

## **Response to Reviewer 2,**

We would like to express our sincere gratitude to Reviewer 2 for their thorough evaluation and constructive comments on our manuscript. We appreciate the reviewer's positive assessment of the study's scientific soundness and methodological robustness. The suggestions provided have helped us significantly improve the clarity, rigor, and reproducibility of our work.

Below, we provide a point-by-point response to the specific comments and technical corrections raised. All changes in the revised manuscript are highlighted **in red** for easy reference.

## **Response to General Comments**

**Comment:** *Overall, this study appears scientifically sound and methodologically robust... I would recommend it for publication after addressing a few minor comments.*

**Response:** We thank the reviewer for this encouraging assessment. We have carefully addressed all the minor comments and technical corrections below to ensure the manuscript meets the high standards of ACP.

## Response to Specific Comments

**Comment 1 (Lines 42-43):** *The statement referring to the “highest agreement (0.85 and 0.83)” for GEOS-Chem may be unclear to readers at this stage, as the specific metric is not yet defined. It would be helpful to clarify here whether these values correspond to the index of agreement (IOA), which is introduced later in the manuscript.*

**Response:** We agree that this clarification is necessary for better readability. We have revised the text in the Abstract to explicitly state that these values refer to the **Index of Agreement (IOA)**. Please see **Line 43** in the revised manuscript: “*...highest agreement (IOA = 0.85 and 0.83)...*”

**Comment 2 (Lines 208-211):** *The description includes the names of specific individuals alongside their institutions in relation to the MIX v1.1 inventory, which seems unnecessary in this context. It would likely be sufficient and more consistent with common practice to cite the inventory itself, along with an appropriate reference or weblink, rather than listing various individual contributors.*

**Response:** We fully agree with the reviewer that listing individual contributors is unnecessary and deviates from standard citation practices. We have removed the names and institutions from the manuscript. Instead, we have updated the text to provide a concise technical description of the MIX v1.1 inventory's specifications (resolution, sectors, and pollutants) to ensure reproducibility, citing the primary reference.

Please see our revisions in **Section 2.1, Lines 207-212**: “*...anthropogenic emissions were based on the MIX v1.1 inventory (Li et al., 2017b). This dataset provides monthly grid-based emission data at a 0.25° spatial resolution across five key sectors (power, industry, residential, transport, and agriculture), meeting the requirements for multi-scale atmospheric chemical transport modeling (<http://meicmodel.org.cn>, last access:13 Apr. 2026).*”

**Comment 3 (Lines 294-300):** *While most of the verification statistics introduced here are widely used and clearly understood, the index of agreement (IOA) may not be familiar to all readers (it was not to me). It would be helpful to include a brief explanation of what IOA represents and how it should be interpreted.*

**Response:** We have added a brief definition and interpretation guide for IOA in the **Observation data section** to assist readers unfamiliar with this metric. Please see our revisions in **Section 2.2.1, Lines 291-293:** *"...The IOA ranges from 0 to 1, where 1 indicates a perfect match between simulated and observed values, while values approaching 0 indicate poor model performance (Willmott, 1981)."*

**Comment 4 (Lines 453 and 458):** *For Figs. 3 and 4, which present the first statistical comparisons in the manuscript, it would be helpful to explicitly state in the captions the time period covered by the analysis as well as the number of data points (e.g., monitoring sites and/or days) included. This would clarify the statistical basis of the results and make the figures more self-contained for readers.*

**Response:** We thank the reviewer for this constructive suggestion. We have updated the captions for both Figure 3 and Figure 4 to explicitly state the analysis period (July–August 2019) and the number of monitoring sites included in the statistics. This addition clarifies the statistical basis of our results and makes the figures more self-contained.

Please see our revisions updated in **Fig. 3 caption (Line 474):** *"... at 1480 monitoring sites during July–August 2019..."* and **Fig. 4 caption (Lines 483-484):** *" Statistics are based on daily data from July -August 2019; number of monitoring sites: China (1480), E (319), N (181), S (256), C (204), NE (166), NW (154), and SW (200)."*

**Comment 5 (Lines 487-493):** *In Section 3.2.3, it would be helpful if the authors could state explicitly which vertical coordinate was used for the ozone-profile comparison (e.g., height above ground level, altitude above sea level, or geopotential height). This could be particularly relevant for high-altitude sites such as Lhasa, where differences in vertical coordinate might*

introduce an apparent vertical shift in the profiles. Figure 5 seems to indicate that HAGL was used, in which case the comparison may already be handled appropriately, but this should be clarified explicitly in the text or figure caption.

**Response:** We thank the reviewer for highlighting this critical methodological detail. We confirm that **Height Above Ground Level (HAGL)** was used for all vertical profile comparisons to ensure consistency across sites with varying topography (e.g., Lhasa). We have revised **Section 2.2.2 (Vertical Observation Data)** to explicitly state that sonde data were processed and interpolated based on HAGL, thereby eliminating potential biases caused by elevation differences.

The followings have been revised in the manuscript:

(1) Revised in **Section 2.2.2, Lines 321-325**: *"To ensure consistency across datasets and comparability with the model output, all sonde data were processed for the 0–20 km **height above ground level (HAGL)** range and interpolated to match the model vertical structure, with data within the 0–16 km **HAGL** layer used in the model evaluation."*

(2) Revised **Section 3.2.3, Figure 5 caption**: *"Figure 5. Comparison of vertical O<sub>3</sub> profiles between four CBC scenario simulations (BASE, H-CMAQ, GEOS-Chem, and CESM2.2) and sounding observations at five stations across China. All profiles are plotted against **Height Above Ground Level (HAGL)**; statistics are based on vertical profile data summarized in **Table S2 (including observation periods and site-specific information)**."*

**Comment 6 (Line 568):** *The comparisons in Section 3.3 demonstrate the clear benefit of dynamic CBCs relative to the static BASE scenario. However, I wonder whether the BASE setup is somewhat overly simplified as a benchmark, since it uses a spatially uniform and temporally constant profile. Could the authors comment on whether this remains common practice in regional CTM applications, and whether more realistic 3-D climatological boundary conditions are available and might constitute a more appropriate benchmark?*

**Response:** We appreciate this insightful comment. First of all, using the default profile-based chemical boundary conditions in CMAQ **does remain a common and practical choice** for baseline, sensitivity, and resource-limited regional applications, particularly because such

profiles are distributed with the model and are straightforward to implement. Secondly, we agree that more realistic three-dimensional, time-varying climatological boundary conditions are available. For example, the CMAQ community provides historical boundary condition datasets derived from global chemical transport models, which can better represent the variability of inflow chemical composition. However, in practice, **many previous regional CMAQ applications have adopted the default profile-based boundary conditions as a baseline configuration**, particularly in sensitivity analyses or methodological studies, due to their simplicity and consistency. In this study, we followed this common practice to establish a controlled benchmark (BASE) that isolates the impact of boundary condition representation. To support this statement on common practices, we have incorporated a recent comprehensive review (Zhu et al., 2024), which quantifies that approximately 70% of recent regional modeling studies still rely on default or unspecified (static) boundary conditions. We have revised the **Conclusion (Section 4)** to explicitly acknowledge this point, cite this evidence, and clarify the scientific rationale for using the simplified BASE scenario in this study.

**Please see our revisions in Section 4 (Conclusion), Lines 778-785:**

*"Our findings demonstrate that the choice of CBCs is not merely a technicality but a dynamic determinant of simulated O<sub>3</sub> levels for regional CTM, especially when facing synoptic regimes that favor long-range transport or vertical exchange. This underscores the necessity of moving beyond static boundary conditions in regional air quality modeling. **Static BCs remain a common baseline in regional modeling, with recent assessments indicating that a majority of studies still rely on default or unspecified boundary conditions (e.g., Zhu et al., 2024). While the simplified BASE scenario may not represent the most realistic boundary condition, it serves as a controlled baseline to isolate the incremental value of time-varying CBC, which is the primary focus of this study.** To advance predictive capability, future efforts should pursue multi-model ensembles to quantify CBC uncertainty, **evaluate 3-D climatological boundary conditions as a refined benchmark**, and explore the integration of real-time global fields into regional CTM forecasting systems. By elucidating the critical interplay between large-scale transport and regional pollution, this study provides a scientific foundation not only for improving O<sub>3</sub> forecasting but also for designing effective transboundary air quality management strategies."* We believe this revision provides quantitative evidence for the prevalence of static BCs while maintaining the original flow of our discussion on future research directions.

**Comment 7 (Lines 729-738):** *Related to the broader implications discussed here, I wonder to what extent conclusions drawn from the July–August 2019 study period can be generalized to other summers, other seasons, and other regions outside China. The discussion of two contrasting synoptic situations is helpful, but some explicit comment on how representative this study period is of typical summertime meteorological conditions would strengthen the manuscript.*

**Response:** We thank the reviewer for raising this important point regarding the generalizability of our findings. We agree that clarifying the representativeness of the study period strengthens the interpretation of our results. We have added a dedicated paragraph in the Conclusion (Section 4) to explicitly address this issue, drawing on the mechanistic insights already established in Section 3.3.

Our justification for the representativeness of the July–August 2019 period rests on three aspects:

1. **Meteorological Representativeness:** The study period covers the peak of the East Asian summer monsoon, capturing the canonical dipole between southeasterly marine inflows (associated with the Western Pacific Subtropical High) and northwesterly continental inflows. These two regimes dominate summer ozone transport patterns over eastern China.
2. **Synoptic Representativeness:** The inclusion of two typhoon events (Lekima and Krosa) and their associated circulation transitions (cyclonic scavenging vs. anticyclonic accumulation) reflects frequent and impactful synoptic disturbances during Chinese summers. The two phases analyzed (P1 and P2) effectively bracket the end-member meteorological conditions that modulate transboundary ozone influence.
3. **Pollution Representativeness:** Both phases exhibited significant ozone pollution episodes, ensuring that the identified CBC mechanisms are relevant to high-pollution scenarios of policy interest, rather than being confined to clean background conditions.

We clarify that while *quantitative magnitudes* of CBC influence may vary with interannual climate variability or across different seasons, the *mechanisms* identified—particularly the heightened sensitivity of ozone simulations to dynamic CBCs under transport-favorable synoptic regimes—are robust and applicable to typical summer pollution episodes in monsoon-affected regions. We have also tempered claims regarding applicability to other seasons or regions outside the East Asian monsoon domain to avoid overgeneralization.

Please see our revisions added to **Section 4 (Conclusion), Lines 748-756:**

*"Regarding the representativeness of these findings, while this study focuses on summer 2019, the selected period captures representative meteorological regimes of the East Asian summer monsoon, including typical southeasterly marine flows and northwesterly continental inflows. The inclusion of typhoon-induced circulation changes (e.g., Lekima and Krosa) further ensures that the findings reflect common synoptic disturbances affecting regional air quality. Although quantitative magnitudes may vary with interannual climate variability, the identified mechanisms regarding CBC sensitivity under transport-favorable conditions are applicable to typical summer pollution episodes in monsoon-affected regions."*

**Comment 8 (Lines 772-774):** *Please check whether the present Data Availability statement is fully in line with ACP/Copernicus requirements. It currently indicates that simulation results are available from the corresponding author, but it may be preferable to archive at least the key output in a public repository with a DOI. The manuscript does specify the WRF and CMAQ versions used, together with the relevant model websites, which is helpful, but for a modelling study of this kind it might also be worth considering whether a brief explicit code-availability statement would be appropriate, especially for any custom processing scripts used to generate the boundary-condition inputs.*

**Response:** We thank the reviewer for this important reminder regarding data transparency and reproducibility. We have carefully reviewed the ACP/Copernicus data policy and have added a dedicated Data Availability section at the end of the manuscript to fully comply with journal requirements.

Specifically, we have:

1. **Catalogued all third-party data sources:** We explicitly listed the access URLs or DOIs for all observational datasets (surface meteorology, O<sub>3</sub> monitoring, ozonesondes, satellite products), reanalysis data (ERA5), emission inventories (MEIC v1.4, MIX v1.1), and global model outputs (H-CMAQ, GEOS-Chem, CESM2.2) used in this study.
2. **Archived custom preprocessing scripts:** Following the reviewer's suggestion, we have uploaded the custom scripts developed for converting global model outputs into CMAQ-compatible boundary conditions to the **Zenodo** public repository, assigned DOI: 10.5281/zenodo.19447294, to ensure long-term accessibility and citability.

3. **Clarified model code availability:** We explicitly stated that the WRF v3.9.1 and CMAQ v5.3.3 source codes are open-source and publicly accessible via their official GitHub repositories.
4. **Provided access pathway for large outputs:** We clarified that additional large-volume model results are stored on the Shuguang high-performance computing system and available from the corresponding author upon reasonable request.

Please see our revisions in **Data Availability** section at the end of the manuscript (before References):

*"The observational datasets used in this study are publicly available from the following sources: surface meteorological data from the China Meteorological Administration (<http://data.cma.cn>, last access: 4 Apr. 2026); surface O<sub>3</sub> concentrations from the China National Environmental Monitoring Center (<https://air.cnemc.cn:18007>, last access: 4 Apr. 2026); ozonesonde profiles from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC, <https://woudc.org>, last access: 4 Apr. 2026), the China Air Pollution Data Center (CAPDC, <https://www.capdatabase.cn>, last access: 4 Apr. 2026), and the National Tibetan Plateau Data Center (TPDC, <https://data.tpsc.ac.cn>, last access: 4 Apr. 2026); and tropospheric O<sub>3</sub> column data from the EMI/GF-5 product (Zhao et al., 2024). Meteorological boundary conditions data derived from the ERA5 reanalysis dataset (Hersbach et al., 2023) are available at <https://doi.org/10.24381/cds.adbb2d47>. The MEIC v1.4 and MIX v1.1 emission inventories are available at <http://meicmodel.org>. Global chemical model outputs used as boundary conditions are available from the EQUATES project (H-CMAQ, <https://www.epa.gov/cmaq/EQUATES>, last access: 4 Apr. 2026), GEOS-Chem (<https://geoschem.github.io/>, last access: 4 Apr. 2026), and CESM2.2/CAM-chem (<https://www2.acom.ucar.edu/gcm/cam-chem>, last access: 4 Apr. 2026). The WRF v3.9.1 (<https://github.com/wrf-model/WRF>, last access: 4 Apr. 2026) and CMAQ v5.3.3 (<https://github.com/USEPA/CMAQ>) model source codes are open-source and publicly accessible via their official GitHub repositories. The custom scripts developed for processing global model outputs into CMAQ-compatible boundary conditions have been archived in the Zenodo repository under DOI: [10.5281/zenodo.19447294]. Additional model results are stored on Shuguang high-performance computing system and available from the corresponding author upon reasonable request ([nan.wang@scu.edu.cn](mailto:nan.wang@scu.edu.cn))."*

## Response to Technical Corrections

We have carefully proofread the manuscript and corrected all the technical issues pointed out by the reviewer.

- **Line 72:** Corrected to "China has". (**Now line 72**)
- **Line 151:** Added missing space in "...distributions (Zhu...)". (**Now line 151**)
- **Line 200:** Removed extra character/data. (**Now line 200**)
- **Line 203:** Removed extra blank space before the period. (**Now line 205**)
- **Line 254:** Removed "the" in "All three global model outputs". (**Now line 253**)
- **Line 336:** Corrected capitalization in "...tropospheric...". (**Now line 338**)
- **Line 339:** Reformatted to "36 x 36 km<sup>2</sup>". (**Now line 341**)
- **Line 346 & throughout:** Ensured "Figure" is spelled out at the beginning of sentences. (**Now lines 349 and 419**)
- **Line 387:** Corrected to "of the CMAQ modeling domain". (**Now line 390-391**)
- **Line 416:** Standardized tense. We have carefully reviewed tense usage throughout the Results and Discussion sections. Following academic conventions, we now consistently use present tense for describing figures, tables, statistical results, and scientific conclusions (e.g., 'Figure 3 illustrates...', 'The results indicate...', 'GEOS-Chem exhibits...'), while retaining past tense only for specific data collection procedures. This revision improves logical clarity and aligns with ACP style guidelines. (**Now line 423 ...**)
- **Line 479:** Corrected to "in those areas". (**Now line 484**)
- **Line 533:** Ensured O<sub>3</sub> uses subscript formatting. (**Now line 548**)

We believe these revisions fully address the reviewer's concerns and significantly enhance the comprehensiveness and robustness of our analysis. We hope the revised manuscript now meets the journal's publication standards, and we sincerely thank the reviewers once again for their time and insightful feedback.