Response Letter

[RC1: Referee #1]

The authors were trying to evaluate the impacts of using prognostic and diagnostic wildfire schemes on ecosystem carbon and hydrological cycles simulated by CLM5-BGC. They found the default CLM5-BGC overestimated/underestimated the burned area in Eastern Siberia/Alaska, causing the overestimating/underestimation of wildfire carbon emissions. In contrast, the CLM5-BGC prescribed with observational burned area showed evident improvement in simulating wildfire carbon emissions for both regions. They further compared the two simulations with different wildfire schemes, in terms of major carbon and water fluxes, and showed larger influences on NEE than those for other variables. The modeling idea was unique, in terms of prescribing remote-sensing burned area within land surface model, especially across the high latitudes regions. However, the model evaluations and intercomparisons still need to be improved. For example, the authors may compare these two model results for more variables (e.g., LAI, GPP, ET, Soil Moisture) using different sources of observations or observation-based products. The authors could also add more thoughts/analyses on thow to quantify and reduce wildfire related biases for CLM5-BGC, in terms of drivers, processes and parameters.

Response: Thank you for your valuable inputs and insights into our article. In this study, we found that the application of the GFED burned area into CLM5-BGC caused significant changes in carbon emission and NEE. Therefore, we added the AKFED carbon emissions and GEOS-Carb CASA-GFED NEE to show the improvement. However, the other fluxes (GPP, NPP, and ET) and LAI did not change considerably after application of the GFED burned area. We discussed that, because the ratio of the fire area to the total area was relatively small, the LAI after fires was not substantially different due to the small fire area compared to the total area (LL). In other words, it is difficult to expect an improvement in LAI, GPP, NPP, and ET through the application of GFED. We, therefore, believe that a direct comparison to direct GPP, NPP, LAI, and ET products is not necessary and beyond the scope of our study.

As per this suggestion from the reviewer, we have added a detailed discussion about the limitations and future direction of the CLM fire module, as shown below:

LL 216: *In addition, wildfires are strongly affected by the weather conditions after the fire ignition. For example, wind and precipitation determine spread and duration of the fire. However, in CLM5-BGC, the fire ignition and fire spread rate are simultaneously calculated based on the weather conditions of fire ignition or pre-fire. Moreover, the persistence of each fire is assumed to be equal to 1 in CLM5-BGC. However, fires can last longer depending on climate conditions, which increase the burned area. Therefore, fire dynamics depending on the weather conditions after the fire ignition are necessary to reduce the biases in fire calculations.*

LL 285: *As the same fractional area burned is imposed on each PFT in a grid, the simulated carbon emission could be different from observed carbon emission. For example, when an* *observation of forest fire is applied into CLM5-BGC, the fractional area burned is imposed on both grasses and trees in the same grid, causing biases in the carbon emission values. Therefore, a reasonable method of imposing grid-level burned areas into the PFT-level is required.*

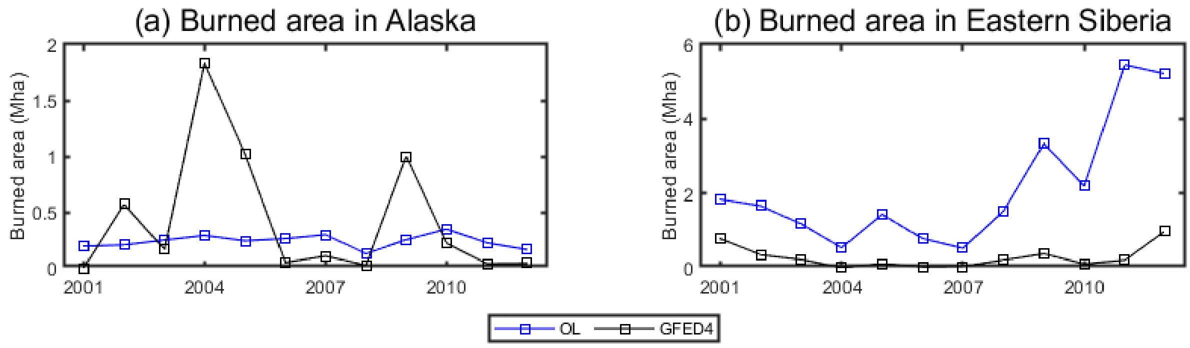
Additionally, sentences between lines 231 and 234 read confusing;

Response: Thank you for pointing this issue out. We have revised them for clarity, as shown below:

LL 237: *Moreover, the correlations between the simulated carbon emissions and AKFED carbon emissions were determined (OL: 0.31 and EXP-GFED4: 0.96). While the root mean square error (RMSE) between the simulated carbon emissions and the AKFED carbon emissions decreased after applying the GFED4 burned area (OL: 20.48 g* m^{-2} *year*$^{-1}$ *and EXP-GFED4: 10.98 g* m^{-2} *year*$^{-1}$*), the RMSE between the simulated carbon emissions and the GFED4 carbon emissions increased (OL: 11.02 g* m^{-2} *year*$^{-1}$ *and EXP-GFED4: 20.93 g* m^{-2} *year*$^{-1}$*).*

and color scheme in Fig. 3 needs to be reversed?

Response: Thank you for your valuable suggestion regarding this figure. Based on your suggestion, we have revised the color in Fig. 3, as shown below:



[RC2: Referee #2]

Hocheol Seo and Yeonjoo Kim integrated GFED burned area dataset into CLM5-BGC model and investigated how fire activity affect ecosystem carbon and water fluxes over Alaska and Easter Siberia. They found that using GFED observed burned area, CLM5-BGC performed better in capturing fire emissions. Moreover, the carbon emissions over Alaska was sensitive to wildfire, while transpiration over Easter Siberia was insensitive to burn. The paper is well constructed. Below are major concerns:

The design of the model experiment needs to be improved to fully account the impact of historical fires and for a fair comparison between OL vs EXP-GFED4 runs.

This study used BGC version of CLM5, that have carbon, nutrient, water cycles. The 200 year spin up might be enough to stabilize soil temperature and moisture, but is too short to stabilize soil carbon pool and ensure a quasi-steady state condition. Suggestion: plot out total ecosystem carbon for the last 10 or 20 years of spinup period, the changes of total ecosystem carbon should be trivial. Also, long-term average of net ecosystem exchange (NEE) should be near zero in the end of spinup. If not, tried a longer spinup period.

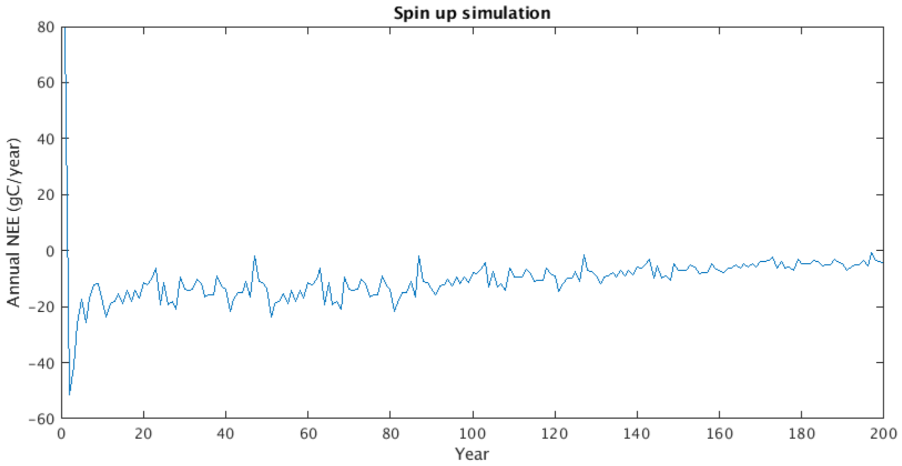
After the spinup, a long-term transient simulation (starting from year 1850 or 1901) is necessary to ensure the land use, warming, and CO2 enrichment signals are all appropriately picked up by the CLM5-BGC model. For example, in this period, we often see initial decline of vegetation carbon due to land use, and then enhanced vegetation growth in response to warming and higher CO2 concentration will overwhelm. Such historical changes of vegetation activities, soil moisture conditions will affect fuel availability and combustibility for simulations from year 2001-2012 (period of focus for analysis). Otherwise, without appropriate spinup and transient simulation, the comparison of fire emissions and transpiration fluxes and others might not be convincing.

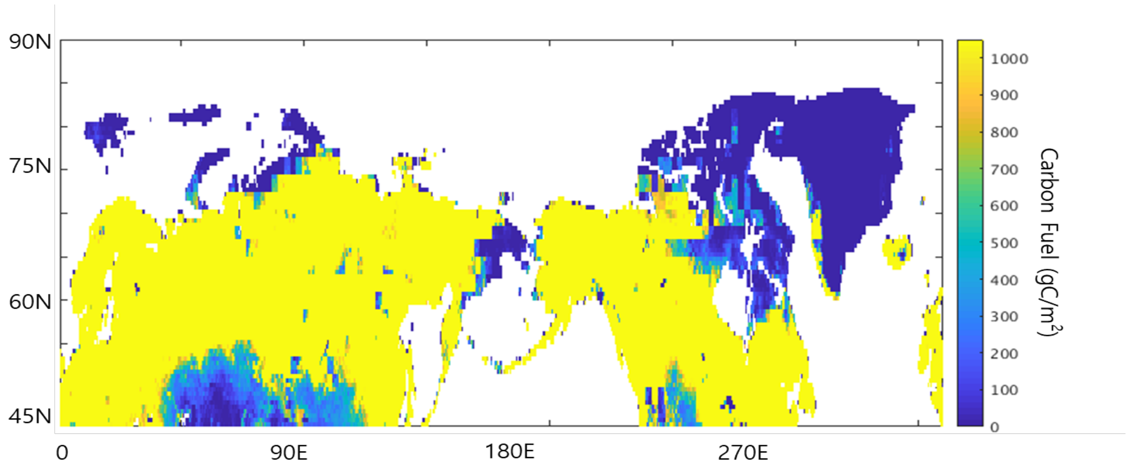
Response: Thank you for your valuable suggestion regarding our article. We did the spin up simulation for 200 years using the initial file, which already stabilized the carbon and water storage of the year 2000 to an equilibrium state. This initial file, which was provided by NCAR, makes us skip both long-term spin-up simulations and transient runs. As there may be stabilization issues caused by differences in resolution, spin-up simulations for an additional 200 years were performed. We have revised the manuscript to specify the spin-up process, as shown below:

LL 174: *Figure 2 shows the spin-up simulation, which stabilizes the land state, including the LAI, soil moisture, and soil temperature, with the initial file of the year 2000 in the equilibrium state. It was repeatedly run for 200 years using 20-year CRU/NCEP forcing data for 1980–2000 before adopting OL and EXP-GFED4.*

Furthermore, we verified that the carbon and soil moisture was enough for stabilization, and the figure below shows that the NEE was near zero during the spin-up period. In addition, we show the value of Fuel C mapped over high latitudes. In most cases of high latitudes, Fuel C exceeded 1050 gC/m^2, which is the upper fuel threshold. This means that there was enough of

Fuel C to burn during the CLM simulation period. Please refer to Equation 2.24.6 in Lawrence et al. (2019).





- CLM5-BGC baseline model performance and improvement

In order to understand how much of improvement was due to the integration of GFED burned area dynamics, it will be necessary to first showed CLM5-BGC baseline model performance over the area of interest. It will be good to compare OL and EXP-GFED4 simulations against observations (Figure 6-10). Suggested datasets are e.g., FLUXCOM GPP/NEP, MODIS LAI, GLEAM ET, GEOCARBON vegetation biomass.

Response: Thank you for your valuable inputs and insights into our article. In this study, we found that the application of the GFED burned area into CLM5-BGC caused significant changes in carbon emission and NEE. Therefore, we added the AKFED carbon emissions and GEOS-Carb CASA-GFED NEE to show the improvement. However, the other fluxes (GPP, NPP, and ET) and LAI did not change considerably after application of the GFED burned area. We discussed that, because the ratio of the fire area to the total area was relatively small, the LAI after fires was not substantially different due to the small fire area compared to the total area (LL 264). In other words, it is difficult to expect an improvement in LAI, GPP, NPP, and

ET through the application of GFED. We, therefore, believe that a direct comparison to direct GPP, NPP, LAI, and ET products is not necessary and beyond the scope of our study.

- Area of focus

The box area in Figure 1 seems arbitrary. It will be better to use geographic boundary (e.g., state of Alaska) instead of a random box.

Response: Thank you for this valuable advice. We have revised the mistake in the domain description, as shown below. We chose the boundary of "Interior Alaska" (200° E–218° E and 61° N–70° N), where fires occur frequently. However, the burned area is underestimated over Interior Alaska. Therefore, the effect of an accurate fire can be clearly shown through a comparison of the two simulations (OL and EXP-GFED4) in this boundary. Boundary b [Eastern Siberia (130° E–148° E and 61° N–70° N)] was chosen because the fire simulation was too overestimated even though both domains have the same size and latitudes.

LL 160: *In this study, we focused on Alaska (200° E–218° E, 61° N–70° N) and Eastern Siberia (130° E–148° E, 61° N–70° N), which are located at northern high latitudes (Figure 1). Both domains have the same size and latitudes.*

LL 495: *Figure 1. Study domain, (a) Alaska (200° E–218° E and 61° N–70° N), and (b) Eastern Siberia (130° E–149° E and 61° N–70° N).*

- Plant functional type differences

It is not clear, how each different plant functional type (PFT) handled when GFED data is integrated to CLM5-BGC at gridcell level. At each gridcell, CLM has multiple PFT that have different level of fuel conditions (e.g., arctic grass vs boreal tree). When the observed burned area gets integrated, how to reasonably assign the burn to each PFT? For example, the observed burn may occur over forest, while in CLM the observed burn is imposed on the whole gridcell that have both trees and grasses.

Response: Thank you pointing this out. The burned area was calculated at the grid level, not at the PFT-level. Once a grid-level burned area is calculated, the same fractional area burned (/s) is imposed on each PFTs in the grid. We have added this explanation in Section 2.1 and a related discussion about this, as shown below:

LL 92: *In CLM, the burned area is calculated at the grid level and the fire emissions are calculated at a PFT level. Once a grid-level burned area is calculated, the same fractional area burned is imposed on each PFT in the grid. The PFT-level carbon emission from the fire is calculated as follows (24.26 in Lawrence et al., 2019):*

$$CE = A \cdot C \cdot CC \qquad (1)$$

where CE is the carbon emission; A is the fractional area burned; C is a vector with the carbon density of leaves, stems, and roots, carbon transfer, and carbon pools; and CC is the corresponding combustion completeness factor vector.

LL 285: *As the same fractional area burned is imposed on each PFT in a grid, the simulated carbon emission could be different from observed carbon emissions. For example, when an observation of forest fire is applied into CLM5-BGC, the fractional area burned is imposed on both grasses and trees in the same grid, causing biases in the carbon emission values. Therefore, a reasonable method of imposing grid-level burned areas into the PFT-level is required.*

Temporal scale issue
GFED is a monthly product, while CLM5-BGC runs at a much finer temporal resolution (e.g., 30min). How to assigned monthly burned area to each individual time step in CLM5-BGC? It will make a big difference to apply the burned area to the beginning versus to the end of each month?

Response: The GFED4 product is provided at a 0.25° × 0.25° resolution and at daily and monthly temporal resolutions. Thus, we applied the daily scaled GFED products to CLM. This daily data is equally divided into a half-hourly model timestep. Please refer to LL 181 in the manuscript.

[CC1: Sarah Gallup]

This study focuses on a decidedly useful topic. The design is a reasonable approach to learning about the limitations and potential to improve CLM's fire simulations. Phrasing and copyediting are substandard. The analysis of the results needs more meat in terms of using details of the two runs to better understand how and why they differ. The model runs would support a substantially tighter and more coherent assessment. What can the authors show or even speculate about why CLM fire matches not only rather poorly to the datasets, but also differently in the two continents? Ssaying CLM Fire is "limited", pointing out that it is imperfect, is less useful than helping the community think about reasons and specifics. Several of the speculations about real-world reasons the CLM fire algorithm is imperfect are insightful and useful.

Response: Thank you for raising this concern. As per the reviewer's suggestion, we have added a detailed discussion about the limitations and future direction of the CLM fire module, as shown below:

LL 216: *In addition, wildfires are strongly affected by the weather conditions after the fire ignition. For example, wind and precipitation determine spread and duration of the fire. However, in CLM5-BGC, the fire ignition and fire spread rate are simultaneously calculated based on the weather conditions of fire ignition or pre-fire. Moreover, the persistence of each fire is assumed to be equal to 1 in CLM5-BGC. However, fires can last longer depending on climate conditions, which increase the burned area. Therefore, fire dynamics depending on the weather conditions after the fire ignition are necessary to reduce the biases in fire calculations.*

LL 285: *As the same fractional area burned is imposed on each PFT in a grid, the simulated carbon emission could be different from observed carbon emissions. For example, when an observation of forest fire is applied into CLM5-BGC, the fractional area burned is imposed on both grasses and trees in the same grid, causing biases in the carbon emission values. Therefore, a reasonable method of imposing grid-level burned areas into the PFT-level is required.*

Some notes about uncertainty in the benchmark datasets seem warranted. As an obvious example, GFED emissions too are a model. While it is reasonable to assume the comparison data is more accurate than an ESM simulation of fire, what considerations about the inevitably imperfect inventories should a reader keep in mind? How similar are the two inventories' derivation algorithms and data sources? Making the comments specifically relevant to the patterns the study finds would be most helpful. As only an example, what is the correlation of GFED and AKFED emissions for the study area and period?

Response: Thank you for providing this valuable suggestion. Indeed, GFED and AKFED emissions are also model outputs. The correlation between GFED and AKFED emissions over Alaska is 0.9. However, when the fire module of CLM5-BGC was developed, the global-scale GFED carbon emissions were benchmarked (Li et al. 2012). Therefore, we compared the simulated carbon emissions and the GFED emissions. We also performed an additional analysis with AKFED emissions to reduce the uncertainties.

Any information about the relevance of peat fire would make this paper a substantially stronger tool for improving fire in CLM. As examples, what is the relative abundance of peat in the study area compared to the rest of Siberia? What portion if any of the "open loop" Siberian burned area and emissions were generated from the peat fire algorithm within CLM fire?

Response: Thank you for this valuable suggestion. Peat fires are becoming increasingly important. However, simulating peat fires using CLM is insufficient. We verified that the peatland proportion of our domain in CLM was too low (Alaska: 0%, Eastern Siberia: 2%); hence, we could ignore the effects of peatland fires. We believe that the distribution of peatlands would be detected more accurately and employed primarily in the model to study the impacts of peat fires.

Thank you for tackling this study.
general - Please either use a consistent number of significant digits, or justify why not.
Response: Thank you for raising this concern and the valuable suggestion. As per the reviewer's suggestion, we have done the following revisions in the manuscript:

LL 256*: In Alaska (Fig. 6a), the difference in LAI between OL and EXP-GFED4 was the largest in 2005 (0.03 m^2/m^2).*
LL 314*: The average change rates of NEE and carbon fluxes were 4914 gC ha^{-1} and 4881 gC ha^{-1} and 771 gC ha^{-1} and 797.6 gC ha^{-1} in Alaska and Eastern Siberia, respectively*.

line 41 - 'Human-caused' is conflated with human-ignited. Warmer climate, too, is human-caused.

Response: We truly appreciate your valuable insight in this matter. As per the reviewer's suggestion, we have revised this in the manuscript, as shown below:

LL 41: *Fires at high latitudes are primarily ignited by natural processes rather than by humans.*

102 - Equations 1 & 2 should be cited, including with equation numbers from Lawrence19

Response: Thank you for pointing this out. As per the reviewer's suggestion, we have added following lines in the manuscript:

LL 93: *The PFT-level carbon emission from the fire is calculated as follows (24.26 in Lawrence et al., 2019)*
LL 103: *In CLM5-BGC, the amount of leaf carbon to litter (Ψ) caused by fire is calculated as follows (24.27 in Lawrence et al., 2019)*

106 - By “leaf size” do you mean LAI? The terms are not interchangeable.

Response: Thank you for raising this valid concern. As per the reviewer’s suggestion, we have done the following revision in the manuscript:

LL 109: *The leaf area index (LAI) is recalculated based on the adjusted amount of leaf carbon. In addition, the methods by which the amount of carbon in live stems, dead stems, and roots and the storage pool are adjusted due to fires are similar to those mentioned above.*

153 - What data source do you use for woodfuel burning estimates?

Response: Thank you for pointing this issue out. As per the reviewer’s suggestion, we have added a description in the manuscript.

LL 157*: $FuelE$ is the carbon emissions from wood-fuel burning in GEOS-Carb CASA-GFED.*

166 - Pls explain why you chose the specific area within Siberia, and what relevant ways it is similar to or different from the rest of Siberia.

Response: We appreciate you asking about this. Boundary b (Eastern Siberia (130°E–148° E and 61° N–70° N)) was chosen because the fire simulation was too overestimated even though both domains have the same size and latitudes.

201 - an egregious example of the need for copyediting. Ditto l. 230-234.

Response: Thank you for pointing this out. As per the reviewer’s suggestion, we have revised this in the manuscript, as shown below:

LL 237: *Moreover, the correlations between the simulated carbon emissions and AKFED carbon emissions were determined (OL: 0.31 and EXP-GFED4: 0.96). While the root mean square error (RMSE) between the simulated carbon emissions and the AKFED carbon emissions decreased after applying the GFED4 burned area (OL: 20.48 g m^{-2} $year^{-1}$ and EXP-GFED4: 10.98 g m^{-2} $year^{-1}$), the RMSE between the simulated carbon emissions and the GFED4 carbon emissions increased (OL: 11.02 g m^{-2} $year^{-1}$ and EXP-GFED4: 20.93 g m^{-2} $year^{-1}$).*

217 - While the general point is very well taken, “no human impacts” is an overstatement. See p.29 of https://fire.ak.blm.gov/content/aicc/Alaska%20Statewide%20Master%20Agreement/3.%20Alaska%20Interagency%20Wildland%20Fire%20Managment%20Plan%20(AIWFMP)/2022%20AIWFMP%20Final%20Signed%202022-02-28.pdf. Responding agencies will “conduct site protection as warranted.”

Response: We thank you for raising this valid concern. As suggested, we have removed this sentence from the manuscript.

237 - OK, but there now exists information about differences between GFED3 and GFED4. To what extent is Veraverbeke's explanation that you reiterate perhaps now addressed – or not?

Response: Thank you for raising this concern. We showed that GFED products have a weakness in representing the carbon emissions over Alaska. We referred to the Veraverbeke's explanation, which showed that there was a possibility that GFED3s underestimated carbon combustions which can be attributed to the presence of fires in boreal forest regions, and we thought this was similar in GFED4.

239 - Rather than speculate, pls look up the numbers and compare them at least to each other and ideally also to additional references.

Response: Thank you for this valuable suggestion. As per the reviewer suggestion, we added the values of the combustion completeness factors in CLM5-BGC, as shown below. We have also added a reference about the combustion completeness factor values in boreal forests.

LL 246: *The combustion completeness factor for leaves is 0.8 and that for stems ranges from 0.27 to 0.8, depending on the PFTs in the CLM5-BGC. According to van der Werf et al. (2010), the combustion completeness of aboveground live biomass, which ranges 0.3~0.4 in the boreal region, is lower than that in other regions. Therefore, the combustion completeness factors for boreal trees may be lower than the current default value in CLM5-BGC.*

Reference: *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, https://doi.org/10.5194/acp-10-11707-2010, 2010.*

256 - rates of change, or changes?

Response: Thank you for pointing this error out. We have corrected it to "rates of changes."

279 - 281 needs replacing. Line 279 is an overstatement; Line 280 was known before the study started simply because all models are imperfect; Line 281 is not a logical conclusion based on the prior two statements. Writing a stronger analysis as requested in the general notes above will provide better material to summarize in this paragraph.

Response: Thank you for your valuable insights and suggestions on this section. As per the reviewer's suggestion, we have revised this sentence, as shown below:

LL 290: *As CLM5-BGC is still limited in representing fire processes, there is a large difference in the burned area between the simulation and observation. By comparing our experiments of OL and EXP-GFED4 in Alaska and Eastern Siberia, we identified the effects of accurate fire simulation on carbon fluxes over Alaska and Eastern Siberia*.