Response to Comments of Reviewer #2

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Title: Global assessment of climatic responses to the ozone-vegetation interactions

The authors are grateful to the editor and reviewers for their time and energy in providing helpful comments that have improved the manuscript. In this document, we describe how we have addressed the reviewer's comments. Referee comments are shown in black italics and author responses are shown in blue regular text. A manuscript with tracking changes is attached separately.

Anonymous referee #2:

The authors use the coupled ModelE2-YIBs model to estimate climate and air pollution responses to ozone-vegetation interactions globally during boreal summers. This is an important and interesting topic that has been studied before by multiple researchers including some of the authors themselves, and surely falls within the scope of ACP.

Response:

Thank you for your positive evaluations.

While a lot of model evaluation work has been presented, as the authors noted, their results contradict with what have been reported previously and may be highly uncertain. It is also disappointing that, with multi-year long simulations, only period-mean results are shown. It'd be nice to see discussions on the temporal variability in their results, the drivers of that, and the (new) implications from temporally-varying sensitivities for estimating future environmental changes.

Response:

ModelE2-YIBs has been thoroughly validated in previous researches (Yue et al., 2017; Unger et al., 2020; Tian et al., 2021). For this study, we focused on the evaluations of carbon, air pollution, and climate variables related to O_3 vegetation feedback (Fig. 1, Fig. 2, and Fig. S2). We conducted time-slice experiments, in which the model years are not correspondent to the actual years. In addition, the long-term trend is limited because the fixed boundary conditions are applied. The simulated temporal variability may influence the significance of derived O_3 vegetation damages. As a result, we modified all the related global/regional values in the revised text to "mean/sum ±

standard deviation”. Related context (other value-related sentences are not shown here, but the revised tables in the Supplementary are shown here):

“In order to show the uncertainty introduced by the internal variability of the model, all the related global/regional values are denoted as “mean/sum ± standard deviation of the last 20 model years”.” (Lines 188-191)

Table S2. Relative changes of terrestrial ecosystems in two major geographic regions in response to O_3-vegetation interactions in model

Region	GPP	Stomatal Conductance	LAI
eastern China	-25.40±1.90%	-30.62±4.30%	-4.53±1.14%
eastern U.S.	-20.14±5.02%	-25.65±9.32%	-5.87±3.11%

Table S3. Changes of climatic variables in two major geographic regions in response to O_3-vegetation interactions in model

Region	Surface Air Temperature (unit: °C)	Precipitation (unit: mm day^{-1})	Sensible Heat Flux (W m^{-2})
eastern China	0.56±0.38°C	-0.79±1.05 (16.18±20.38%)	7.12±3.86 (25.46±14.71%)
eastern U.S.	0.33±0.87 °C	-0.45±1.33 (-9.82±14.20%)	6.3±5.4 (16.54±15.59%)

Table S4. Changes of air pollution in two major geographic regions in response to O_3-vegetation interactions in model

Region	MDA8 O_3 (ppbv)	$PM_{2.5}$ (unit: μg m^{-3})	AOD
eastern China	1.46±3.02	-1.94±1.67 (-8.52±6.88%)	-0.06±0.05 (-14.67±16.75%)
eastern U.S.	1.15±1.77	-0.27±0.36 (-6.01±7.9%)	-0.01±0.01 (-8.15±9.38%)

Specific comments:

L15: define ModelE2-YIBs

Response:

We revised the sentence as follows:

"Using a climate-vegetation-chemistry coupled model (the NASA GISS ModelE2 coupled with Yale Interactive terrestrial Biosphere, or ModelE2-YIBs), we assess the global climatic responses to O_3-vegetation interactions during boreal summer of the present day (2005-2014)." (Lines 15-18)

L18: delete "the"

Response:

Corrected as suggested.

"High O_3 pollution reduces stomatal conductance, resulting in warmer and drier conditions worldwide." (Lines 18-19)

L23: specify surface O_3 concentration metric used

Response:

Specified as follow:

"Surface maximum daily 8-hour average O_3 concentrations increase by +1.46±3.02 ppbv in eastern China and +1.15±1.77 ppbv in eastern U.S due to the O_3-induced inhibition of stomatal uptake." (Lines 23-25)

L25-27: quantitatively state the impact on aerosols, which is claimed as a highlight of this study

Response:

Add quantitatively state as suggested:

"With reduced atmospheric stability following the warmer climate, increased cloudiness but decreased relative humidity jointly reduce aerosol optical depth by -0.06±0.01 (-14.67±12.15%) over eastern China." (Lines 26-28)

L43: there are quite a few concentration-based metrics used to assess O_3 impact, not just AOT40

Response:

Thank you for indicating the deficiencies, we made the following revisions:

“Several exposure-based indexes such as accumulated hourly O_3 concentrations over a threshold of 40 ppb (AOT40) and sum of all hourly average concentrations (SUM00) are used to assess O_3-induced vegetation damage (Fuhrer et al., 1997; Paoletti et al., 2007). In addition, the flux-related POD_y method (phytotoxic O_3 dose above a threshold flux of y) is also widely applied to consider the dynamic adjustment of stomatal conductance (Buker et al., 2015; Sicard et al., 2016).” (Lines 44-50)

L60: please specify the study period by Gong et al.

Response:

Specified as suggested.

“Gong et al. (2020) revealed that O_3-vegetation interactions increased regional O_3 concentrations by 1.8 ppbv in the eastern U.S., 1.3 ppbv in Europe, and 2.1ppbv in eastern China for the year 2010.” (Lines 65-67)

L63: please specify tool used by Sadiq et al.

Response:

Specified as suggested.

“As a comparison, Sadiq et al. (2017) found consistently stronger feedback on O_3 concentrations in these polluted regions using the scheme of Lombardozzi et al (2012) embedded in the Community Earth System Model (CESM).” (Lines 67-70)

L89: Why is YIBs spelled out here, after its first appearance at L60?

Response:

Corrected.

L100 and section 2.1: In general the approach applied in this work is old with no major updates from the authors’ previous works on similar topics. ModelE now has version 4 (https://data.giss.nasa.gov/modelE/) that should address some of the deficits in previous versions of the model. The model was run at 2x2.5 deg/40 layer resolution which is far from sufficient to resolve processes that could impact weather states, chemical environments and feedbacks that are studied here. The accuracy of parameters in Table S1, based on Sitch et al., should also be extensively discussed. For example, the sensitivity parameters in Sitch et al. seem to be sensitive to life stages of trees and climatic conditions which is not accounted for/discussed in this study.

Response:

Model development is a very complex process, and we did a lot of work related to module coupling in the early stages. Although ModelE is now available in version 4, this version does not include the dynamic vegetation model YIBs that has been extensively validated for many biological processes (photosynthesis, stomatal conductance, phenology, biomass, soil carbon, carbon sink etc.) and ozone vegetation damages. Additionally, the development status of the atmospheric chemistry module in the new version of ModelE is not very clear. We recognize that modeling at a relatively coarse resolution has its limitations. However, within the scope of this study, this resolution is sufficient to discuss relevant issues and provide valuable insights, which has been well validated in previous work. In the discussion section, we acknowledged the limitations of model resolution, and will consider higher resolution models in future studies. Considering the effects of tree growth stages poses a common challenge in developing current models, and related efforts are in progress. In the discussion section, we also acknowledged the limits of the Sitch et al. (2007) scheme, which could be further improved with more available observations in the future:

"…, observations have shown large variability of plant sensitivities to O_3 damages. The Sitch et al. (2007) scheme employed the low to high ranges of sensitivity to indicate the inter-specific variabilities. In this study, we employed only the high O_3 sensitivity to explore the maximum responses. The possible uncertainties due to varied O_3 damage sensitivities deserved further investigations." (Lines 395-399)

L140/142: Can the authors please come up with new experiment names that are more self-explanatory?

Response:

Thank you for the suggestion. We change the experiment names as follow:

"The control experiment "O3_offline" was conducted without the O_3 damages to vegetation. As a comparison, the sensitivity experiment "O3_online" contained online O_3-vegetation interaction with high O_3 sensitivity." (Lines 173-175)

L143-154: The description on model configuration is very confusing. Was the 2010s anthropogenic/biomass burning emissions applied for 30 year simulations (including spin-up)? Does the model simulations include other natural emissions such as soil, lightning, BVOCs, etc, and if so, in later sections, could their sensitivities be shown? Was the PFT type input (shown in Fig. S1) temporally fixed throughout the simulation period and if so why would land use/land cover change not represented in the system?

Response:

For the first question: Yes, the 2010s emissions are applied for 30-year period of simulations. This is a method commonly used for time-slice simulations (e.g., Sadiq et al., 2017; Gong et al., 2020). The first 10 years are spin-up and only the results of the last 20 years are analyzed in order to ensure greater stability of the output data. We revised the text to clarify:

"For both experiments, the anthropogenic emissions of 2010 (the average of 2005-2014) for 8 species…" (Lines 175-177)

"The cover fraction of 8 PFTs (Fig. S1) fixed at 2010 were adopted from the land use harmonization (LUH2) dataset (Hurtt et al., 2020)." (Lines 183-184)

"For each time-slice simulation, the model was run for 30 years with all the input data fixed and the first 10 years are used as the spin up." (Lines 185-186)

For the second question: NO_x from soil in our model is fixed. NO_x from lighting (Fig. R1 b) changes following the relative humidity and precipitation patterns (Fig. 4b & 4c). In case of isoprene, the change in BVOC emissions is negligible (Fig. R2 a).

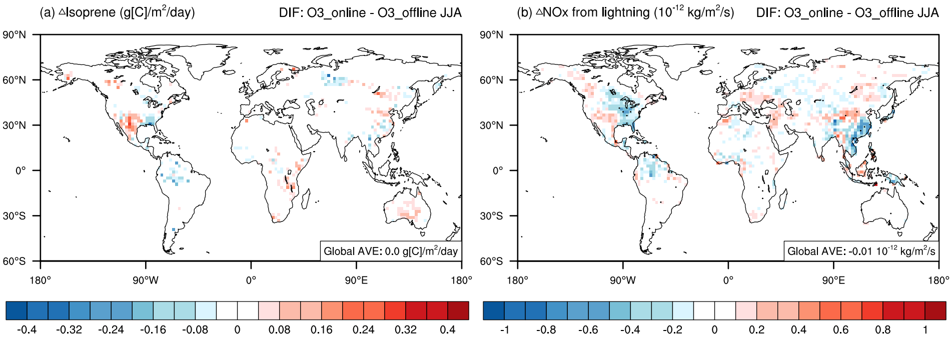

Figure R2. Changes of boreal summertime natural emissions induced by O_3-vegetation interactions at the present day. Results shown are changes of (a) isoprene (b) and NO_x from lightning between simulations O3_online and O3_offline. Black dots denote areas with significant changes ($p < 0.1$).

For the third question: The PFT types input are temporally fixed. We clarified in the revised paper as follows: "The cover fraction of 8 PFTs (Fig. S1) fixed at 2010 were adopted from the land use harmonization (LUH2) dataset (Hurtt et al., 2020)." (Lines 183-184)

L153: Why only boreal summers are focused on for a global (including the southern hemisphere) assessment? Also note that high O_3 days are not necessarily high O_3 flux days.

Response:

This is because boreal summer is the main growing season for most of the vegetation worldwide, and the main area of O_3 pollution is in the northern hemisphere. Previous studies also focused on the growing season (Lombardozzi et al., 2015) or boreal summer (Sadiq et al., 2017) period when most of photosynthesis and O_3 pollution reached the peak values. To make it clearer, we added more information as follows in the Supplementary and main context:

"We calculated the average of the last 20 years and focused on the boreal summer season (June-July-August, JJA) when the interaction of vegetation and surface O_3 reaches the maximum in one year (Fig. S3)." (Lines 186-188)

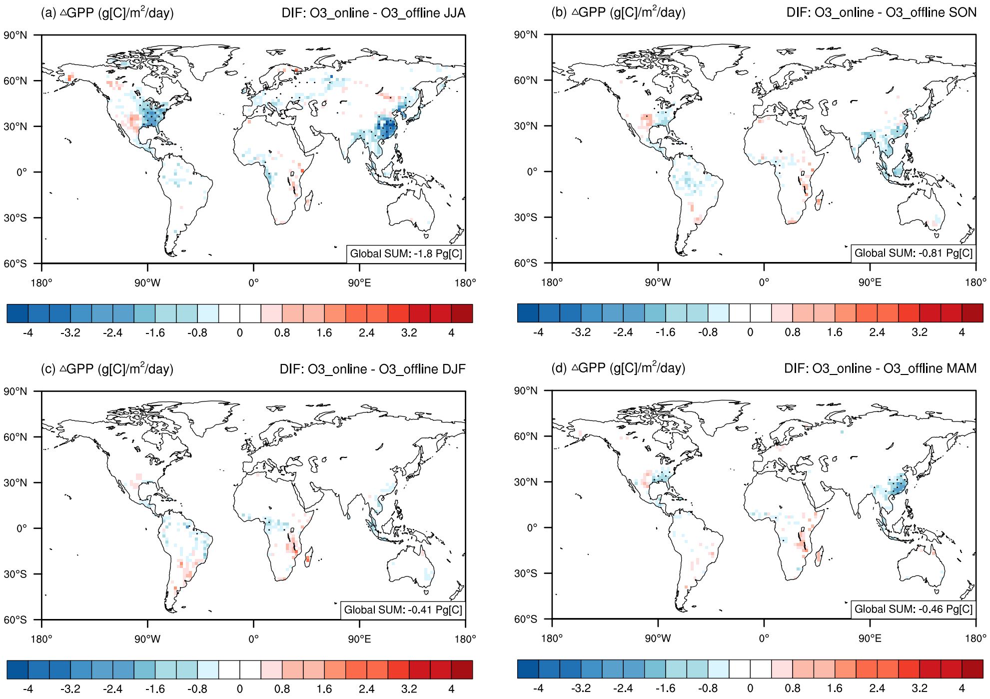

Fig. S3. Changes of GPP induced by O_3-vegetation interactions in different seasons at the present day. Results shown are changes of (a) JJA (June-July-August), (b) SON (September-October-November), (c) DJF (December-January-Feburary), and (d) MAM (March-April-May) between simulations O3_online and O3_offline. Black dots denote areas with significant changes ($p < 0.1$).

L156: no need to include "special"

Response:

Deleted as suggested.

L159: add model after "for"

Response:

Corrected as suggested.

Section 2.3: More descriptions on the used datasets and their respective accuracies (particularly for remote sensing and derived data) are needed. The different temporal coverages of these datasets are very confusing and hard to be linked to the results presented later.

Response:

We described the observational datasets as follow:

"The worldwide observations of the maximum daily 8-hour average O_3 (MDA8 O_3) concentrations were mainly collected from three regional networks: Air Quality Monitoring Network operated by Ministry of Ecology and Environment (AQMN-MEE) in China, the Clean Air Status and Trends Network (CASTNET) in the U.S., and the European Monitoring and Evaluation Programme (EMEP) in Europe. Observations used for validation beyond China, sourced from Sofen et al. (2016), are averaged over the period 2005-2014. This dataset encompasses 7288 station records worldwide and excludes the uncertainty associated with high mountain-top sites." (Lines 198-206)

"The simulated aerosol optical depth (AOD) and LAI were validated using satellite-based data from the Moderate Resolution Imaging Spectroradiometer (MODIS) retrievals collection 5 (Remer et al., 2005) (http://modis.gsfc.nasa.gov/) averaged for the years 2005-2014." (Lines 207-210)

L162-165: There are clearly O_3 observation data in Africa and South America in Fig 1b. What are their sources?

Response:

As we mentioned above, this dataset is obtained from Sofen et al. (2016), which compiled O_3 concentrations worldwide except for China. The data in Africa and South America is from World Data Center for Greenhouse Gases (WDCGG; http://ds.data.jma.go.jp/gmd/wdcgg/) from the World Meteorological Organization (WMO) Global Atmospheric Watch (GAW; http://www.wmo.int/pages/prog/arep/gaw/gaw_home_en.html).

L168: Which version of MODIS data? Does LAI data also come from MODIS?

Response:

Yes, LAI data is also from MODIS. We clarified as follows:

"The simulated aerosol optical depth (AOD) and LAI were validated using satellite-based data from the Moderate Resolution Imaging Spectroradiometer (MODIS) retrievals collection 5 (Remer et al., 2005) (http://modis.gsfc.nasa.gov/) averaged for the years 2005-2014." (Lines 207-210)

L187: MDA8 is not necessarily the best metric for evaluating ozone flux and vegetation impacts. It is worth noting that the poor coverage of O_3 observations can affect the global model evaluation.

Response:

We focus on the MDA8 O_3 variable because O_3-vegetation interactions occur mainly in the daytime. Indeed, sparse ozone observations present a challenge for both observational and modeling research nowadays. However, there are many observational sites in the areas where the majority O_3-vegetation interactions locate, which is sufficient to support the validity of our study.

Section 3.1: Evaluation is done on a global scale - this should also be done and summarized by various regions of the world (particularly, but not limited to the two hotspot regions). It is unclear why Case "10NO3" was evaluated and what the reported performance for this case means.

Response:

As can be seen from the spatial distribution of damage to GPP, we focused on these two key areas because this is where ozone-vegetation interactions are most significant. 10NO3 (now named O3_offline) was chosen as the reference experiment because this experiment was conducted as a baseline experiment (or normal state in which the model is developed). Validation results by comparison with observations show that our modeling experiments can be used in the following related studies. We made clarification as follow:

"We first evaluated the air pollutants simulated by the control simulation O3_offline of ModelE2-YIBs model (Fig. 1)." (Lines 227-228)

L198: There is no illustration of spatiotemporal variability in emissions that can support to this statement.

Response:

We added a reference to support this statement:

"Both the simulations and observations showed AOD hotspots over North Africa and the Middle East where dust emissions dominate, and in northern India and eastern China where anthropogenic emissions are large (Feng et al., 2020)." (Lines 240-242)

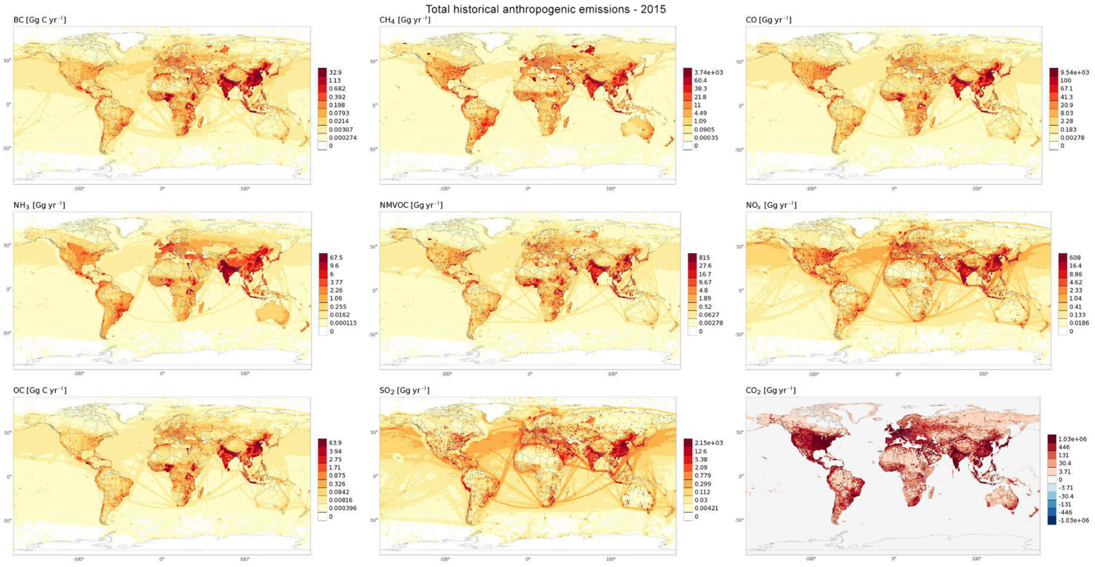

Figure R1. Total anthropogenic emissions in 2015 by species. (figure from Feng, L., Smith, S. J., Braun, C., Crippa, M., Gidden, M. J., Hoesly, R., Klimont, Z., van Marle, M., van den Berg, M., and van der Werf, G. R.: The generation of gridded emissions data for CMIP6, Geosci. Model Dev., 13, 461–482, https://doi.org/10.5194/gmd-13-461-2020, 2020.)

L265-269: Note that many of these processes discussed here may be well represented in models running at coarse resolutions.

Response: We recognize that modeling at a relatively coarse resolution has its limitations. However, within the scope of this study, this resolution is sufficient to discuss relevant issues and provide valuable insights, which has been well validated in previous work. In the discussion section, we acknowledged the limitations of model resolution, and will consider higher resolution models in future studies:

"Furthermore, the 2°×2.5° resolution of current ModelE2-YIBs has limitation due to the high computational demands. However, high-resolution models exhibit improved simulations of extreme events (Chang et al., 2020; Ban et al., 2021), which have certain effect on O_3-vegetation interactions (Mills et al., 2016; Lin et al., 2020). While chemical transport models with relatively coarse resolution can raise biases in simulated air pollutants, they still capture large-scale patterns similar to fine-resolution results and is reasonable compared to observational data (Wang et al., 2013; Li et al., 2016; Lei et al., 2020)." (Lines 406-413)

L287-302: What about aerosol climate impacts that feed back to ozone?

Response:

We did not isolate the impacts of aerosol climate effects, which can be considered in the future work. This paragraph focuses on the aerosol response to O_3-vegetation interactions and this work focuses primarily on the effects of O_3-vegetation interactions as well. Additionally, with relatively small changes in aerosols, the O_3 feedback from it may be even smaller.

L337-371: This long list of limitations make the interpretation of the reported model results harder. The authors may want to articulate what useful information can still be gained from this sensitivity analysis in spite of all these sources of uncertainty.

Response:

Thank you for your suggestions. We listed all the possible limitations of this study to inform the readers of modeling uncertainties. However, some of these limitations, such as O_3 damage scheme, O_3 damaging sensitivities, and missing of large-scale validations, are mainly related to the limitations in observations that are out of the scope of this study and capability of our efforts. In this study, we employed the standard deviation in numbers and 90% confidence tests in figures to indicate the significant and robust feedbacks from O_3-vegetation interactions. We also summarized in the last paragraph the key findings and the associated implications:

"Despite these uncertainties, our simulations revealed considerable changes of both climate and air pollutants in response to O_3-vegetation interactions. The most intense warming, dryness, and O_3 enhancement were predicted in eastern China and eastern U.S., affecting the regional climate and threatening public health for these top two economic centers. In contrast, we for the first time revealed the reduction of aerosol loading in those hotspot regions, suggesting both positive and negative effects to air pollutants by O_3-vegetation feedback. Such interactions should be considered in the Earth system models so as to better project future changes in climate and air pollutants following the anthropogenic interventions to both O_3 precursor emissions and ecosystem functions." (Lines 421-430)

Fig. 1 caption: replacing upper, left, bottom and middle with letter labels; add "the" before 2010s (and throughout the paper). Why did the model fail to capture high O_3 in the western US and the Middle East?

Response:

Revised as suggested. The model indeed underestimates surface ozone in the above-mentioned regions, especially in western U.S. This underestimation is likely attributed to the biases in emission inventories and simulated meteorology. The model employed fixed anthropogenic and biomass burning emissions averaged for 2005-2014. The biases in these emissions, especially the missing of interannually-varied wildfire emissions, may cause the underestimations of surface O_3 in western U.S. Moreover, simulated temperature by ModelE2-YIBs is much lower than observations in western U.S. (Fig. S2). Such biases in the simulated climate may reduce O_3 production by reducing the photochemical reaction rate in the specific regions. In the revised paper, we clarified as follows:

"However, the modeled result is overestimated over the North China Plain and slightly underestimated over the U.S., likely due to the biases in the emission inventories and predicted climate that drive the O_3 production." (Lines 235-238)

Fig. S2 caption: replacing upper, left, bottom and middle with letter labels

Response:

Revised as suggested.

Fig. S3-S4 colors are very hard to discern. Can the color schemes be adjusted?

Response:

Adjusted as follows:

"

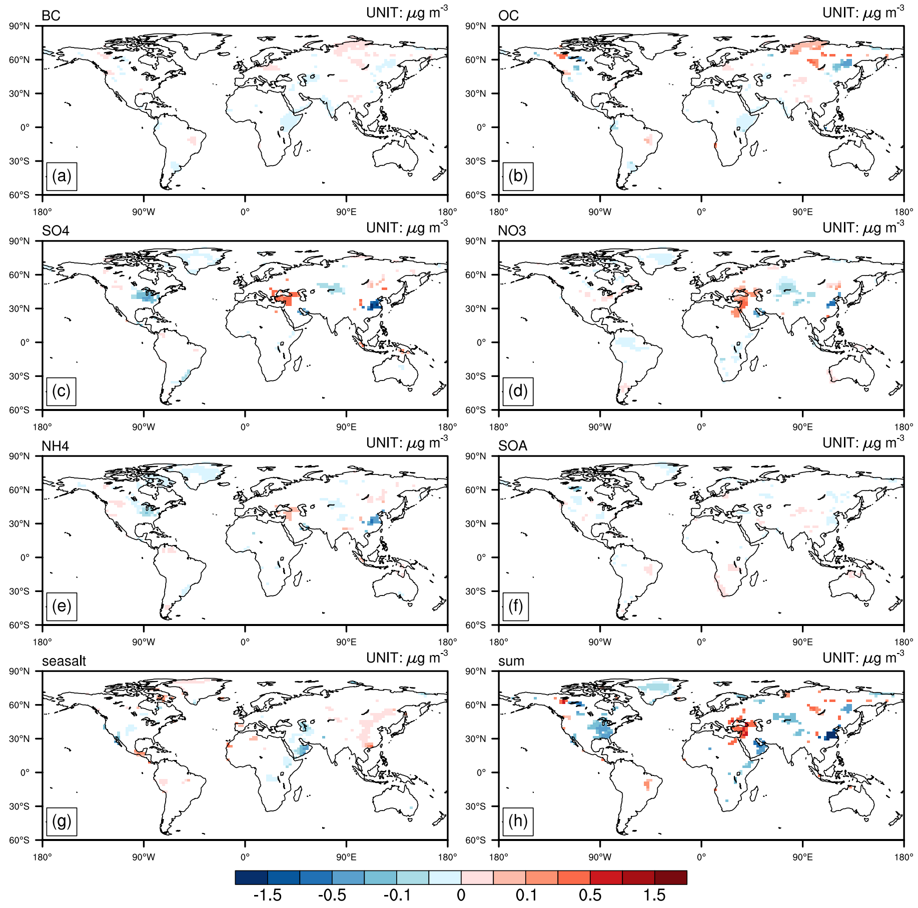

Fig. S4. Changes in 7 types (a-g) summer $PM_{2.5}$ (without silts) and their sum (h) at present day in the model by O_3-vegetation interactions. Results shown are the differences of $PM_{2.5}$ between O3_online and O3_offline. Only the significant changes ($p < 0.1$) are presented.

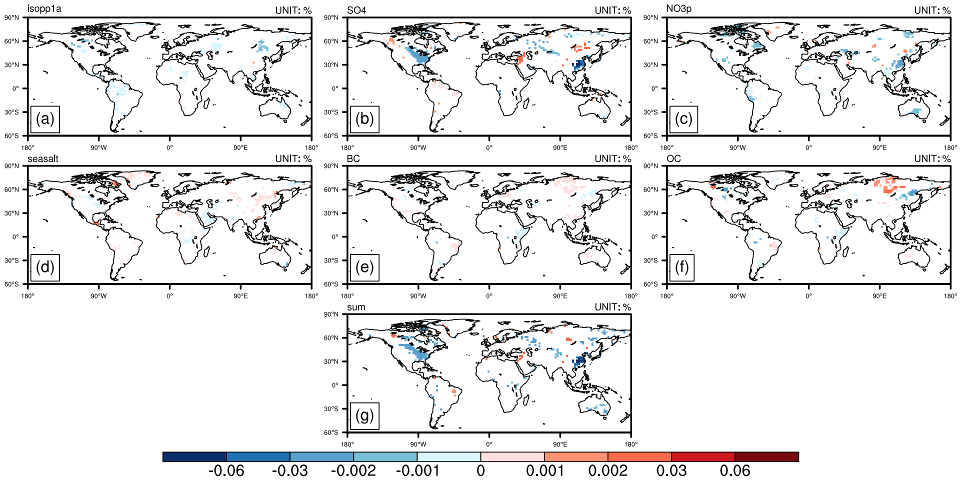

Fig. S5. Changes in 6 types (a-f) summer aerosol optical depth (AOD) and their sum (g) in at present day in the model by O_3-vegetation interactions. Results shown are the differences of AOD between O3_online and O3_offline. Only the significant changes ($p < 0.1$) are presented.

References:

Feng, L., Smith, S. J., Braun, C., Crippa, M., Gidden, M. J., Hoesly, R., Klimont, Z., van Marle, M., van den Berg, M., and van der Werf, G. R.: The generation of gridded emissions data for CMIP6, Geosci. Model Dev., 13, 461–482, https://doi.org/10.5194/gmd-13-461-2020, 2020.

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Yue, X., Strada, S., Unger, N., and Wang, A.: Future inhibition of ecosystem productivity by increasing wildfire pollution over boreal North America, Atmos. Chem. Phys., 17, 13699–13719, https://doi.org/10.5194/acp-17-13699-2017, 2017.