Response to Anonymous Referee #1

MS No.: egusphere-2025-4017

Title: Decadal Evolution of Aerosol-Mediated Ozone Responses in Eastern China under Clean Air Actions and Carbon Neutrality Policies

The manuscript presents a timely modeling study on the crucial yet complex role of aerosol effects (AEs) in shaping ozone (O_3) trends over the Yangtze River Delta (YRD) region. The authors employ the enhanced WRF-Chem framework to explicitly and separately quantify the impacts of aerosol-radiation interactions (ARI) and heterogeneous chemistry (HET) across different policy phases and seasons, and project their influence under future carbon neutrality scenarios.

The topic is of high scientific and policy relevance, given the persistent O_3 pollution in China amidst successful $PM_{2.5}$ reduction. The study is well-designed, with a rigorous experimental setup (SET1-SET3) that effectively disentangles the contributions of emissions, meteorology, and aerosol processes. The findings, particularly the seasonally contrasting mechanisms (ARI-dominated in winter vs. HET-dominated in summer) and the potential for unintended O_3 increases from $PM_{2.5}$/NOx reductions under AEs, are novel and provide valuable insights for future air quality management. The manuscript is generally well organized and written. I recommend the manuscript for publication after minor revisions. Specific comments are listed below.

Response: We sincerely appreciate the reviewer's thorough evaluation and constructive comments. We have thoroughly revised the manuscript in accordance with these suggestions, which have substantially improved the quality and clarity of the work. Detailed responses to each comment are provided below, with all page and line numbers referring to the clean revised version of the manuscript.

1. While the manuscript refers to previous validation studies, it would be helpful to include at least one summary table or figure comparing observed and simulated O_3 (and/or key meteorological variables) for the current study period and region. This addition would improve the transparency and completeness of the paper, especially for readers who may not be familiar with the authors' earlier work.

Response: We sincerely thank the reviewer for this valuable suggestion. Although the performance of our WRF-Chem configuration has been validated in detail in our previous study (Li et al., 2024a), we agree that providing an explicit model–observation comparison for the specific study period will enhance the transparency and completeness of the manuscript. Accordingly, we have added a new validation table in the Supplement (Table S2), summarizing the model performance for $PM_{2.5}$, O_3, and key meteorological variables (2-m temperature, relative humidity, and 10-m wind speed). The table reports mean bias (MB), normalized mean bias (NMB), and correlation coefficient (R) based on observations from the national air-quality and meteorological monitoring networks across the Yangtze River Delta. The results show that the model captures the seasonal and diurnal variability of O_3 and meteorological parameters with satisfactory statistical performance. A brief summary of these evaluation results has also been added to Section 3 of the revised manuscript.

Newly added table in supplement:

Table S2. Averaged model performance of T_2, RH_2, WS_{10}, $PM_{2.5}$ and O_3 in YRD.

Parameter	Season	Month	MB[a]	NMB[b]/%	R[c]
T_2 (℃)	Summer	Jul	-0.03	-0.08	0.82
	Winter	Jan	0.25	3.76	0.78
RH_2 (%)	Summer	Jul	-1.26	-1.89	0.57
	Winter	Jan	-1.74	-1.99	0.69
WS_{10} (m/s)	Summer	Jul	0.58	16.88	0.64
	Winter	Jan	0.77	20.32	0.78
$PM_{2.5}$ (μg/m^3)	Summer	Jul	-1.75	-4.85	0.74
	Winter	Jan	-4.34	-8.36	0.63
O_3 (ppb)	Summer	Jul	1.54	5.33	0.66
	Winter	Jan	-5.26	-14.02	0.58

MB[a]: mean bias; NMB[b]: normal mean bias; R[c]: correlation coefficient.

Manuscript changes (Section 3, Page 10, lines 222-226):

"The accuracy of simulated meteorological parameters and pollutant concentrations under scenario (20E20M_AEs) has been thoroughly validated against ground-based observations in earlier work (Li et al., 2024a). As summarized in Table S2, the model reasonably captures the magnitude, seasonal variability of $PM_{2.5}$, O_3, as well as the major features of temperature, relative humidity, and wind speed. These results provide confidence in the model's ability to represent the atmospheric conditions relevant to the subsequent analysis."

References:

Li, Y., Wang, T., Wang, Q. g., Li, M., Qu, Y., Wu, H., and Xie, M.: Exploring the role of aerosol-ozone interactions on O3 surge and PM2.5 decline during the clean air action period in Eastern China 2014–2020, Atmos. Res., 302, 107294, https://doi.org/10.1016/j.atmosres.2024.107294, 2024a.

2. The assumption of proportional reductions (10–90%) across all pollutants is understandable for simplicity but may not fully capture realistic sectoral differences in future emission pathways. Please discuss this limitation and, if possible, comment on how it might influence the overall conclusions.

Response: We thank the reviewer for this valuable comment. We agree that applying proportional reductions to all pollutants is a simplification that does not fully represent sector-specific emission trajectories under carbon neutrality policies. This assumption was adopted mainly to maintain a consistent and comparable framework for evaluating the nonlinear O_3 responses to precursor reductions and aerosol effects, rather than to reproduce specific policy pathways. We acknowledge that such heterogeneity may influence the magnitude of O_3 responses and modify the relative contributions of different precursor groups. This limitation has now been explicitly discussed in the revised manuscript. In future work, we plan to incorporate sector-resolved, scenario-specific emission pathways to better represent realistic emission evolution and to further assess how these structural differences may modulate O_3 sensitivity.

Manuscript changes (Section 3.4, Page 23, lines 485-491):

"The proportional 10-90% reductions applied uniformly across all pollutant species were designed as an idealized framework to systematically examine nonlinear O_3 responses under consistent boundary conditions. In practice, however, future emission pathways are expected to exhibit pronounced sectoral and spatial heterogeneity—for example, SO_2 and primary $PM_{2.5}$ typically decline faster than VOCs and NH_3, and the pace of reductions varies across industrial, transportation, and residential sectors. Such differences may influence the magnitude of O_3 responses and the balance among precursor contributions. Recognizing this limitation, future work will incorporate sector-resolved and scenario-specific emission pathways to provide a more realistic assessment of O_3 sensitivity under evolving emission structures."

3. From Sections 3.1 to 3.4, please clarify how the mean pollutant concentrations were calculated—are they spatial grid averages or site-based averages? This information is important for interpreting the representativeness of spatial and temporal trends.

Response: Thanks for the question. The calculation of average pollutants concentration in Sections 3.1 to 3.4 was based on the grid average within the specified region.

4. It seems that the effects of ARI and HET are independent, i.e., there may be nonlinear interaction between the two effects. This should be noted and discussed.

Response: We thank the reviewer for raising this insightful point. We agree that aerosol–radiation interactions (ARI) and heterogeneous chemistry (HET) are not strictly independent and that nonlinear interactions between them may occur. To address this, we have added a dedicated paragraph in the revised manuscript.

Manuscript changes (Section 3.2, Pages 17-18, lines 357-367):

"Previous studies showed that ARI and HET were not fully independent and could interact through aerosol–meteorology–chemistry feedbacks (Chen et al., 2019; Liu et al., 2023b; Kong et al., 2018; Li et al., 2020a). ARI-induced increases in near-surface relative humidity typically enhanced aerosol hygroscopic growth and expanded aerosol surface area. The resulting increase in aerosol liquid water promoted gas-to-particle partitioning and facilitated aqueous- and surface-phase reactions, thereby accelerating heterogeneous oxidation pathways involving SO_2 and NOx. The strengthened heterogeneous formation of secondary inorganic aerosols further modified solar radiation and potentially intensified the ARI effect. In the present study, our primary focus was to quantify the separate and combined contributions of ARI and HET to O_3 changes across different stages of the CAAP. Accordingly, we isolated their individual impacts rather than examining their nonlinear coupling. We acknowledged that ARI–HET interactions might also affect O_3 under certain chemical and meteorological conditions, and we indicated that future work would incorporate dedicated coupled-sensitivity experiments to more explicitly quantify these nonlinearities and their implications for O_3 formation.”

References:

Chen, J., Li, Z., Lv, M., Wang, Y., Wang, W., Zhang, Y., Wang, H., Yan, X., Sun, Y., and Cribb, M.: Aerosol hygroscopic growth, contributing factors, and impact on haze events in a severely polluted region in northern China, Atmos. Chem. Phys., 19, 1327-1342, https://doi.org/10.5194/acp-19-1327-2019, 2019.

Kong, L., Du, C., Zhanzakova, A., Cheng, T., Yang, X., Wang, L., Fu, H., Chen, J., and Zhang, S.: Trends in heterogeneous aqueous reaction in continuous haze episodes in suburban Shanghai: an in-depth case study, Sci. Total Environ., 634, 1192-1204, https://doi.org/10.1016/j.scitotenv.2018.04.086, 2018.

Li, J., Han, Z., Li, J., Liu, R., Wu, Y., Liang, L., and Zhang, R.: The formation and evolution of secondary organic aerosol during haze events in Beijing in wintertime, Sci. Total Environ., 703, 134937, https://doi.org/10.1016/j.scitotenv.2019.134937, 2020a.

Liu, Z., Wang, H., Peng, Y., Zhang, W., Che, H., Zhang, Y., Liu, H., Wang, Y., Zhao, M., Zhang, X. The combined effects of heterogeneous chemistry and aerosol-radiation interaction on severe haze simulation by atmospheric chemistry model in Middle-Eastern China. Atmos. Environ. 302, 119729. https://doi.org/10.1016/j.atmosenv.2023.119729, 2023b.

5. Line175: Table 1 contains typographical issues: several entries for “10% reduction” appear where “40%, 60%, 80%” were intended—please correct.

Response: We sincerely thank the reviewer for noticing this error. After careful checking, we confirm that the ratios listed as 10% for CUT_MEIC_40, CUT_MEIC_60, and CUT_MEIC_80 in Table 1 were a writing error. The correct reduction ratios have now been revised in Table 1 in the updated manuscript (**Page 8, line 181**).

6. Line 445: Please clarify what specific "carbon neutrality–aligned emission trajectories" are referred to here. Is it the specific 50% reduction scenario, or a broader set of pathways?

Response: We thank the reviewer for pointing out this ambiguity. In the revised manuscript, we have clarified that the term “carbon-neutrality–aligned emission trajectories” refers specifically to the proportional multi-pollutant reduction pathways (10–90%) used in this study. These pathways are not intended to represent a single policy scenario such as the 50% reduction case; rather, they serve as stylized, economy-wide emission decline trajectories consistent with the long-term direction required for carbon neutrality. The revised text now explicitly states this definition to avoid misunderstanding.

Manuscript changes (Section 3.4, Page 22, lines 470-473):

"These results underscore the seasonal asymmetry of O_3 responses under the carbon-neutrality–aligned emission trajectories used in this study—namely the proportional precursor-reduction pathways designed to reflect long-term, economy-wide emission declines. While such stringent reductions may inadvertently aggravate wintertime O_3 pollution, they yield substantial co-benefits for summer O_3 mitigation."

7. Ensure consistent use of "Clean Air Action Plan (CAAP)" throughout the manuscript. Avoid alternating between "CAAP" and "Clean Air Action Plan" in figure captions and text for terminological uniformity.

Response: We thank the reviewer for this helpful comment. We have carefully checked the entire manuscript, including all figure captions and supplementary materials, and ensured consistent use of the term "Clean Air Action Plan (CAAP)" throughout. Instances where "Clean Air Action Plan" or mixed forms previously appeared have now been corrected for terminological uniformity.

8. Please consistently use "VOCs" (plural) when referring to volatile organic compounds.

Response: We thank the reviewer for pointing this out. We have thoroughly checked the entire manuscript, including the main text, figures, and supplementary materials, and have now corrected all instances of "VOC" to the consistent plural form "VOCs" when referring to volatile organic compounds.

9. English of the manuscript needs to be improved.

Response: We thank the reviewer for this helpful suggestion. The manuscript has been thoroughly revised to improve clarity, grammar, and overall readability, with particular attention paid to the **Methods and Results** sections, where technical descriptions and interpretations have been carefully polished and refined. In addition to our own revisions, the manuscript has undergone an additional round of professional-level language editing. We believe these revisions have substantially improved the fluency and clarity of the manuscript.

We would like to once again express our sincere gratitude to the reviewers for their thoughtful and constructive comments. Their insights have been invaluable and have greatly enhanced the clarity, rigor, and overall quality of our manuscript.