Global assessment of climatic responses to the ozone-vegetation interactions

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Abstract. The coupling between surface ozone (O_3) and vegetation significantly influences regional to global climate. O_3 uptake by plant stomata inhibits photosynthetic rate and stomatal conductance, impacting evapotranspiration through land surface ecosystems. Using the climate-vegetation-chemistry coupled ModelE2-YIBs model, we assess the global climatic responses to O_3-vegetation interactions during boreal summer of 2010s (2005-2014). High O_3 pollution reduces stomatal conductance, resulting in the warmer and drier conditions worldwide. The most significant responses are found in the eastern U.S. and eastern China, where local latent heat flux decreases by -8.17% and -9.48%, respectively. Consequently, surface air temperature rises by +0.33 °C and +0.56 °C, and sensible heat flux rises by +16.54% and +25.46% in the two hotspot regions. The O_3-vegetation interaction also affects atmospheric pollutants. Surface O_3 concentrations increase by +1.26 ppbv in eastern China and +0.98 ppbv in eastern U.S. due to the O_3-induced inhibition of stomatal uptake. With reduced atmospheric stability following the warmer climate, increased cloudiness but decreased relative humidity jointly reduce aerosol optical depth (AOD) over eastern China. This study suggests that vegetation feedback should be considered for a more accurate assessment of climatic perturbations caused by tropospheric O_3.
1 Introduction

Tropospheric ozone (O\textsubscript{3}), one of the most detrimental air pollutants (Myhre et al., 2013), not only poses threats to human health (Norval et al., 2011; Nuvolone et al., 2018) but also induces phytotoxic effects to vegetation (Mills et al., 2007; Pleijel et al., 2007). When exposed to certain levels of O\textsubscript{3}, plant photosynthesis and stomatal conductance is inhibited due to the O\textsubscript{3} oxidation of cellular, enzyme, and chlorophyll (Dizengremel, 2001; Fiscus et al., 2005; Jolivet et al., 2016). Consequently, the carbon assimilation of terrestrial ecosystems is limited (Yue and Unger, 2014; Oliver et al., 2018) and the land-air exchange rates of water and heat fluxes are altered (Lombardozzi et al., 2015).

Experimental studies have shown that the excessive O\textsubscript{3} exposure reduced both plant photosynthesis and stomatal conductance (Ainsworth et al., 2012; Lombardozzi et al., 2013). The reduction rates are dependent on the O\textsubscript{3} stomatal fluxes as well as the damaging sensitivities that vary among different vegetation types (Nussbaum and Fuhrer, 2000; Karlsson et al., 2004; Pleijel et al., 2004). Traditional exposure-based indexes like accumulated hourly O\textsubscript{3} concentrations over a threshold of 40 ppb (AOT\textsubscript{40}) are widely used to assess O\textsubscript{3}-induced vegetation damage (Fuhrer et al., 1997). However, such statistical schemes fail to account for the dynamic adjustment of vegetation physiological processes. Taking into account the variability of plant sensitivities, different O\textsubscript{3} damage schemes were proposed to quantify the O\textsubscript{3} impacts on land carbon assimilation from regional to global scales (Anav et al., 2011; Lam et al., 2023; Lei et al., 2020). For example, Sitch et al. (2007) calculated the simultaneous damages to both photosynthesis and stomatal conductance based on the instantaneous O\textsubscript{3} stomatal uptake. In contrast, Lombardozzi et al. (2012) estimated the inconsistent reductions in plant photosynthesis and stomatal conductance using different response relationships to the cumulative O\textsubscript{3} stomatal uptake. Applications of different schemes resulted in a wide range of reductions in gross primary productivity (GPP) by 2-12% globally with regional hotspots up to 20-30% (Lombardozzi et al., 2015; Unger et al., 2020; Zhou et al., 2024).

The O\textsubscript{3}-induced inhibition in stomatal conductance decreases dry deposition and consequently enhances surface O\textsubscript{3} concentrations (Clifton et al., 2020; Wesely and
Using the Sitch et al. (2007) scheme with high O₃ damaging sensitivities in the climate model ModelE2-YIBs, Gong et al. (2020) revealed that O₃-vegetation interactions increased regional O₃ concentrations by 1.8 ppbv in the eastern U.S., 1.3 ppbv in Europe, and 2.1 ppbv in eastern China. As a comparison, Sadiq et al. (2017) found a consistent but stronger positive feedback on O₃ concentrations in these polluted regions using the scheme of Lombardozzi et al (2012) embedded in a different climate model. Inclusion of O₃-vegetation interactions will cause stronger damages to land carbon assimilation due to the feedbacks of both ecosystem and surface O₃. On one hand, the damages to leaf photosynthesis inhibit plant growth and decrease leaf area index (LAI), leading to higher reduction percentage in GPP compared to simulations without LAI changes (Yue et al., 2020). On the other hand, the O₃ enhancement due to vegetation feedback may cause additional vegetation damage and result in further GPP losses (Lei et al., 2021). As a result, the O₃-vegetation interactions should be considered in the global estimate of O₃ damages to ecosystem functions.

In addition to affecting surface O₃, the O₃-vegetation interaction can also alter the water and energy exchange between land and atmosphere. For example, Lombardozzi et al. (2015) used the Community Land Model (CLM) and estimated that the cumulative uptake of O₃ by the leaves resulted in reduction of 2.2% in transpiration but increase of 5.4% in runoff globally. Arnold et al. (2018) used the Community Earth System Model (CESM) and found that plant exposure to O₃ could decrease the land-air moisture fluxes and atmospheric humidity, which further reduced shortwave cloud forcing in polluted regions and induced widespread surface warming up to +1.5 K. Two recent studies utilized the WRF-chem model and revealed considerable warming and the associated meteorological perturbations due to the O₃-vegetation interactions in China (Zhu et al., 2022; Jin et al., 2023). However, all these modeling studies applied the same O₃ vegetation damage scheme proposed by Lombardozzi et al. (2012). It’s necessary to assess the climatic responses to O₃-vegetation interactions using different schemes so as to explore the robust responses and the associated uncertainties.

In this study, we quantified the global impacts of O₃-vegetation interaction on climatic conditions and surface air pollutants during 2010s using the Earth system...
model NASA GISS ModelE2 coupled with Yale Interactive terrestrial Biosphere (YIBs) model (Yue and Unger, 2015). This fully coupled framework was implemented with the semi-mechanistic O₃ damage scheme proposed by Sitch et al. (2007), which calculated aggregate O₃ damage to photosynthesis based on varied sensitivities to instant stomatal O₃ uptake for eight plant functional types (PFTs). We performed sensitivity experiments to quantify the responses of surface air temperature and precipitation to O₃-vegetation interaction. The feedbacks to aerosols and O₃ concentrations were also examined.

2 Method

2.1 Model descriptions

The ModelE2-YIBs is a fully coupled climate-carbon-chemistry model combining the NASA GISS ModelE2 with the YIBs vegetation model. ModelE2 is a general circulation model with the horizontal resolution of 2°×2.5° in latitude and longitude and 40 vertical layers up to 0.1 hPa. It dynamically simulates gas-phase chemistry (NOₓ - HOₓ - Oₓ - CO - CH₄ - NMVOCs), aerosols (sulfate, nitrate, black and organic carbon, dust, and sea salt), and their interactions (Menon and Rotstayn, 2006). The radiation module includes direct and indirect aerosol radiative effects and accounts for absorption of multiple greenhouse gases (GHGs). For cloud optical parameters, it uses Mie scattering, ray tracing, and matrix theory (Schmidt et al., 2006). The model outperforms 20 other IPCC-class climate models in simulating surface solar radiation (Wild et al., 2013) and has been extensively validated for meteorological and hydrological variables against observations and reanalysis data (Schmidt et al., 2014).

The YIBs model employs the well-established Farquhar model for leaf photosynthesis and Ball-Berry model for stomatal conductance (Farquhar et al., 1980; Ball et al., 1987) as follows:

\[ A_{\text{tot}} = \min (J_c, J_e, J_s) \]  \hspace{1cm} (1)

\[ g_s = m \left( \frac{A_{\text{tot}} - R_d \times RH}{c_s} \right) + b \]  \hspace{1cm} (2)

Here, the total leaf photosynthesis, denoted as \( A_{\text{tot}} \), is calculated as the minimum value among the ribulose-1,5-bisphosphate carboxylase-limited rate of carboxylation (\( J_c \)),
light-limited rate ($I_\text{d}$), and export-limited rate ($I_\text{e}$). The stomatal conductance ($g_\%$) is linked to the variations of $A_\text{tot}$ with parameters such as dark respiration rate ($R_d$), relative humidity ($RH$), and CO$_2$ concentration at the leaf surface ($c_s$). The model simulates the biophysical processes of eight PFTs including tundra, C$_3$/C$_4$ grass, shrubland, deciduous broadleaf forest, evergreen broadleaf forest, evergreen needleleaf forest, and cropland. Different values are assigned to parameters $m$ and $b$ for each PFT (Table S1). The carbon uptake by the leaf is then accumulated and allocated to different organs to support the plant development with dynamical changes in LAI and tree growth.

### 2.2 The O$_3$-vegetation damage scheme

The YIBs model employs a semi-mechanistic parameterization proposed by Sitch et al. (2007) to estimate the impact of O$_3$ on photosynthesis through stomatal uptake. The scheme applies an undamaged factor ($F$) to both $A_\text{tot}$ and $g_s$ as follows:

$$A_\text{totd} = A_\text{tot} \cdot F$$

$$g_{sd} = g_s \cdot F$$

where $A_\text{totd}$ and $g_{sd}$ are the unaffected photosynthesis and stomatal conductance separately. The factor $F$ is defined as:

$$F = 1 - a_h \cdot \max [F_{O_3} - F_{O_3,\text{crit}}, 0.0]$$

$a_h$ is the high O$_3$ sensitivity coefficient and $F_{O_3,\text{crit}}$ is the specific threshold for O$_3$ damages, both of which vary with vegetation types (Table S1).

$$F_{O_3} = \frac{[O_3]}{R_a + k_{O_3}}$$

where $[O_3]$ represents surface O$_3$ concentrations, $R_a$ stands for the aerodynamic and boundary layer resistance. The constant $k_{O_3}$=1.67 is the ratio of stomatal resistance for O$_3$ to that for water.

### 2.3 Experiments

To explore the coupled O$_3$-vegetation effect, we performed two sets of simulations using the ModelE2-YIBs model. The control experiment “10NO3” was conducted...
without the O$_3$ damages to vegetation. As a comparison, the sensitivity experiment “10HO3” contained online O$_3$-vegetation interaction with high O$_3$ sensitivity. For both experiments, the 2010s anthropogenic emissions for 8 species (BC, OC, CO, NH$_3$, NO$_x$, SO$_2$, Alkenes, and Paraffin) from 8 economic sources (agriculture, energy, industry, transportation, resident, solvent, waste, and international shipping) and biomass burning source were collected from the Coupled Model Intercomparison Project phase 6 (CMIP6) (van Marle et al., 2017; Hoesly et al., 2018). The ensemble mean of monthly sea surface temperature (SST) and sea ice fraction (SIC) simulated by 21 CMIP6 models during the time period 2005-2014 was employed as the boundary conditions. The cover fraction of 8 PFTs (Fig. S1) were adopted from the land use harmonization (LUH2) dataset (Hurtt et al., 2020). For each simulation, the model was run for 30 years with the first 10 years used as the spin up. We calculated the average of the last 20 years and focused on the boreal summer season (June-July-August, JJA) when surface O$_3$ reaches the maximum in one year. We explored the climatic responses to O$_3$-vegetation interactions as the differences between “10HO3” and “10NO3” on the global scale with the special focus over the hotspot regions such as eastern U.S. (30–40° N, 80–90 °W) and eastern China (22.5–38° N, 106–122° E).

### 2.4 Data for evaluations

We evaluated the simulated air pollutants, carbon fluxes, and meteorological variables using observational and reanalysis datasets. The worldwide observations of O$_3$ concentrations were collected from three regional networks: Air Quality Monitoring Network operated by Ministry of Ecology and Environment (AQM-N-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. For the latter two networks, we chose the average over 2009-2011, while for AQMN-MEE, the mean value of 2014-2018 was used due to its establishment in 2013. The simulated aerosol optical depth (AOD) was validated using satellite-based data from the Moderate Resolution Imaging Spectroradiometer (MODIS) retrievals (Remer et al., 2005) for the years 2009-2011. The simulated GPP was evaluated against the data product upscaled from the
FLUXNET eddy covariance measurements for 2009-2011 (Jung et al., 2009). The daily temperature at 2m ($T_{2m}$) in 2009-2011 was obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis 1 (NCEP1) (Kalnay et al., 1996). For precipitation, we used the monthly data from Global Precipitation Climatology Project (GPCP) (Huffman et al., 1997; Adler et al., 2018). All these datasets were interpolated to the same resolution as ModelE2-YIBs model. Normalized mean biases (NMBs) were applied to quantify the deviations of simulations from observations as follows:

$$NMB = \sum_{i}^{n} (S_i - O_i) / \sum_{i}^{n} O_i \times 100\%$$

(7)

Here, $S_i$ and $O_i$ represent the simulated and observed values, respectively. $n$ denotes the total grid number used in the comparisons.

3. Results

3.1 Model evaluations

We first evaluated the air pollutants simulated by the ModelE2-YIBs model (Fig. 1). Over a total of 491 grids with site-level $O_3$ measurements (Fig. 1b), the model adequately replicated the magnitude and spatial distribution of the maximum daily 8-hour average (MDA8) $O_3$ concentrations ($[O_3]$), with correlation coefficient ($r$) of 0.58 and NMB of -1.27% (Fig. 1c). Simulated summertime surface $[O_3]$ was high in regions with large anthropogenic emissions, such as western Europe and eastern China (Ohara et al., 2007), as well as in central Africa with frequent fire emissions (van der Werf et al., 2017). On the global scale, the model yielded an average $[O_3]$ of 44.36 ppbv and observations showed an average of 44.57 ppbv over the same grids. However, the modeled result is overestimated over the North China Plain and slightly underestimated over the U.S. Simulated AOD at 550 nm (Fig. 1d) showed similar spatial pattern as the satellite retrievals (Fig. 1e) with a high R=0.77 and low NMB of -6.27% globally (Fig. 1f). 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.
We then evaluated the simulated GPP and LAI for the boreal summer period (Fig. 2). Observations showed GPP hotspots over boreal forests such as eastern U.S., Eurasia, and East Asia and the tropical forests such as Amazon, central Africa, and Indonesia (Fig. 2b). The seasonal total GPP was estimated to be 41.63Pg[C], which accounted for 35% of the annual amount. Simulations well captured the observed GPP pattern on the global scale, with r = 0.63 and NMB = -12.44% over 2581 grids (Fig. 2c), with underestimation in the tundra area and slight overestimation in the tropical rain forest and evergreen forest regions. The model simulated a seasonal total GPP of 36.45 Pg[C], equivalent to 34% of the annual amount. Simulated LAI showed similar patterns as GPP (Fig. 2d) and resembled observed LAI (Fig. 2e) with a high spatial correlation r = 0.79 and a low NMB = -5.19% over 4435 grids globally (Fig. 2f).

We further validated the simulated meteorology (Fig. S2). For temperature, the model (Fig. S2a) reproduced observed (Fig. S2b) pattern with low NMB of 8.49% and high r of 0.99 against observations (Fig. S2c). For precipitation, both simulations (Fig. S2d) and observations (Fig. S2e) showed high values in the tropical oceans with NMB = 16.91% and r = 0.74 between them (Fig. S2f). Overall, the model showed good performance in the simulations of air pollutants, biospheric parameters, and meteorological fields, and provided a useful tool for studying the O₃-vegetation interactions.

3.2 O₃ damage to terrestrial ecosystems

We assessed the damaging effects of surface O₃ to ecosystems (Fig. 3). The impacts of O₃ on biospheric variables were mainly located in regions characterized by abundant vegetation cover and elevated O₃ concentrations. On the global scale, O₃ induced the GPP reduction of -0.87 PgC yr⁻¹ (-3.09%, Fig. 3a). This deleterious effect was more pronounced in specific regions, notably eastern China and eastern U.S., with significant GPP declines of -18.43% and -16.12%, respectively, under high O₃ sensitivity conditions (Fig. 3a and Table S2). Meanwhile, stomatal conductance significantly decreased in the middle latitudes of Northern Hemisphere (Fig. 3b). The most substantial relative change of -30.62% was observed in eastern China, followed
by -25.65% in the eastern U.S. (Fig. 3b and Table S2). These values were stronger than that for GPP (Fig. 3a), likely due to the climatic feedback to O₃-vegetation interactions. The opening of plant stoma plays a crucial role in regulating the energy and water exchange between land surface and the atmosphere. The inhibition of stomatal conductance by surface O₃ leads to the warmer (Fig. 4a) and drier (Fig. 4b) climate in those hotspot regions, resulting in even stronger inhibition effects on stomatal conductance. Following the changes in GPP, global LAI on average decreased by 0.01 m² m⁻² (-0.62%) with regional maximums of -4.53% in eastern China and -5.87% in eastern U.S. (Table S2).

3.3 Global climatic responses to O₃-vegetation interactions

In response to the O₃-induced inhibition of stomatal conductance, surface air temperature increased by 0.05°C (Fig. 4a) while precipitation decreased by -0.01 mm day⁻¹ (Fig. 4b) on the global scale. The most significant change was the warming of 0.56°C and precipitation reduction of -0.79 mm day⁻¹ (-16.18%) in eastern China (Table S3), following the largest inhibition to stomatal conductance (Fig. 3b). Such warming and rainfall deficit also appeared in eastern U.S. and western Europe, where the O₃-vegetation interactions were notable. The O₃-induced inhibition to stomatal conductance decreased latent heat flux (Fig. 4e) and the consequent precipitation (Fig. 4b) in those hotspot regions. Meanwhile, the reduction of latent heat flux promotes surface temperature (Fig. 4a), resulting in the increase of sensible heat flux (Fig. 4f). Such warming was also reported in field experiments, where relatively high O₃ exposure resulted in noticeable increases of canopy temperature along with reductions of transpiration (Bernacchi et al., 2011; VanLoocke et al., 2012). Globally, temperature and precipitation showed patchy responses with both positive and negative anomalies, suggesting that the regional hotspots of O₃-induced meteorological changes propagate to surrounding areas through atmospheric perturbations.

We further examined the changes in air humidity and cloudiness. Surface relative humidity decreased by 0.18% globally with a similar pattern as that of precipitation.
(Fig. 4c). The most significant reductions were over eastern China and eastern U.S., where both the warming (Fig. 4a) and rainfall deficit (Fig. 4b) contributed to the drought. However, in the adjacent regions such as northern China and central U.S., both rainfall and surface relative humidity showed certain enhancement. These changes were associated with the regional increase of cloud cover (Fig. 4d). The sensible heat flux increased by 6.3 W m$^{-2}$ (16.54%) and 7.12 W m$^{-2}$ (25.46%) in eastern U.S. and eastern China, respectively, suggesting a transfer of thermal energy from land to the atmosphere by O$_3$-vegetation interactions (Fig. 4f and Table S3). The warming effect further triggered anomalous updrafts in the lower troposphere, represented by the changes in vertical velocity (Fig. 5), leading to enhanced convection, reduced atmospheric stability, and consequently an increase in low-level cloudiness (Fig. 4d). However, despite the usual cooling effect associated with increased cloud cover due to reductions in radiation, in regions predominantly influenced by O$_3$-vegetation interactions, this cooling effect was outweighed by the O$_3$-induced warming through inhibition of stomatal conductance. Therefore, temperatures exhibited an overall increase of 0.56 °C in eastern China and 0.33 °C in the eastern U.S. (Table S3).

3.4 Changes of air pollution by O$_3$-vegetation interactions

Changes in surface water and heat fluxes induced by O$_3$-vegetation interactions could feed back to affect air pollutants such as O$_3$ and aerosols. As Fig. 6a and Table S4 show, surface O$_3$ concentrations enhanced 1.26 ppbv in eastern China and 0.98 ppbv in eastern U.S. due to the decreased dry deposition following O$_3$ inhibition on stomatal conductance. It indicates that the high contemporary O$_3$ pollution may worsen air quality through O$_3$-vegetation interactions. However, negative O$_3$ changes were predicted in central U.S. and western China, where the increased rainfall dampened O$_3$ through chemical reactions and wet deposition. On a global scale, surface O$_3$ showed a limited increase of 0.02 ppbv due to the offset between positive and negative feedbacks. The enhancement of O$_3$ concentrations in polluted regions may exacerbate the warming effect of O$_3$ and cause additional damages to vegetation.

Aerosols also exhibited evident changes by the O$_3$-vegetation interactions. The
AOD showed significant reductions over the hotspot regions such as eastern China and eastern U.S. (Fig. 6b). In the ModelE2-YIBs model, sulfate was especially sensitive to cloud which could enhance the aerosol scavenging through cloud water precipitation (Koch et al., 2006). The large enhancement of cloudiness removed sulfate more efficiently than other aerosol species, leading to an average decline of -1.94 μg m\(^{-3}\) (-8.52%) in PM\(_{2.5}\) loading over eastern China (Fig. S3 and Table S4). Meanwhile, the reduction of surface relative humidity (Fig. 4c) in the regions with strong O\(_3\)-vegetation interactions limited the hygroscopic growth of aerosols, leading to a more noticeable decrease in AOD (Petters and Kreidenweis, 2007; Revised algorithm for estimating light extinction from IMPROVE particle speciation data, 2023) by -0.06 (-14.67%) in eastern China (Table S4). The similar aerosol changes were found in eastern U.S. but with smaller reductions of PM\(_{2.5}\) by -0.27 μg m\(^{-3}\) (-6.01%) and AOD by -0.01 (-8.25%) (Table S4). Beyond the key O\(_3\)-vegetation coupling regions, positive but insignificant changes in AOD were predicted, leading to the moderate AOD changes on the global scale (Fig. 6b).

4. Conclusions and discussion

We examined the O\(_3\)-vegetation feedback to climate and air pollution in the 2010s using the fully coupled climate-carbon-chemistry model ModelE2-YIBs. During boreal summer, surface O\(_3\) resulted in strong damages to GPP and inhibitions to stomatal conductance with regional hotspots over eastern China and eastern U.S. Consequently, surface transpiration was weakened, leading to decreased latent heat fluxes and relative humidity but increased surface air temperature. Meanwhile, the surface warming increased cloud cover by reducing atmospheric stability. The enhancement of cloudiness further decreased surface temperature and promoted precipitation nearby the key regions with intense O\(_3\)-vegetation interactions. The O\(_3\)-induced inhibition to stomatal conductance resulted in a localized increase in O\(_3\) concentrations. In contrast, the increased cloud cover and decreased relative humidity jointly reduced AOD in hotspot regions. On the global scale, the mean changes of both climate and air pollution were moderate due to the offset between the changes with opposite signs.
Our predicted changes in water/heat fluxes by O$_3$-vegetation interactions were consistent with previous studies (Lombardozzi et al., 2015; Arnold et al., 2018; Gong et al., 2020). For example, the simulations by Lombardozzi et al. (2015) revealed that surface O$_3$ reduces global GPP by 8%-12% and transpiration by 2-2.4% with regional reductions up to 20% for GPP and 15% for transpiration in eastern China and U.S. These changes were in general consistent with our results though we predicted larger reductions in transpiration than GPP due to O$_3$-vegetation interactions. Using the same scheme as Lombardozzi et al. (2015), Sadiq et al. (2017) showed that O$_3$-vegetation coupling induced the surface warming of 0.5-1°C and O$_3$ enhancement of 4-6 ppbv in eastern China and eastern U.S. The magnitude of these responses was much stronger than our predictions. In contrast, the regional simulations by Jin et al. (2023) revealed that O$_3$-vegetation coupling led to the increases of temperature up to 0.16°C and surface O$_3$ up to 0.6 ppbv in eastern China, both of which were smaller than our predictions. The damage scheme they use, which depends on cumulative O$_3$ uptake, omits the difference in impact on sunlit or shaded leaves and will overestimate the O$_3$ damage on GPP compared to the scheme we use, which considers transient O$_3$ flux (Cao et al., 2023). The discrepancies of O$_3$-vegetation feedback using the same O$_3$ damage schemes revealed the uncertainties from climate and chemistry models. Our predictions were within the range of previous estimates for both climatic and O$_3$ changes.

There were some limitations in our simulated O$_3$-vegetation interactions. First, the semi-mechanistic O$_3$ damage scheme we used in the study linked the damages to photosynthesis with those to stomatal conductance (Sitch et al., 2007), leading to stronger inhibition percentage in stomatal conductance than that in photosynthesis considering the O$_3$-vegetation feedback. However, some observations showed that the damage to stomatal conductance occurred more slowly and might not be proportional to the decline of photosynthetic rates (Gregg et al., 2006; Lombardozzi et al., 2012). Second, 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. Third, large-scale observations were not available to validate the simulated regional to global responses of climate and air pollutants. The O$_3$ vegetation damage scheme was extensively validated against site-level measurements of both photosynthesis (Yue and Unger, 2018) and stomatal conductance (Yue et al., 2016). However, we were conservative about the derived global responses given that previous studies showed large discrepancies using the same O$_3$ damage scheme but implemented in different climate and/or chemistry models (Lombardozzi et al., 2015; Sadiq et al., 2017; Jin et al., 2023). Furthermore, the 2°×2.5° resolution of current ModelE2-YIBs has limitation due to the high computational demands. Ito et al. (2020) shows that the ModelE2.1 with fixed vegetation traits reproduces carbon fluxes well, and that the model results are involved in the CMIP6 Coupled Climate-Carbon Cycle MIP (C4MIP). However, analysis of the climate model shows that high-resolution exhibits improved simulations of extreme events (Chang et al., 2020; Ban et al., 2021), and the application of chemical transport model shows that relatively coarse resolution can raise biases in simulated air pollutants, though it captures the large-scale general pattern almost the same as fine-resolution results and is reasonable as compared to observational data (Wang et al., 2013; Li et al., 2016; Lei et al., 2020). Moreover, we omit the slow climatic feedback caused by air-sea interaction in the simulations. Studies have revealed that these interactions may result in different climatic perturbations from those simulations with fast responses of land surface alone (Yue et al., 2011). A dynamic ocean model is considered to enrich the future research. Meanwhile, this study does not isolate the different impacts of aerosols, even though the radiation module includes both direct and indirect radiative effects. We will investigate this further in the future by identifying the main processes.

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.
Data Availability
The observational data and model outputs that support the findings in this study are available from corresponding authors upon reasonable request.

Author contributions
XY conceived the project. XZ performed the model simulations, conducted results analysis and wrote the draft manuscript. XY, CT and XL assisted in the interpretation of the results and contributed to the discussion and improvement of the paper.

Competing interests
The authors declare that they have no conflict of interest.

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Figure 1. Evaluation of the boreal summertime (June-August) air pollutants in 2010s simulated by the ModelE2-YIBs model. Surface daily maximum 8-hour ozone (MDA8 O₃, upper) and aerosol optical depth (AOD, bottom) from the simulation 10NO3 (left) and observations (middle) are compared. The correlation coefficients (r), normalized mean bias (NMB), and number of grid cells (n) for the comparisons are listed on the scatter plots (e & f). The dashed line denotes the 1 : 1 ratio. The red line is the linear regression between the simulation and observation.
Figure 2. The same as Fig.1 but for gross primary productivity (GPP, upper panels) and leaf area index (LAI, bottom panels).
Figure 3. Changes of boreal summertime biospheric variables induced by O3 damages in 2010s. Results shown are changes of (a) GPP, (b) canopy conductance, and (c) LAI between simulations 10HO3 and 10NO3. Black dots denote areas with significant changes ($p < 0.1$). Please notice the differences in the color scales.
Figure 4. Changes of boreal summertime meteorological fields by ozone-vegetation interactions in 2010s. Results shown are changes of (a) surface temperature, (b) precipitation, (c) surface relative humidity, (d) low level cloudiness, (e) latent heat flux, and (f) sensible heat flux between simulations 10HO3 and 10NO3. For heat fluxes, positive values (shaded in red color) indicate the upward fluxes change. Black dots denote areas with significant changes ($p < 0.1$). Please notice the differences in the color scales.
Figure 5. Vertical profile of vertical velocity. Results shown are changes of the vertical velocity in (a) Eastern China and (b) Eastern US between simulations 10HO3 and 10NO3. Solid red line denotes the value 0. Please notice the differences in the scales.
Fig. 6. Changes of summertime atmospheric pollution caused by ozone-vegetation interactions in 2010s. Results shown are changes of (a) ozone, (b) AOD, and (c) PM$_{2.5}$ between 10HO3 and 10NO3. Black dots denote areas with significant changes ($p < 0.1$). Please notice the differences in the color scales.
References


