Response to the reviewer 3

We are grateful to the referees for their time and energy in providing helpful comments and guidance that have improved the manuscript. In this document, we describe how we have addressed the reviewer's comments. Referee comments are shown in black and author responses are shown in blue text.

This work integrates and couples together a global atmospheric chemistry model (GEOS-Chem) and a terrestrial biosphere model (YIBs) in order to investigate the feedbacks associated between the two, often separately simulated, systems. First, the authors evaluate their integrated model against observed or baseline measures of plant activity (GPP/LAI) and an example chemical species (ozone concentration). They also compare the performance of the coupled and integrated models against observed ozone dry deposition velocities, finding the coupled model an improvement. Using this coupled model, the authors then investigate the impact ozone concentration has on plant activity using differing sensitivities to ozone damage. Overall, this work is timely and addresses an important issue within the modeling of these systems. The description of the model and evaluation is carried-out well with appropriately supportive figures. However, the paper does not go far enough to be truly impactful and confidently useful to the community in its present form, but rather, substantial addition and expansion is required for publishing in GMD. The authors should either expand the evaluation of the model to show that coupling truly does improve comparisons or provide additional applicational evidence for the importance of such coupling to understanding biosphere-atmosphere interactions. Further specific comments and recommendations are listed below.

➔ Thank you for your positive evaluations. All the questions and concerns have been carefully answered and the paper has been revised accordingly.

1) While the PM impact on plants is mentioned as an important process to consider in

the introduction (lines 63-69), there is no integration description or evaluation in this paper, and no further mention until the last paragraph. Perhaps clarify the focus of the paper at the beginning to adjust expectations.

Response: We aim to develop a fully coupled biosphere-chemistry model GC-YIBs. We clarify in the introduction section that: "For the first step, we focus on the coupling between O_3 and vegetation. The interactions between aerosols and vegetation will be developed and evaluated in the future." (Lines 113-115) The aerosols-vegetation interaction has been marked with blue dashed box in Fig. 1.

2) Aerosols are not always beneficial to vegetation if the total radiation decreases more than the enhancing effect caused by diffusion (line 64).

Response: The effect of aerosols on vegetation has been modified as following: "Unlike O_3, the effect of aerosols on vegetation is dependent on the aerosol concentrations. Moderate increase of aerosols in the atmosphere is beneficial to vegetation (Mahowald, 2011; Schiferl and Heald, 2018). The aerosol-induced enhancement in diffuse light results in more radiation reaching surface from all directions than solely from above. As a result, leaves in the shade or at the bottom can receive more radiation and are able to assimilate more CO_2 through photosynthesis, leading to an increase of canopy productivity (Mercado et al., 2009; Yue and Unger, 2018). However, excessive aerosol loadings reduce canopy productivity because the total radiation is largely weakened (Alton, 2008; Yue and Unger, 2017)." (Lines 64-73)

3) Since GC-YIBs integrates two existing models, sections 2.1 and 2.2 can be trimmed to only include the relevant equations and processes discussed in the remainder of the paper.

Response: Thank you for your suggestion. Reviewer#2 expects us to add more details about the YIBs model. We have described some important processes within YIBs (e.g., the method calculating LAI, equations 3-7). These descriptions are especially useful to those unfamiliar with the YIBs model.

4) More description of the "satellite-based land types and cover fraction" (lines 122 and 229) would be useful as this is quite vague.

Response: We added Fig. S1 to show the land types used in YIBs. In addition, the conversion relationships between YIBs and GEOS-Chem deposition land types has been added (Table S2 and Fig. S2).

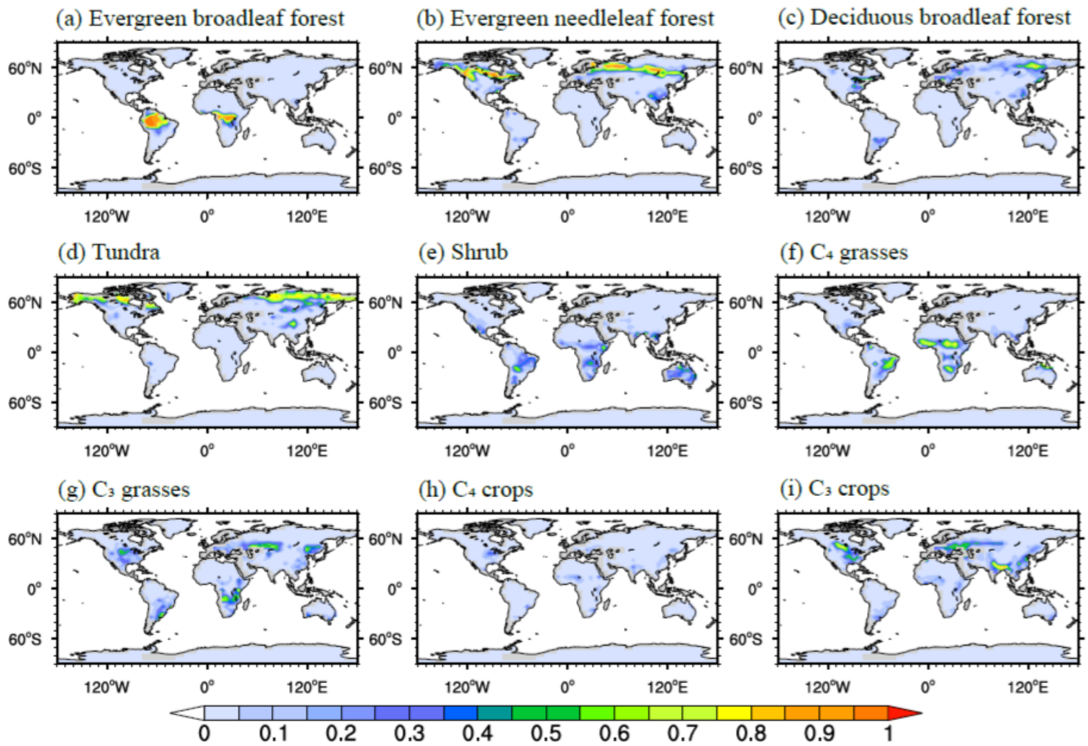

Figure S1 Fractional coverage of each land type at each grid cell.

5) The fact that coefficient α is uncertain and will be varied in different simulations is not clear from the current description in line 153.

Response: We added Table S1 to clarify: "For a specific PFT, the values of coefficient a vary from low to high to represent a range of uncertainties for ozone vegetation damaging (Table S1)." (Lines 192-193)

Table S1 The coefficient α of O_3-damaging sensitivity for a specific PFT.

PFTs	α for high sensitivity ($mmol^{-1}\ m^{-2}$)	α for low sensitivity ($mmol^{-1}\ m^{-2}$)
Evergreen broadleaf forest	0.15	0.04
Evergreen needleleaf forest	0.075	0.02
Deciduous broadleaf forest	0.15	0.04
Shrub	0.1	0.03
Tundra	0.1	0.03
C_4 grasses	0.735	0.13
C_3 grasses	1.4	0.25
C_3 crops	1.4	0.25
C_4 crops	0.735	0.13

6) Much work has been done to evaluate the GEOS-Chem dry deposition scheme for ozone and understand the importance of dry deposition schemes in general (e.g. Silva and Heald 2018, JGR, Wong et al 2019, ACP) but these issues are not mentioned here (neither sections 2.2 nor 4). Especially important to consider is lack of observations to truly constrain ozone dry deposition globally and the uncertainty over various timescales and in spatially heterogenous regions.

Response: Related work has been added: "Previous studies have well evaluated the dry deposition scheme used in the GEOS-Chem model against observations globally and regionally (Hardacre et al., 2015; Silva and Heald, 2018; Wong et al., 2019). They found that GEOS-Chem can generally capture the diurnal and seasonal cycles except for the amplitude of O_3 dry deposition velocity (Silva and Heald, 2018)." (Lines 251-255)

7) The title of section 2.5 should read "Evaluation data", as models are evaluated, not validated.

Response: Corrected as suggested.

8) Why are only 9 sites used for the comparison of ozone dry deposition velocity (lines 266, 341-355, Table 2, Figure 8)? Many more data are available as in Silva and Heald 2018.

Response: In revised paper, we expand our evaluations of O_3 dry deposition velocity to 19 sites (27 samples), including Amazon, coniferous and deciduous forests. The data sources are listed in Table 2. The related evaluations have been added and shown in new Figs 7-9 and Fig. S6.

Table 2 List of measurement sites used for dry deposition evaluation.

Land type	Longitude	Latitude	Season	Daytime V_d (cm s^{-1})	References
Deciduous forest	80.9°W	44.3°N	summer	0.92	Padro et al. (1991)
			winter	0.28	
	72.2°W	42.7°N	summer	0.61	Munger et al. (1996)
			winter	0.28	
	75.2°W	43.6°N	summer	0.82	Finkelstein et al. (2000)
	78.8°W	41.6°N	summer	0.83	
	99.7°E	18.3°N	spring	0.38	Matsuda et al. (2005)
			summer	0.65	
	0.84°W	51.17°N	Jul-Aug	0.85	Fowler et al. (2009)
	0.7°W	44.2°N	Jun	0.62	Lamarque et al. (2013)
	79.56°W	44.19°N	summer	0.91	Wu et al. (2016)
Amazon forest	61.8°W	10.1°S	wet	1.1	Rummel et al. (2007)
	117.9°E	4.9°N	wet	1.0	Fowler et al. (2011)
Coniferous forest	3.4°W	55.3°N	spring	0.58	Coe et al. (1995)
	66.7°W	54.8°N	summer	0.26	Munger et al. (1996)
	11.1°E	60.4°N	spring	0.31	Hole et al. (2004)
			summer	0.48	
			autumn	0.2	
			winter	0.074	
	8.4°E	56.3°N	spring	0.68	Mikkelsen et al. (2004)
			summer	0.8	
			autumn	0.83	
	18.53°E	49.55°N	Jul-Aug	0.5	Zapletal et al. (2011)
	79.1°W	36°N	spring	0.79	Finkelstein et al. (2000)
	120.6°W	38.9°N	summer	0.59	Kurpius et al. (2002)
	0.7°W	44.2°N	summer	0.48	Lamaud et al. (1994)
	105.5°E	40°N	summer	0.39	Turnipseed et al. (2009)

9) Given the small sample size and scattered data (Figure 8), the statistics cited for the comparison of dry deposition velocities in coupled GC-YIBs compared to offline GC-YIBs do not provide for high confidence that the model is truly improved with the coupling of these systems (lines 341-355). A more robust analysis should be undertaken to account for the errors in both the observed and simulated values and present the confidence with which the model could be said to truly be improved.

Response: In the revised paper, we collect data from 19 sites (27 samples) to re-evaluate the model performance in simulating daytime O_3 dry deposition velocity (Fig. 7). Additionally, we evaluate the seasonal and diurnal cycles of simulated O_3 dry deposition velocity (Figs 8 and 9). These updated results show that GC-YIBs indeed improves the performance in simulating daytime O_3 dry deposition velocity and its temporal variability (seasonal and diurnal cycles). The following information has been added in the revised paper:

"We collect long-term measurements from 4 sites across northern America and western Europe to evaluate the model performance in simulating seasonal cycle of O_3 dry deposition velocity (Fig. 8). The GC model well captures the seasonal cycles of O_3 dry deposition velocity in all sites with the correlation coefficients of 0.95 in Harvard, 0.8 in Hyytiala, 0.68 in Ulborg, and 0.71 in Auchencorth. However, the magnitude of O_3 dry deposition velocity is overestimated in Harvard and Hyytiala sites (NME of 60% and 42%, respectively) but underestimated in Ulborg and Auchencorth sites (NME of 48.7% and 58.9%, respectively) at growing seasons. Compared to the GC model, simulated O_3 dry deposition velocity with the GC-YIBs model shows large improvements over Harvard (Hyytiala) sites, where the model-to-observation NME decreases from 60% (42%) to 32% (28%).

Additionally, we investigate the diurnal cycle of O_3 dry deposition velocity at 15 sites (Fig. S6). Observed O_3 dry deposition velocities show single diurnal peak with the maximum from local 8 a.m. to 4 p.m. (Fig. 9). Compared to observations, the GC model has good performance in simulating the diurnal cycle with correlation coefficients of 0.94 for Amazon forest, 0.96 for coniferous forest, and 0.95 for deciduous forest. The GC model underestimates daytime O_3 dry deposition velocity at Amazon forest (NME of 29.8%) but overestimates it at coniferous and deciduous forests (NME of 21.9% and 22.9%, respectively). Compared to the GC model, the simulated daytime O_3 dry deposition velocities using the GC-YIBs model are closer to observations in all three biomes. The NMEs decrease by 9.1% for Amazon forest, 6.8% for coniferous forest, and 7.9% for deciduous forest." (Lines 416-438)

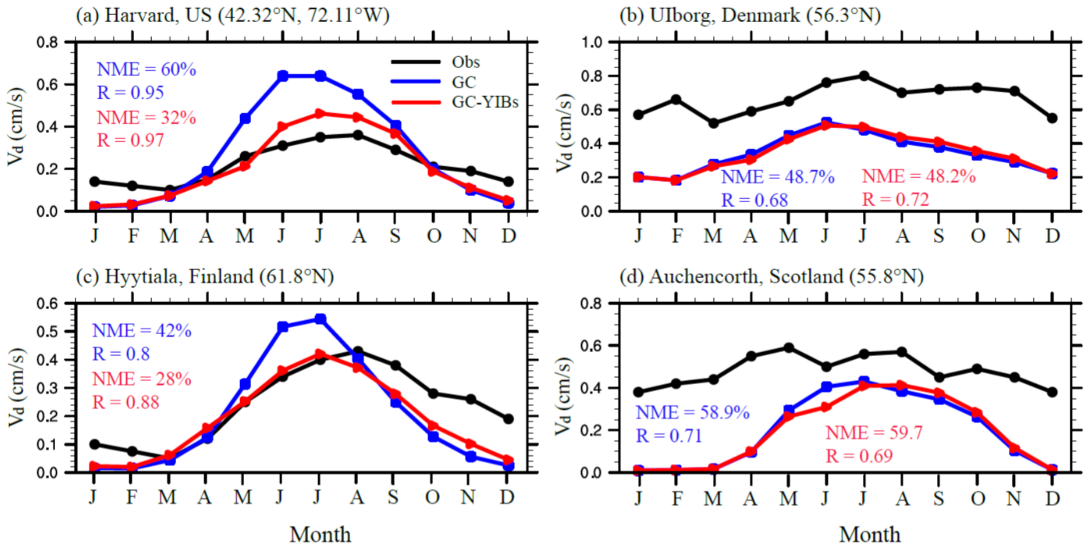

Figure 8 Comparison of monthly O_3 dry deposition velocity at Harvard **(a)**, Ulborg **(b)**, Hyytiala **(c)** and Auchencorth **(d)** sites. The black lines represent observed O_3 dry deposition velocity. The blue and red lines represent simulated O_3 dry deposition velocity from GC (Offline simulation) and GC-YIBs (Online_ALL simulation) models, respectively.

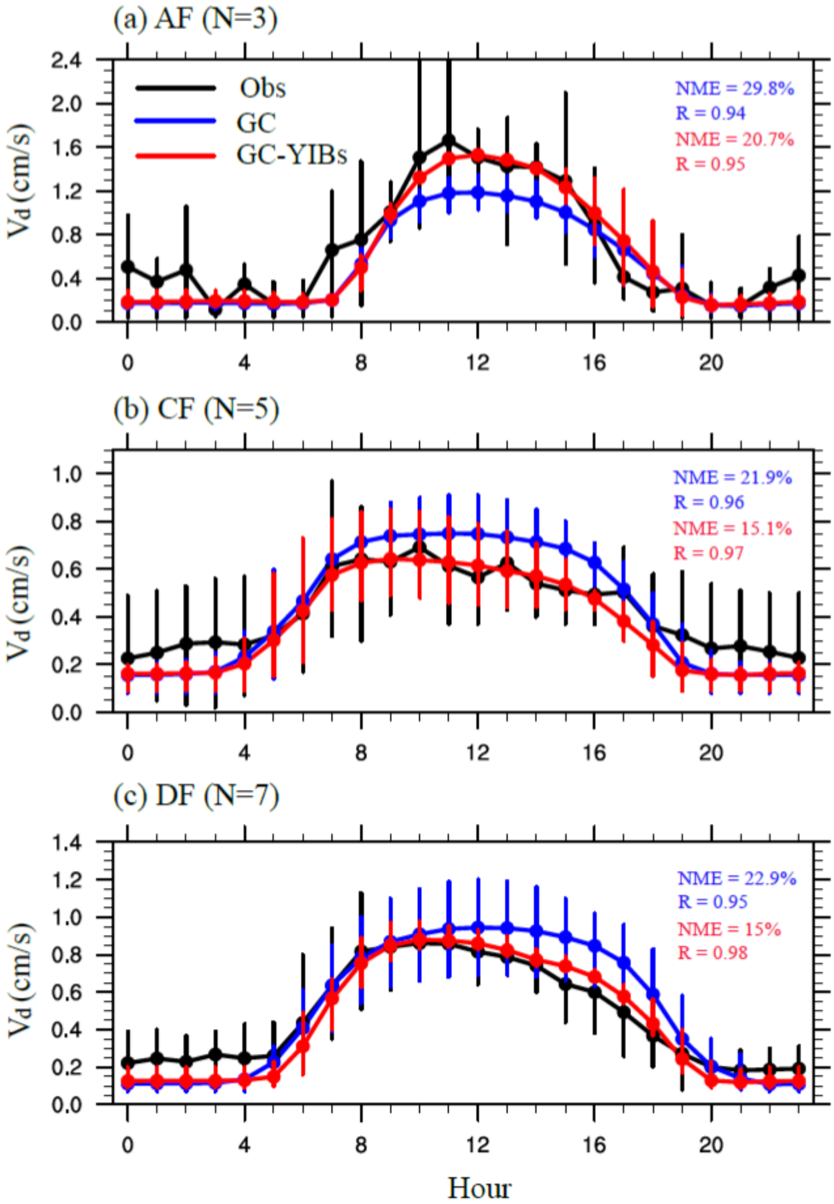

Figure 9 Comparison of multi-site mean diurnal cycle of O_3 dry deposition velocity at Amazon **(a)**, coniferous **(b)** and deciduous **(c)** forests. Error bars represent the range of values from different sites. Black lines represent observed O_3 dry deposition velocity. The blue and red lines represent simulated O_3 dry deposition velocity by GC (Offline simulation) and online GC-YIBs (Online_ALL simulation) models, respectively. The site number (N), R, and NME are shown for each panel.

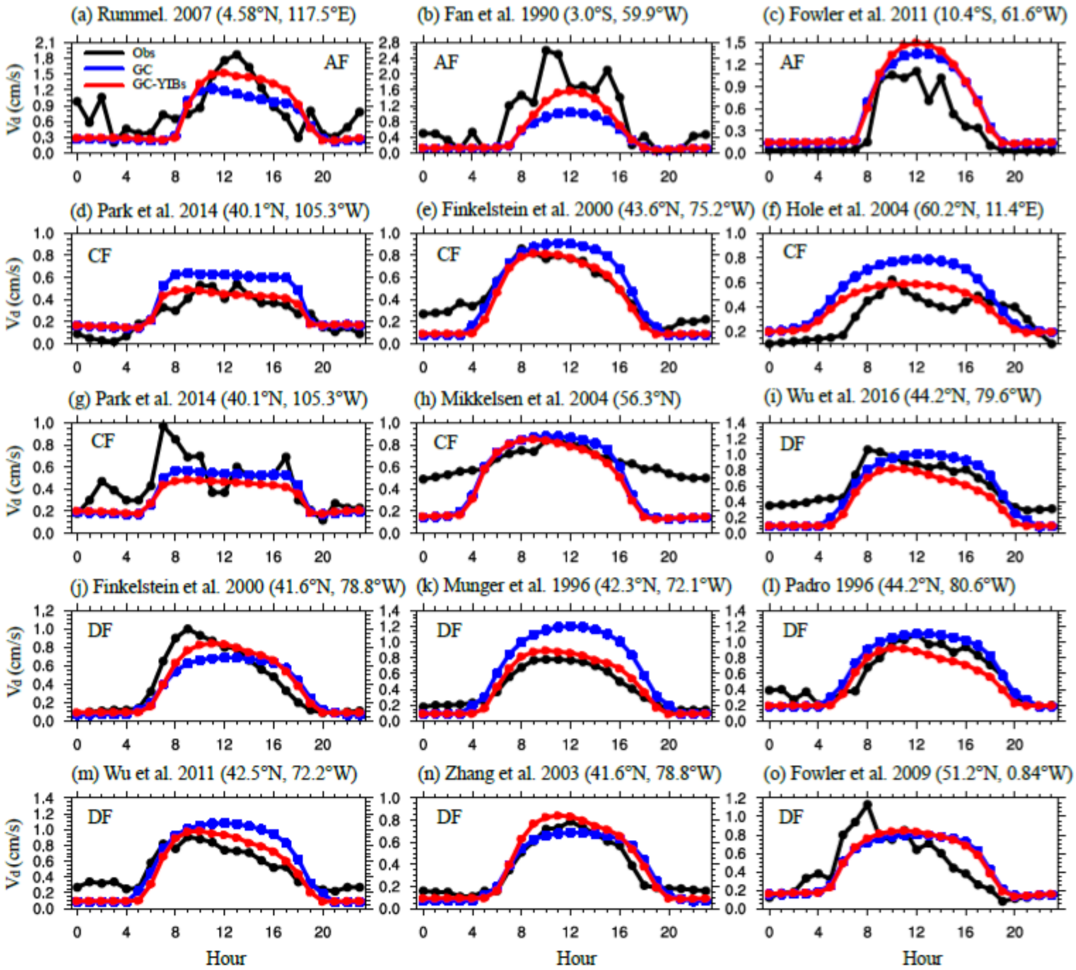

Figure S6 Observed and simulated diurnal cycle of O_3 dry deposition velocity over Amazon (a-c), coniferous (d-h) and deciduous (i-o) forests. The black lines represent observed O_3 dry deposition velocity. The blue and red lines represent simulated O_3 dry deposition velocity from GC (Offline simulation) and GC-YIBs (Online_ALL simulation) models, respectively.

10) Further description of the limitations and errors of both the observed LAI and GPP product should be included (section 2.5), and clarification should be made that GPP is not observed (line 271).

Response: (i) The following information has been added in section 2.5: “Although these products may have certain biases, they have been widely used to evaluate land surface models because direct observations of GPP and LAI are not available on the global scale (Slevin et al., 2017; Swart et al., 2019; Yue and Unger, 2015).” (Lines 315-318) (ii) The original line 271 “The simulated GPP and LAI are compared with observations for the period of 2010-2012 (Fig. 2)." has been revised as "The simulated GPP and LAI are compared with observed LAI and benchmark GPP for the period of 2010-2012 (Fig. 2)."

11) How do the simulated GPP/LAI and ozone concentrations from offline GC-YIBs compare to those values from the original YIBs and GC, respectively? Are the original model configurations degraded or enhanced by the integration and use of a common land type and meteorological driver? Are the magnitudes of these changes similar to the noted improvements seen when the coupling is turned on?

Response: (i) In this study, the simulations in offline YIBs are same as those in the original YIBs. The offline GC is different from original GC. Offline GC calculates O_3 dry deposition velocities using YIBs land types but original GC calculates O_3 dry deposition velocities using Olson land types. The biases induced by different land types has been discussed in section 2.3: "Replacing of Olson with YIBs land types induces global mean difference of -0.59 ppbv on surface [O_3] (Fig. S3). Large discrepancies are found in Africa and southern Amazon, where the local [O_3] decreases by more than 2 ppbv with the new land types. However, limited differences are shown in mid-high latitudes of Northern Hemisphere (NH, Fig. S3)." (Lines 283-287)

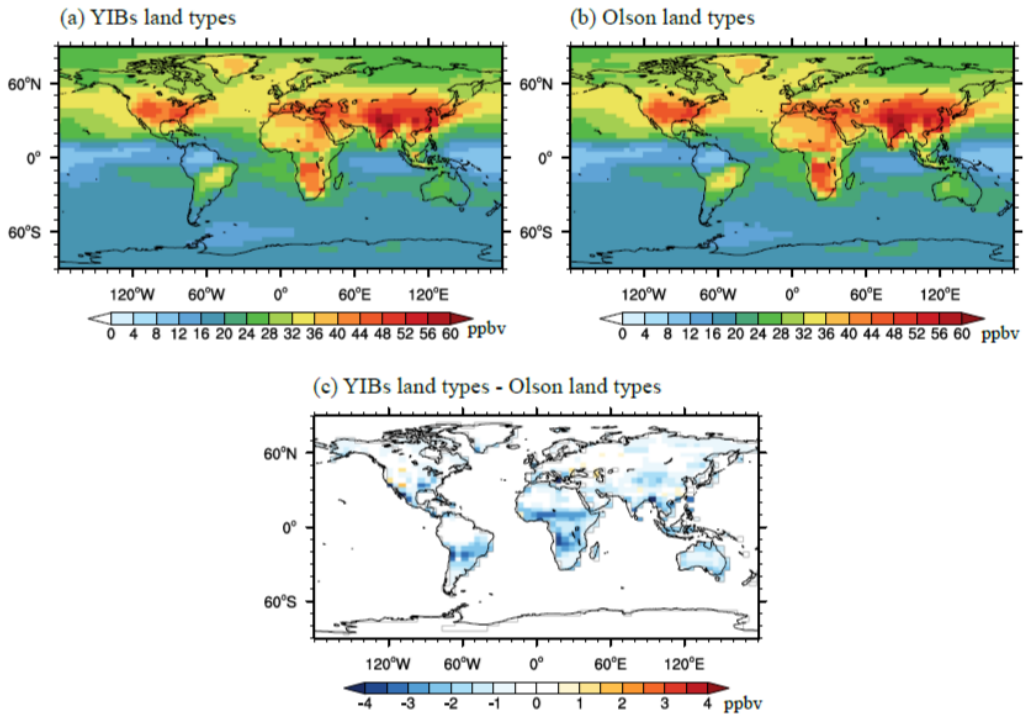

Figure S3 Comparison of YIBs and Olson land types. **(a)** and **(b)** represent the simulated MDA8 [O_3] using YIBs land types and Olson land types, respectively. **(c)** represents the simulated MDA8 [O_3] difference between YIBs and Olson land types.

12) Line 281 attributes the GPP bias to an underestimation in the benchmark GPP for tropical rainforest. Could the differences from using a different meteorology dataset instead be biasing the model (line 283)?

Response: Yue and Unger (2018) showed the YIBs model driven by WFDEI meteorology predicted higher GPP than benchmark in tropical rainforest (Fig. R1). Next, they further evaluated the simulated GPP at evergreen broadleaf forest (EBF) sites from FLUXNET (Fig. R2) and found that YIBs GPP reproduced ground-based observations well. As a result, they concluded that benchmark GPP underestimated the GPP for tropical rainforest. Similar to previous study, our study also reveals a larger GPP predicted by the YIBs model driven by MERRA2 meteorology. We think that such differences between observations and simulations are in part attributed to the underestimation of GPP for tropical rainforest in the benchmark product.

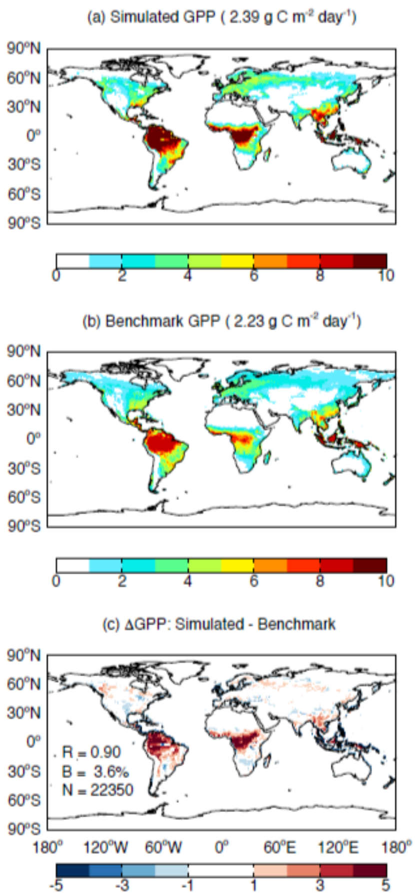

Figure R1 Comparison of YIBs and Benchmark GPP from Yue and Unger (2018).

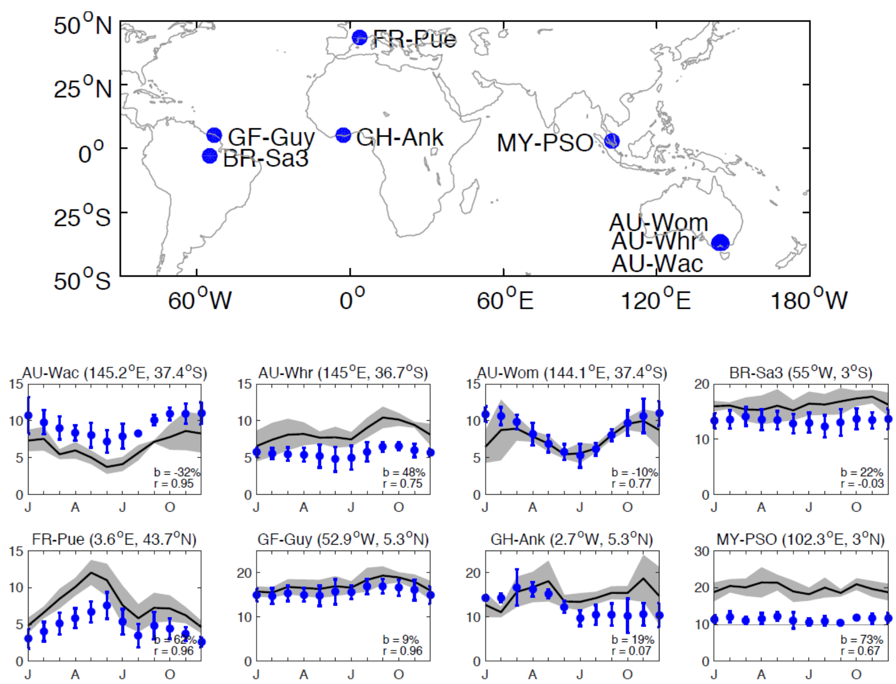

Figure R2 Evaluation of YIBs GPP at EBF sites from Yue and Unger (2018)

13) Compared to what other drivers (BVOC emissions changes?) are dry deposition velocities the dominant driver in the change in O_3 (line 324)? Try testing the impacts of the changing other drivers, rather than relying only on consistent spatial patterns (line 323).

Response: The isoprene and NO_x emission changes caused by coupled LAI has been added as Fig. S5 in the revised paper. The description of this figure has been added "In a comparison, updated LAI induces limited changes in the isoprene and NO_x emissions (Fig. S5), suggesting that changes of dry deposition velocity are the dominant drivers of O_3 changes". (Lines 379-382)

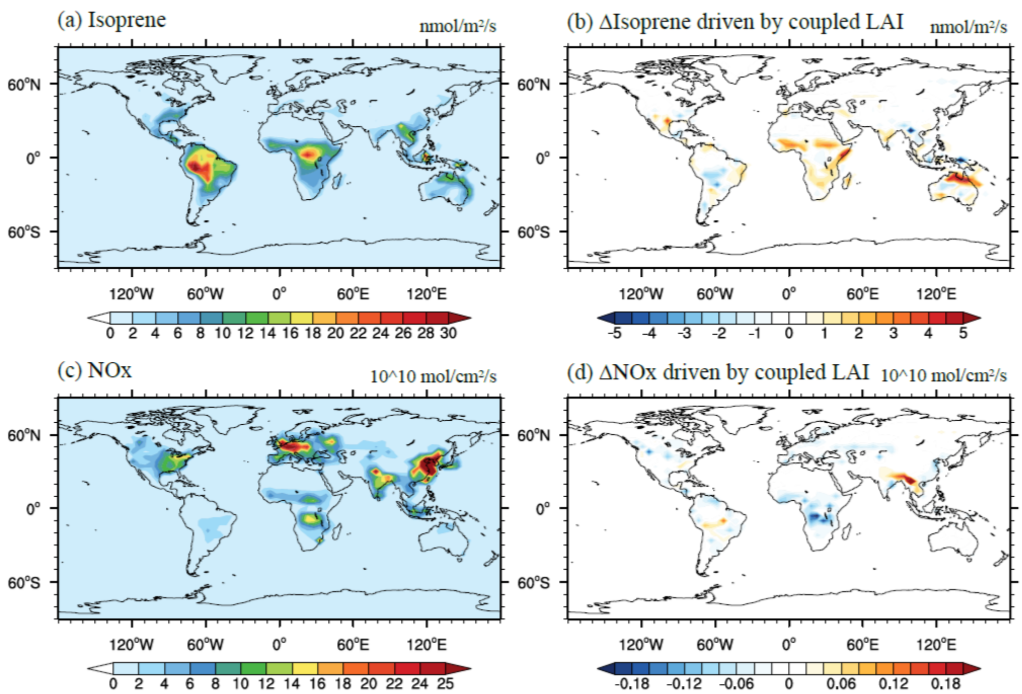

Figure S5 Simulated annual isoprene **(a)** and NO_x **(c)** emissions from online GC-YIBs model and its changes **(b-d)** caused by coupled LAI averaged for period of 2010-2012.

14) The coupling of these systems for the assessment of ozone damages to vegetation is presented as a key motivation for this study, but the differences in damage between this coupled model and previous models are not discussed (mentioned only in line 372). The discussion should be expanded to explain the differences and highlight the advantages of coupling the systems in section 3.3.

Response: The following information has been added in section 3.3:

"The reductions of GPP are slightly higher than our previous estimates using prescribed LAI and/or surface [O_3] in the simulations (Yue and Unger, 2014, 2015), likely because GC-YIBs considers O_3-vegetation interactions. The feedback of such interaction to both chemistry and biosphere will be explored in future studies." (Lines 455-459)

15) Other studies including Lin et al, 2019 GBC for the GFDL models have also investigated the coupled biosphere and atmosphere in similar ways with regards to ozone and are worth discussion in addition to the CESM work. If the ozone dry deposition is the chief application of the model so far, more clarity should be made in the discussion of the uncertainties that already exist in simulating dry deposition globally.

Response: Lin et al. (2019) discussed the influences of different dry deposition schemes on simulated surface [O_3]. They found that using V_d from LM4.0 in an atmospheric chemistry model reduces mean surface [O_3] biases by ~10 ppb relative to the widely used Wesely scheme. However, in their comparisons, they are using different meteorological forcings as the Wesely scheme (in the framework of GEOS-Chem) is driven by MERRA2 reanalyses while the LM4.0 uses another one (http://hydrology.princeton.edu/data.php). As a result, their improvements are jointly contributed by changes in dry deposition and meteorological forcings.

We added following statement to acknowledge the limits and uncertainties of dry deposition schemes: "Although the stomatal conductance scheme of Wesely (1989) has been widely used in chemical transport and climate models, considerable limits still exist because this scheme does not consider the response of stomatal conductance to phenology, CO_2 concentrations, and soil water availability (Lin et al., 2017; Rydsaa et al., 2016). Previous studies have well evaluated the dry deposition scheme used in the GEOS-Chem model against observations globally and regionally (Hardacre et al., 2015; Lin et al., 2019; Silva and Heald, 2018; Wong et al., 2019). They found that GEOS-Chem can generally capture the diurnal and seasonal cycles except for the amplitude of O_3 dry deposition velocity (Silva and Heald, 2018)." (Lines 247-255)

16) One way to justify the slow model speed (line 420) for the modest model improvements shown through coupling would be to expand upon the usefulness of the applications only so far mentioned in lines 428-444.

Response: In the discussion, we first explained the limitations and uncertainties of this study. Then we discussed the importance of this study and the future research plans.

17) While supported in part at Harvard, GEOS-Chem is developed and maintained by a global community of atmospheric chemists, not one group (line 449), and should be acknowledged as such.

Response: Acknowledgement has been modified as "The GEOS-Chem model was developed by the Atmospheric Chemistry Modeling Group at Harvard University led by Prof. Daniel Jacob and <u>improved by a global community of atmospheric chemists</u>." (Line 548)

18) Minor grammatical issues are present throughout, especially omission of articles before nouns. (example, line 48 "from terrestrial biosphere").

Response: Corrected as suggested.

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