentice, I. C., Oren, R. and Norby, R. J.: Evaluation of 11 terrestrial carbon-nitrogen cycle models against observations from two temperate Free-Air CO_2 Enrichment studies, New Phytologist, 202(3), 803–822, doi:10.1111/nph.12697, 2014.

Case	GPP (PgC $year^{-1}$)	NBP (PgC $year^{-1}$)	Missing variability	ΔGPP (PgC $year^{-1}$)	ΔNBP (PgC $year^{-1}$)
3hCO2	127.545	0.527	--	--	--
dCO2	128.038	0.626	No diurnal variability (dCO2-3hCO2)	0.492	0.099
mCO2	128.040	0.627	No day-to-day variability (mCO2-dCO2)	0.003	0.001
maCO2	128.059	0.632	No seasonal variability (maCO2-mCO2)	0.019	0.005
magCO2	128.007	0.620	No spatial variability (magCO2-maCO2)	-0.052	-0.012
magtCO2	128.004	0.618	No interannual variability (anomalies) (magtCO2-magCO2)	-0.003	-0.002
cCO2	128.082	0.616	No interannual variability (trend) (cCO2-magtCO2)	0.078	-0.002

Table 1: Changes in mean global GPP and NBP for 2001-2014, resulting from a series of simulations representing the removal of temporal and spatial variability of atmospheric CO_2 concentrations. Delta (Δ) indicates the difference due to removal of a spatial/temporal variability (see Fig. 1 for description).

Case	GPP (PgC $year^{-1}$)	ΔGPP to magCO2 (PgC $year^{-1}$)	NBP (PgC $year^{-1}$)	ΔNBP to magCO2 (PgC $year^{-1}$)
3hCO2	127.545	-0.461	0.527	-0.093
dCO2	128.038	0.031	0.626	0.007
mCO2	128.040	0.033	0.627	0.007
maCO2	128.059	0.052	0.632	0.012
magCO2	128.007	--	0.620	--
magtCO2	128.004	-0.003	0.618	-0.001
cCO2	128.082	0.075	0.616	-0.004

Table 2: Differences in mean global GPP and NBP compared to the case that uses the most popular atmospheric CO_2 forcing (magCO2). The values are global mean of 2001-2014.

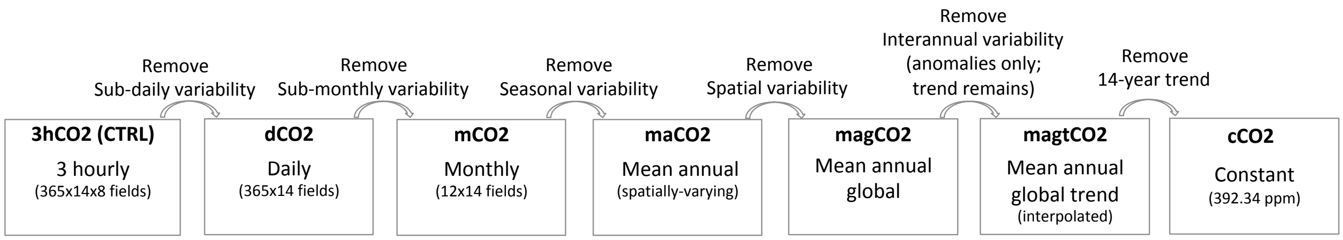
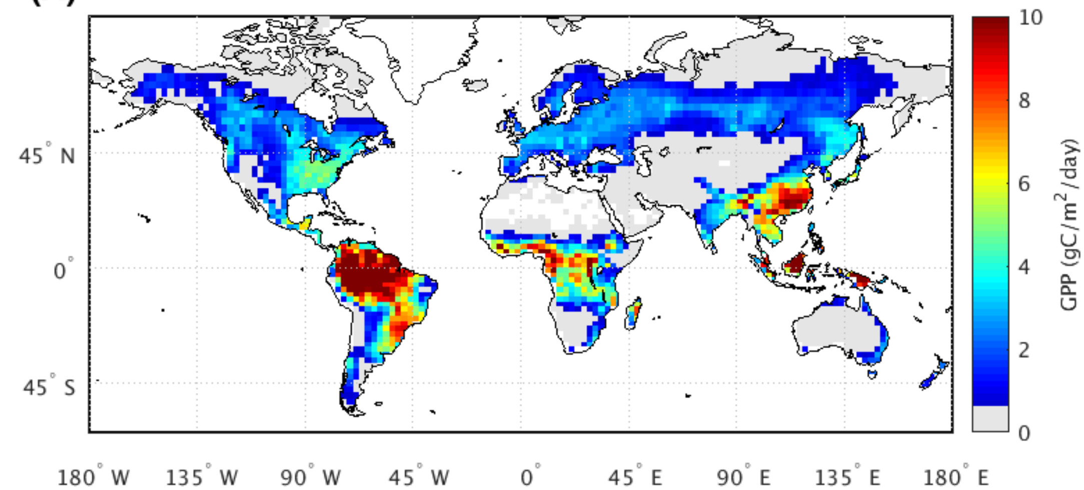
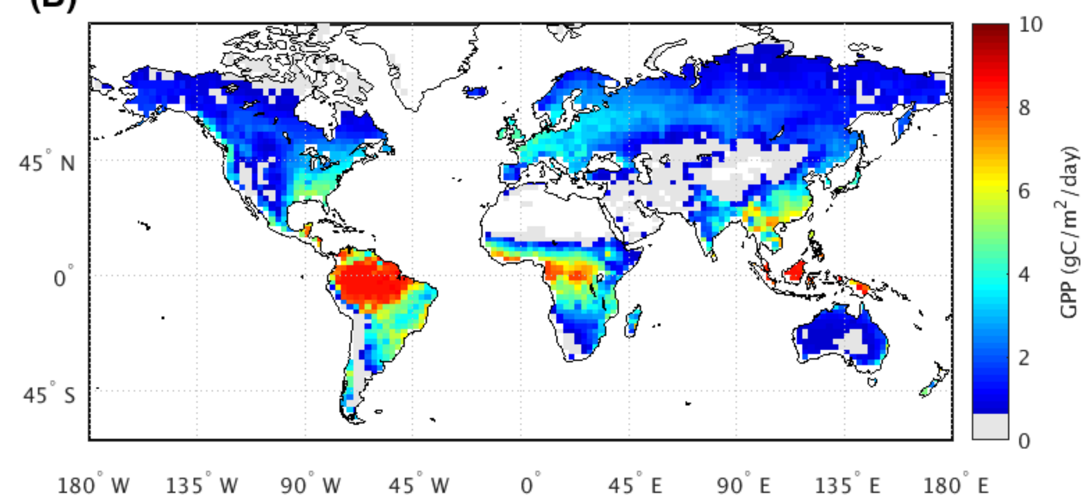


Fig. 1: Schematic of the six simulations examined in this study, which were designed to isolate the impacts of the different facets spatiotemporal CO_2 variability on simulated carbon fluxes. The CO_2 concentrations were reconstructed from the NOAA CarbonTracker 3-hourly global CO_2 data.

(A)


45° N
0°
45° S
180° W
135° W
90° W
45° W
0°
45° E
90° E
135° E
180° E
10
8
6
4
2
0
GPP (gC/m^2/day)

(B)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45° E
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10
8
6
4
2
0
GPP (gC/m^2/day)

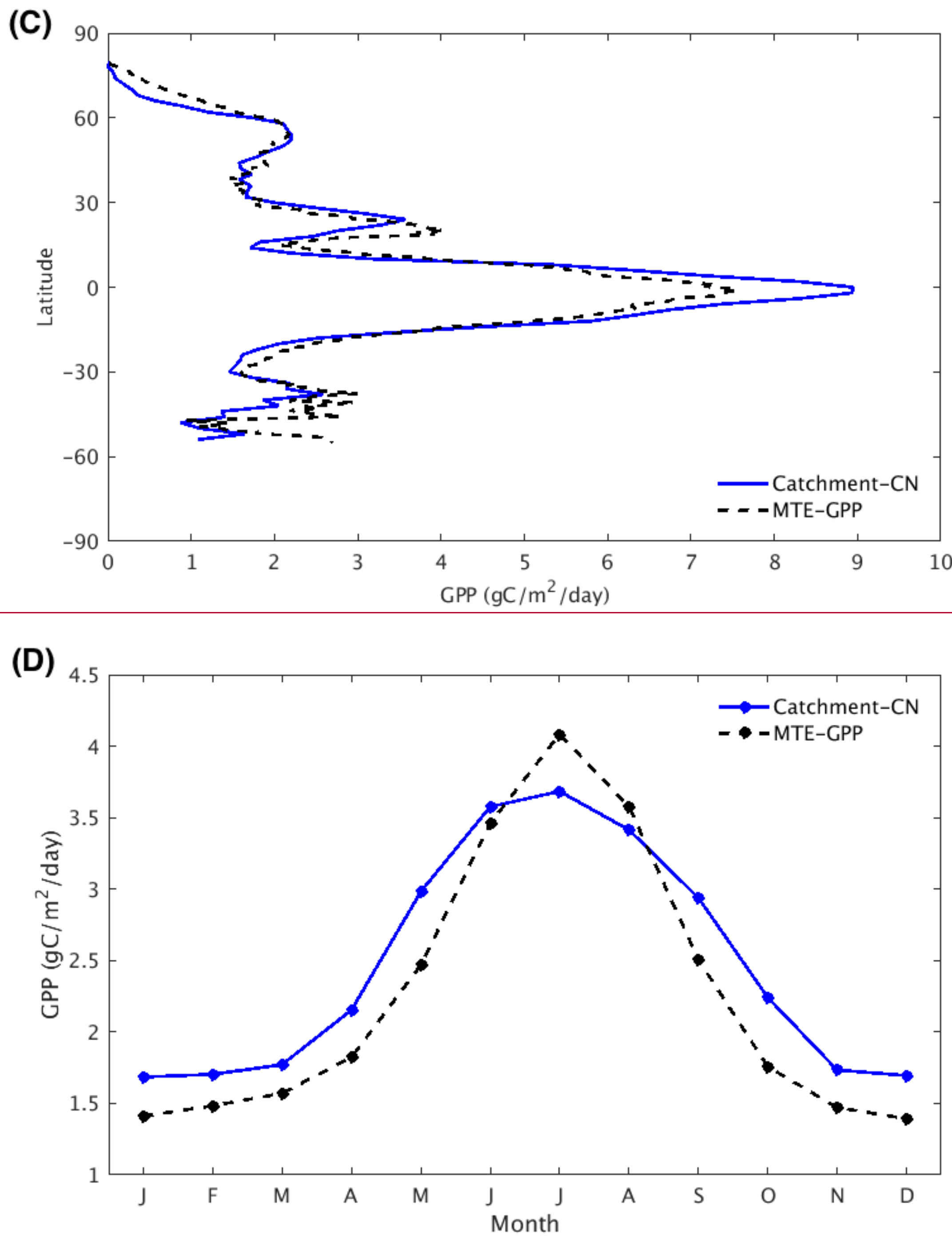


Fig. 2: Spatial patterns of 2002-2011 mean GPP (gC/m^2/day) from (a) Catchment-CN GPP and (b) MTE-GPP, and (c) z~~Z~~onal mean GPP and (d) annual cycle of GPP (solid blue: Catchment-CN model; dotted black: MTE-GPP).

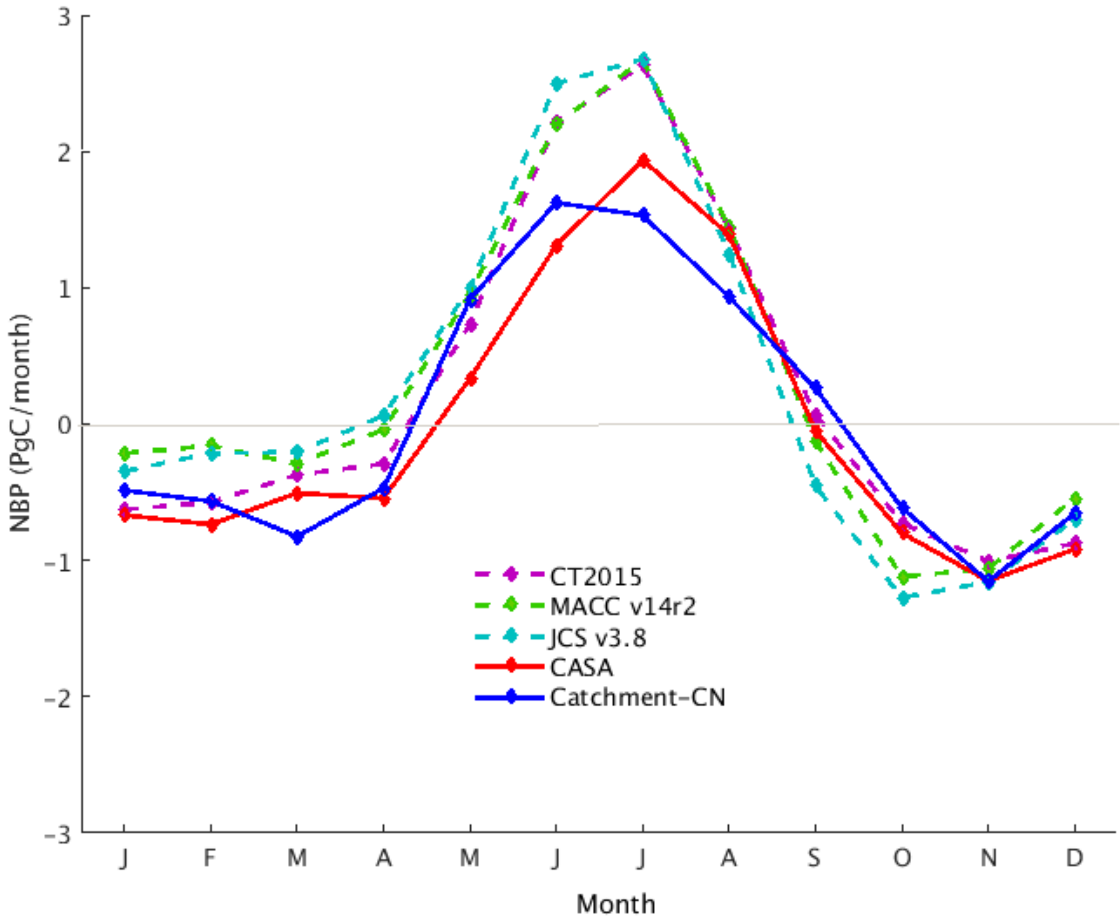


Fig. 3: Monthly mean of terrestrial NBP of the Catchment-CN model (blue), of the CASA-GFED3 model (red), and of three atmospheric inversions (dotted lines), for the period of 2004-2014. Positive (negative) NBP values indicate that land is a carbon ~~source~~ sink (source~~ink~~).

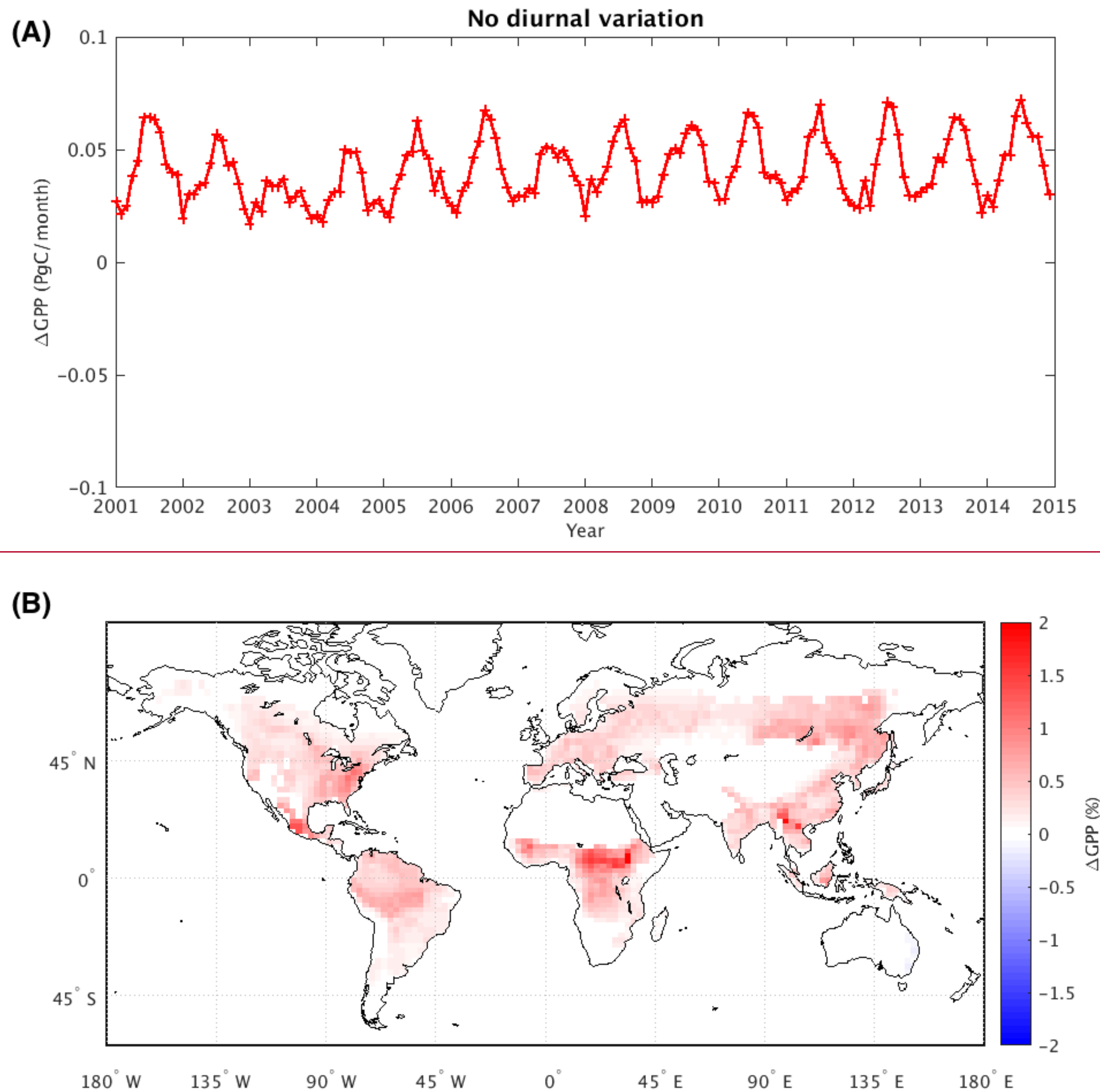


Fig. 4: (a) Change in mean global GPP (PgC month^{-1}) due to removal of diurnal variability of atmospheric CO_2 concentration (i.e., GPP from the dCO2 experiment minus that from the control). (b) Map of time-averaged GPP changes in percent (%). The tile-based model GPP values were aggregated to 2° x 2.5° for visualization purposes.

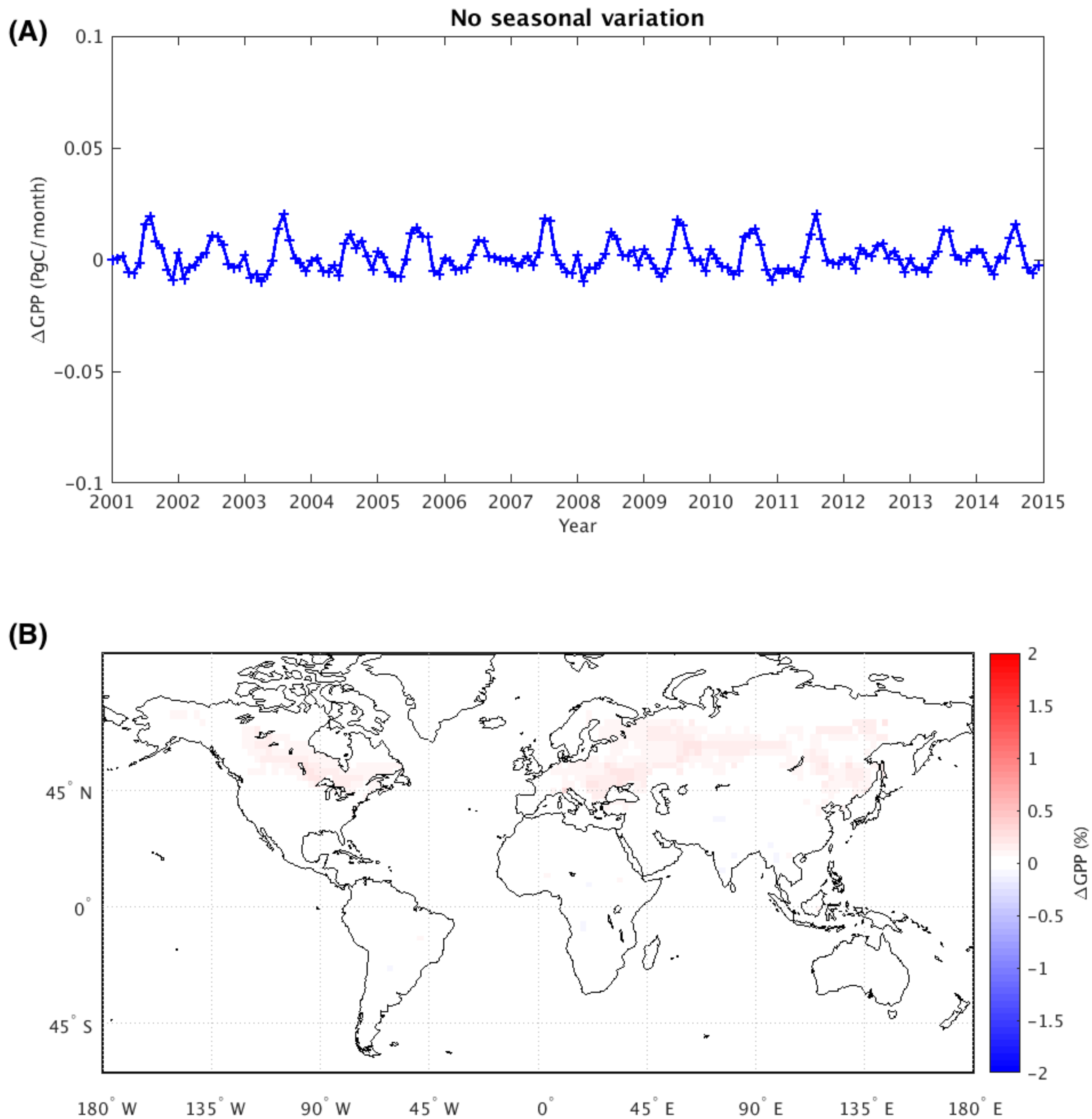


Fig. 5: (a) Change in mean global GPP (PgC month^{-1}) due to removal of ~~interannual~~ seasonal variability of atmospheric CO_2 concentration (i.e., GPP from the mam~~am~~CO2 experiment minus that from the mCO2 experiment). (b) Map of time-averaged GPP changes in percent (%).

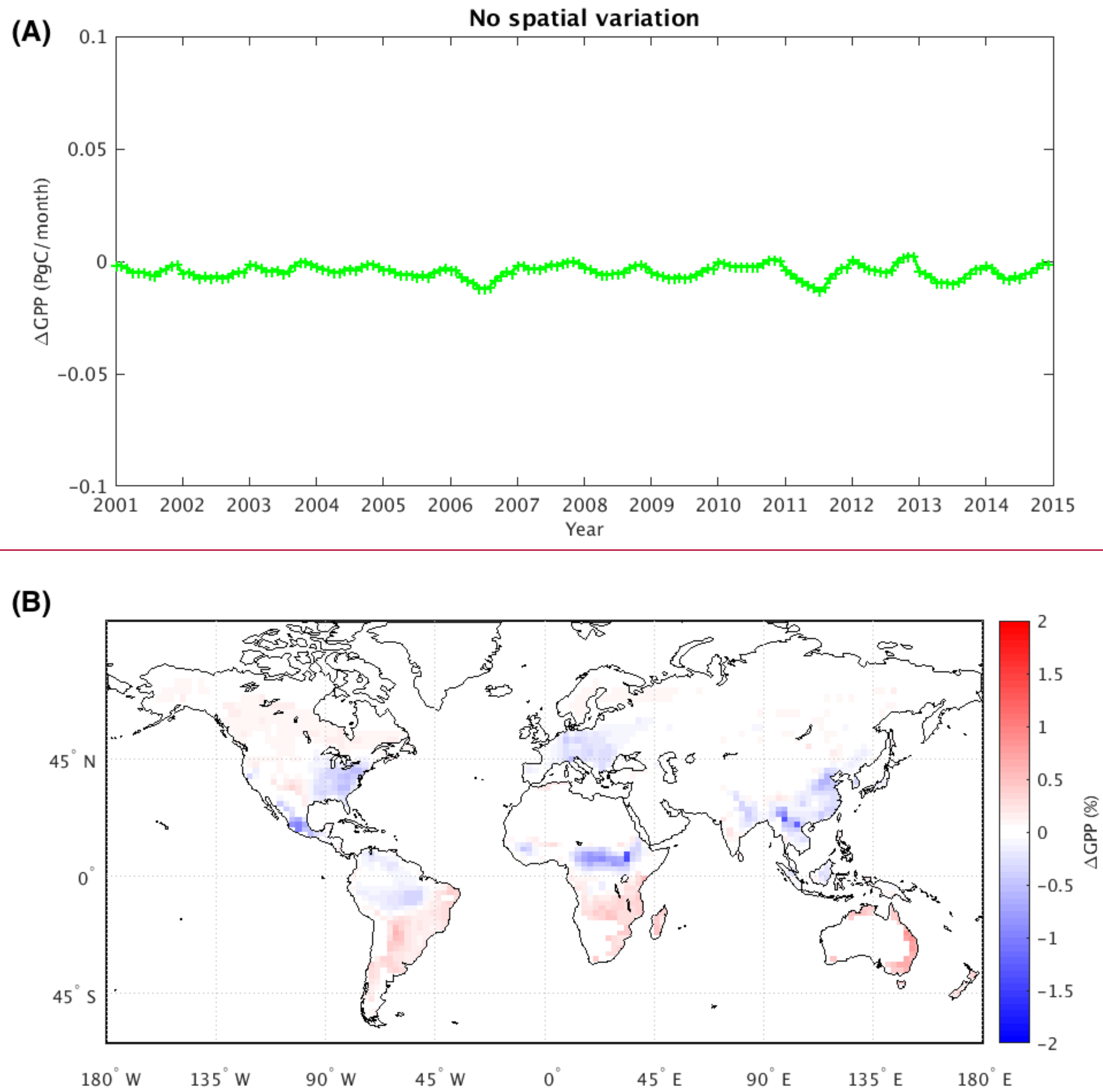
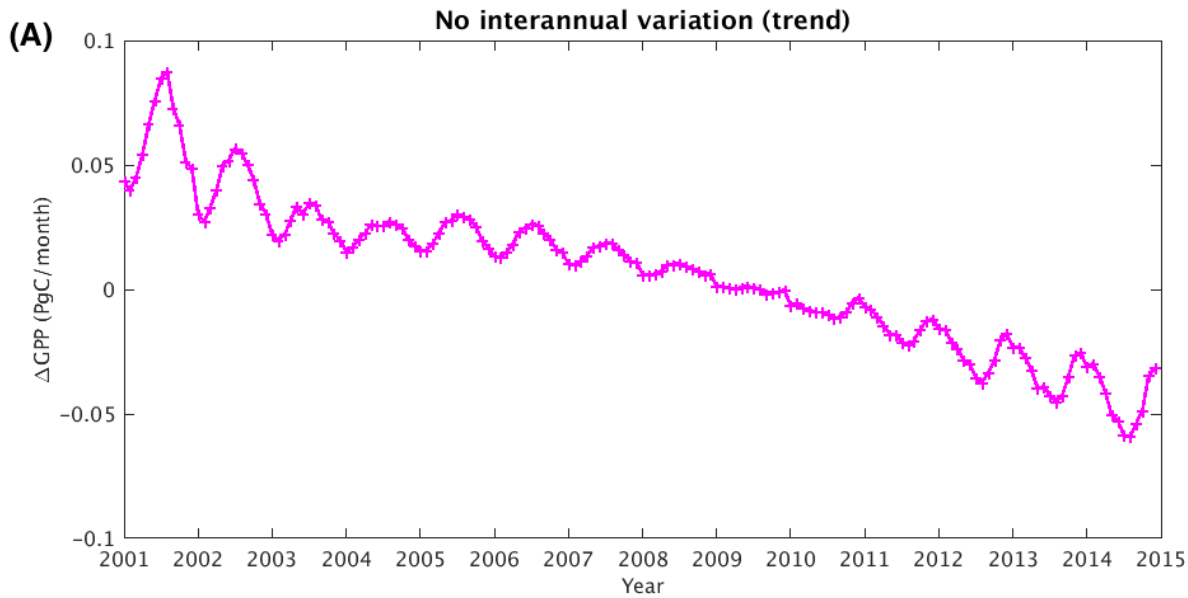


Fig. 6: (a) Change in mean global GPP (PgC month^{-1}) due to removal of ~~seasonal~~ spatial variability of atmospheric CO_2 concentration (i.e., GPP from the magaCO2 experiment minus that from the maamCO2 experiment). (b) Map of time-averaged GPP changes in percent (%).



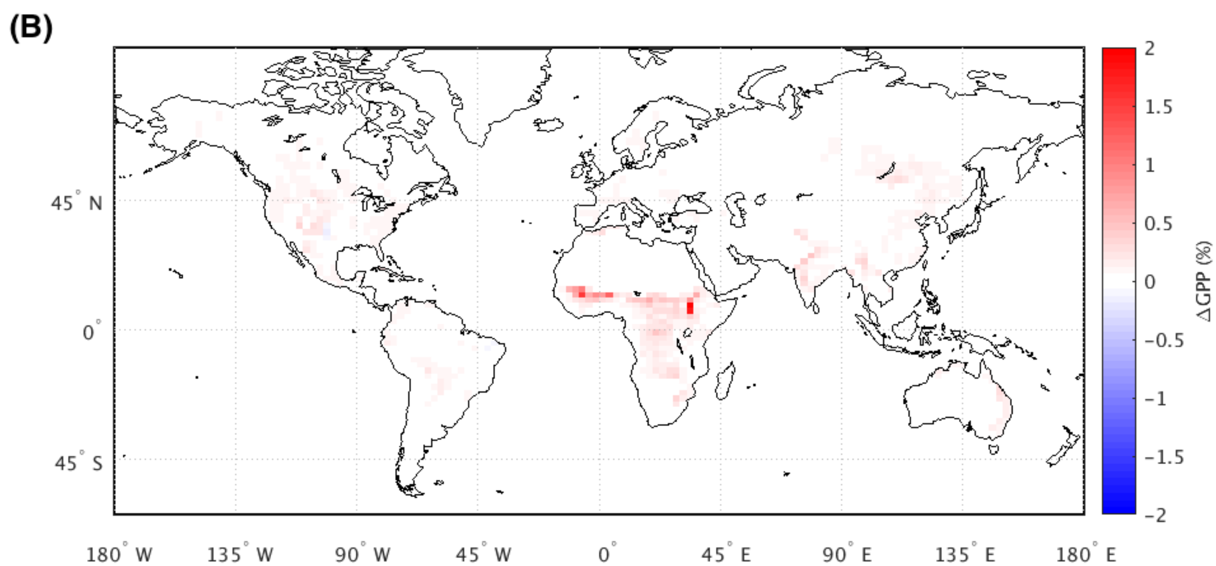
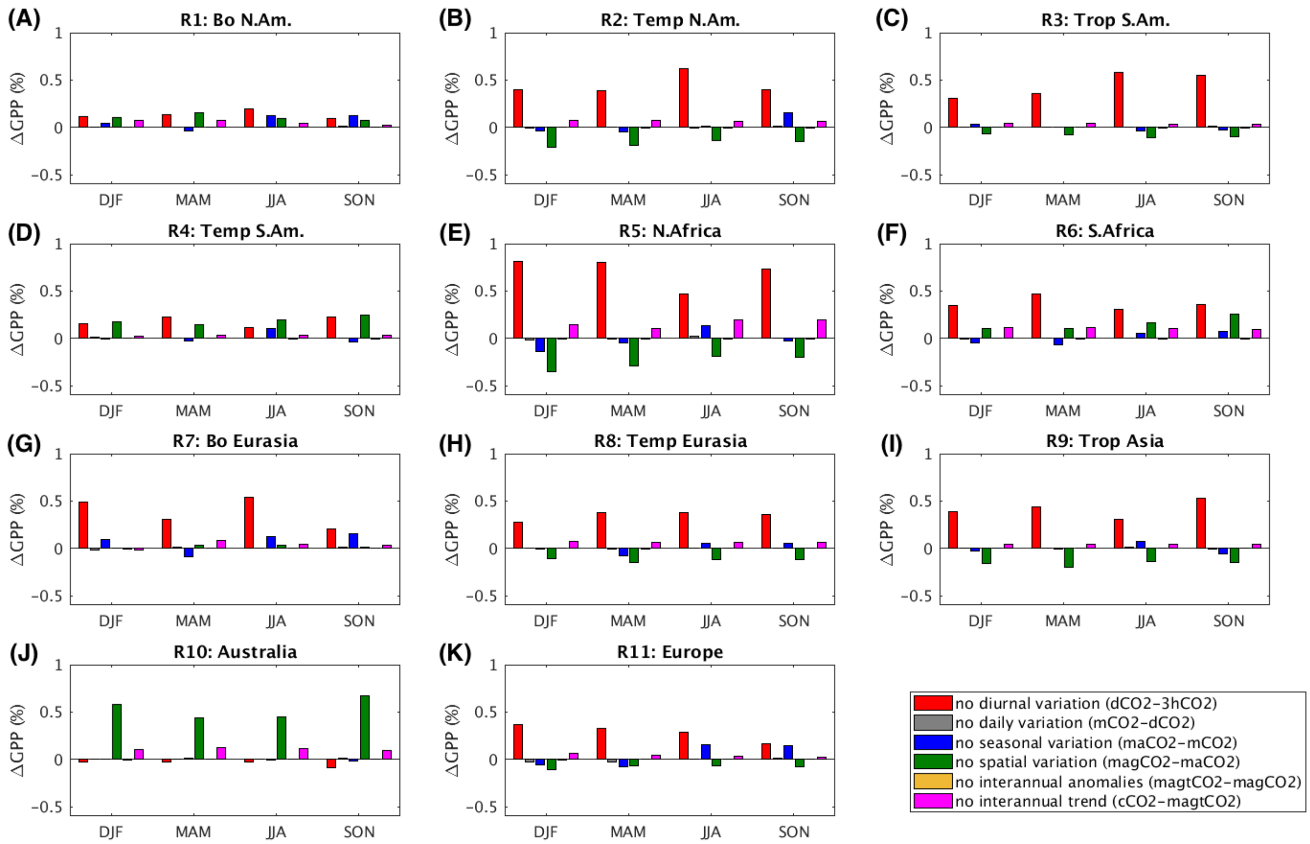


Fig. 7: (a) Change in mean global GPP (PgC month^{-1}) due to removal of ~~spatial~~ the trend in the interannual variability of atmospheric CO_2 concentration (i.e., GPP from cCO2 experiment minus that from ~~ta~~ magCO2 experiment). (b) Map of time-averaged GPP changes in percent (%).



(A)
R1: Bo N.Am.
(B)
R2: Temp N.Am.
(C)
R3: Trop S.Am.
(D)
R4: Temp S.Am.
(E)
R5: N.Africa
(F)
R6: S.Africa
(G)
R7: Bo Eurasia
(H)
R8: Temp Eurasia
(I)
R9: Trop Asia
(J)
R10: Australia
(K)
R11: Europe
ΔGPP (%)
DJF
MAM
JJA
SON
no diurnal variation (dCO2−3hCO2)
no daily variation (mCO2−dCO2)
no seasonal variation (maCO2−mCO2)
no spatial variation (magCO2−maCO2)
no interannual anomalies (magtCO2−magCO2)
no interannual trend (cCO2−magtCO2)

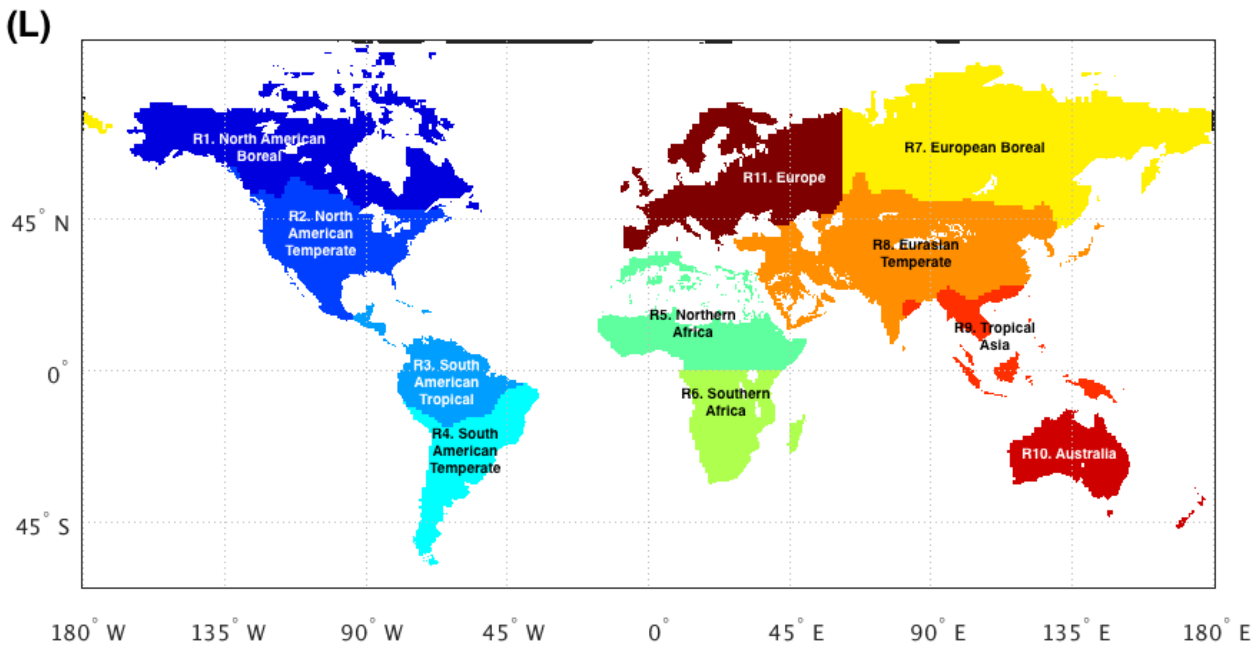


Fig. 8: Regional- and seasonal-scale impacts of spatiotemporal CO_2 variabilities on GPP. Incremental cChange in GPP toassociated with each added facet of CO_2 variability is shown are inas a % of the previous experiment's regional GPP. The map in the bottom panel shows the regional boundaries of TransCom land regions (reconstructed from the basis function map in http://transcom.project.asu.edu/transcom03_protocol_basisMap.php).