



Resolving the complex responses of ozone transport and chemistry to typhoons in South China: Insights from process-level analysis

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Abstract.

Typhoons are major synoptic systems linked to ozone (O_3) pollution in the Pearl River Delta, South China, particularly in autumn and summer. Although previous studies have identified various mechanisms of typhoon-induced O_3 pollution, analyses of meteorological conditions or overall process contributions alone do not fully explain how typhoons affect O_3 pollution through specific atmospheric processes, particularly transport and chemistry. Here, we combine O_3 mass budget analysis, source apportionment, precursor-transport sensitivity simulations and chemical diagnostics based on WRF-CMAQ models to investigate the responses of these processes to typhoons in autumn and summer. Typhoons enhance O_3 transport through both vertical exchange and horizontal transport, with increased transport of O_3 derived from upwind emissions in both seasons and background O_3 mainly in autumn. Transported precursors also contribute considerably to local O_3 pollution ($>10 \mu g m^{-3}$), which is further enhanced under typhoon influence, primarily driven by increased contributions from acyl peroxy nitrates (APNs) and NO_x . Local photochemistry exhibits more complex responses: typhoons accelerate O_3 production in autumn but suppress it in summer, reduce HO_x cycling efficiency while enhancing O_3 production efficiency, alter VOC contributions to OH reactivity, and generally shift O_3 production toward more NO_x -limited conditions. These findings reveal that typhoons influence regional O_3 pollution through multiple transport pathways, transported precursor contributions and different aspects of photochemistry, providing further process-level evidence for understanding the mechanisms underlying typhoon-induced O_3 pollution.



1 Introduction

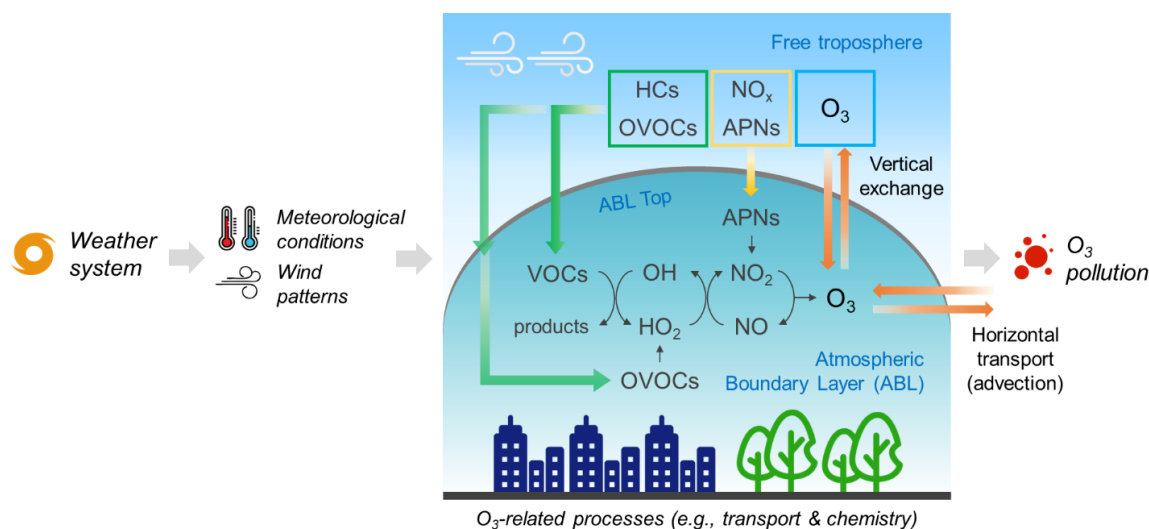
Tropospheric ozone (O_3) is a major air pollutant influencing air quality globally (Monks et al., 2015; Schultz et al., 2017; Fowler et al., 2020). Despite substantial emission controls, elevated O_3 concentrations still occur frequently in many regions, posing significant threats to human health, ecosystems and crop yields (Mills et al., 2018; Zhang et al., 2019). Severe O_3 pollution episodes are often associated with the influence of extreme synoptic systems, such as typhoons, defined as intense tropical cyclones over the Northwest Pacific (Wang et al., 2017; Lu et al., 2018, 2019a; You et al., 2024). As the intensity, frequency and spatial distribution of typhoons are projected to change under global warming (Emanuel, 2013; Walsh et al., 2016; Studholme et al., 2021; Kang et al., 2024), understanding how typhoons influence O_3 pollution and its underlying processes has become increasingly important.

As summarized in Table S1, typhoon-related O_3 pollution in the coastal regions of the Northwest Pacific has received growing attention in recent years. Previous studies have identified various mechanisms linking typhoons to regional O_3 pollution through analyses of meteorological conditions and O_3 concentrations, increasingly complemented by model-based quantitative assessments of atmospheric process contributions. Typhoons are characterized by strong cyclonic winds and substantial influences on regional atmospheric circulation, which can enhance the transport of O_3 and its precursors. Meanwhile, typhoon-induced changes in local meteorological conditions (e.g., reduced cloud cover) may also enhance solar radiation and accelerate photochemical O_3 production, or favor O_3 accumulation under stagnant conditions. Recent studies have also highlighted the potential role of enhanced biogenic volatile organic compound (VOC) emissions in aggravating typhoon-related O_3 pollution (Wang et al., 2022). These findings indicate that typhoons can influence O_3 pollution through multiple mechanisms, whose relative importance often varies among regions, seasons and episodes.

Although analyses of meteorological conditions and overall process contributions have helped identify important mechanisms of typhoon-induced O_3 pollution, they do not fully explain how typhoons affect O_3 pollution through specific atmospheric processes, particularly transport and chemistry. Following the “**weather-process-pollution**” analysis framework (Fig. 1), a more complete understanding of these mechanisms requires examining how these processes respond to typhoon-related meteorological changes and contribute to regional O_3 pollution. O_3 transport involves two major pathways: horizontal transport across regional boundaries and vertical exchange across the top of the atmospheric boundary layer (ABL) (Qu et al., 2023). In addition to direct O_3 transport, O_3 precursors, mainly including NO_x , hydrocarbons (HCs), acyl peroxy nitrates (APNs) and oxygenated VOCs (OVOCs), can also be transported across regions and subsequently contribute to local O_3 production (Fig. 1; Qu et al., 2024; Yan et al., 2026). Meanwhile, typhoon-related changes in meteorological conditions and transported air masses can modify the local photochemical environment, affecting O_3 production rates and efficiency, precursor sensitivity and VOC contributions to OH reactivity (Dai et al., 2023). However, an overall enhancement in O_3 transport does not necessarily reveal which transport pathways are strengthened or how transported precursor contributions change. Similarly,



75 changes in net chemical contributions do not reveal how O_3 production rates, chemical efficiencies, VOC contributions and precursor sensitivity change. Resolving these specific responses can help clarify how typhoons modify O_3 transport and chemistry, providing stronger process-level evidence for the underlying pollution mechanisms.



80 **Figure 1.** Conceptual framework linking typhoon-induced meteorological and wind changes, O_3 -related processes and regional O_3 pollution responses. VOCs, volatile organic compounds; OVOCs, oxygenated VOCs; HCs, hydrocarbons; APNs, acyl peroxy nitrates.

In our previous study (Qu et al., 2021; hereafter referred to as Part I), we combined a five-year observational analysis with WRF-CMAQ simulations to investigate typhoon-related meteorological and O_3 responses in the Pearl River Delta (PRD), one of the regions most frequently affected by typhoons in South China (Wang et al., 2017; Lu et al., 2018, 2019a; You et al., 2024). The study focused on autumn and summer, the two major seasons of typhoon-induced O_3 pollution in this region. The
 85 observational analysis identified statistically significant differences in several meteorological variables between typhoon-induced and no-typhoon conditions, while the WRF-CMAQ simulations quantified the net contributions of major atmospheric processes to typhoon-induced O_3 enhancement. The results revealed contrasting seasonal responses of local O_3 production and accumulation, whereas enhanced transport was identified as the dominant contributor to typhoon-induced O_3 pollution in both
 90 seasons. These findings provided an overall understanding of typhoon-induced O_3 pollution mechanisms in the PRD, but did not fully resolve how individual transport and chemical processes respond to typhoon influence.

Building on Part I and related research (Table S1), the present study integrates multiple diagnostic approaches based on WRF-CMAQ simulations to systematically investigate how O_3 transport and chemistry respond to typhoon influence in the PRD. By comparing typhoon-induced and no-typhoon conditions (defined in Sect. 2.2), we examine changes in O_3 transport
 95 pathways, transported precursor contributions and local photochemistry, including differences between autumn and summer. Specifically, O_3 mass budgets within the ABL are quantified to characterize changes in horizontal transport and vertical exchange, while source apportionment is used to quantify the contributions of different source regions to transported O_3 . A



series of sensitivity simulations is conducted to quantify the contributions of four transported precursor groups (NO_x , HCs, APNs and OVOCs) to O_3 , and multiple chemical indicators are analyzed to characterize changes in O_3 production rates, chemical efficiencies, VOC contributions to OH reactivity and precursor sensitivity. Together, these analyses link the overall O_3 changes under typhoon influence to the responses of individual transport and chemical processes. The model configuration and analysis framework are described in Sect. 2, the results are presented in Sect. 3, and the main findings, implications and limitations are discussed in Sect. 4.

2 Method

2.1 Overview of the analysis framework

In this study, we applied a process-based analysis framework using WRF-CMAQ simulations to investigate O_3 transport and chemical responses to typhoon influence. The framework consists of three complementary components. First, regional O_3 mass budgets within the ABL of the PRD are quantified to diagnose changes in horizontal transport and vertical exchange. Combined with source apportionment, these analyses further identify the source regions of O_3 transported through different pathways. Second, a series of sensitivity simulations is conducted to quantify the contributions of various transported precursor groups, including NO_x , HCs, APNs and OVOCs, to O_3 . Third, multiple indicators describing the chemical characteristics of O_3 production are analyzed to characterize changes in local photochemistry. Together, these analyses provide a quantitative assessment of O_3 transport pathways, transported precursor contributions and photochemical responses under typhoon-induced and no-typhoon conditions in autumn and summer. The following sections first summarize the WRF-CMAQ configuration, simulation design and model evaluation, followed by descriptions of the individual analysis methods.

2.2 WRF-CMAQ simulations

The WRF-CMAQ simulations from Part I were used for the process-based analyses in this study, covering the periods of 11 October–10 November 2015 and 1–31 July 2016 to represent severe O_3 pollution conditions in autumn and summer, respectively. Following Part I, O_3 pollution days were defined as days when either the maximum hourly O_3 concentration exceeded $200 \mu\text{g m}^{-3}$ or the maximum daily 8-hour mean (MDA8) O_3 concentration exceeded $160 \mu\text{g m}^{-3}$ in any municipality of the PRD. Based on these criteria, 16 and 11 O_3 pollution days were identified for the two periods, respectively (Table S2). These pollution days were further categorized into different scenarios following the five-year analysis in Part I, with typhoon-induced and no-typhoon days selected for comparison. Typhoon information, including typhoon center locations, was obtained from the China Meteorological Administration best-track dataset (Ying et al., 2014). Typhoon-induced days were defined as O_3 pollution days when at least one typhoon was present over the Northwest Pacific, and the distance between the PRD and the closest typhoon center at 14:00 local time fell within the 20th–80th percentile range of distances for typhoon-influenced pollution days in the corresponding seasons during 2014–2018. Days with typhoons that were too close or too distant were excluded from the comparisons. No-typhoon days were defined as O_3 pollution days without typhoon occurrence over the



Northwest Pacific. Each scenario contained 4-6 O₃ pollution days per season, as listed in Table S2. Further details of the
 130 scenario classification are provided in Qu et al. (2021).

WRF (version 3.2; Skamarock et al., 2008) and CMAQ (version 5.0.2; US EPA Office of Research and Development, 2014)
 were applied to simulate meteorological and chemical fields, respectively, using two nested domains with horizontal
 resolutions of 36 and 12 km (Fig. S1). The second domain (“d02” in Fig. S1) covers East and Central China, enabling the
 135 simulation of cross-regional O₃ transport to the PRD. The WRF and CMAQ simulations used 35 and 19 vertical layers,
 respectively. The WRF configuration, including physical parameterizations, initial conditions and data assimilation sources,
 is summarized in Table S3. The SAPRC07 chemical mechanism (Carter, 2010) and AERO6 scheme were adopted to represent
 gas-phase chemistry and aerosol processes in CMAQ. Multiple anthropogenic emission inventories were used, including the
 local inventory for emissions within the PRD (provided by the Guangdong Environmental Monitoring Center), MEIC version
 140 1.3 for emissions in mainland China outside the PRD (Li et al., 2017a; Zheng et al. 2018), MIX version 1.1 for emissions in
 other Asian areas (Li et al., 2017b), and East Asian shipping emissions from Liu et al. (2016). Biogenic emissions were
 estimated using the MEGAN model (version 2.10; Guenther et al., 2012), and biomass burning emissions were derived from
 the FINN inventory (version 1.5; Wiedinmyer et al., 2011).

The WRF-CMAQ simulations were systematically evaluated against observations of meteorological variables, O₃ and its key
 precursors, such as NO₂ and non-methane hydrocarbons (NMHCs), in Part I (Qu et al., 2021). Overall, the simulations showed
 acceptable performance in reproducing observed meteorological conditions and pollutant concentrations during both periods.
 In particular, simulated O₃ MDA8 exhibited normalized biases of 15% and 17% in autumn and summer, respectively, with
 high correlations with observations ($R > 0.8$). The normalized mean biases of simulated NO₂ and NMHCs were also within
 150 $\pm 20\%$. More detailed descriptions of model configuration and validation results are provided in Part I and subsequent studies
 using the same model system (Qu et al., 2023, 2025, 2026).

2.3 O₃ mass budget

The regional O₃ mass budget is used to quantify the hourly contributions of O₃-related atmospheric processes, such as transport
 and chemistry, to variations in the total O₃ mass within the ABL of the targeted region (the PRD for this study). Unlike the
 155 commonly used O₃ concentration budget derived from the CMAQ Integrated Process Rate (IPR) outputs, which diagnoses
 process contributions to O₃ concentration changes, O₃ mass budget directly calculates the fluxes of individual transport and
 chemical processes. By quantifying O₃ mass entering, leaving and being chemically produced or consumed within the regional
 ABL, the results of O₃ mass budget allow more direct comparisons among the contributions of different processes to regional
 O₃ variability (Qu et al., 2023).

160 The processes considered in the O₃ mass budget include:



(i) Horizontal (advective) transport, resolved into the transport across the north, south, west and east boundaries of the PRD (Fig. S2). For a single grid column within the ABL, the horizontal transport flux through an interface with the adjacent grid over a time interval dt can be calculated as (Yang et al., 2012; Chang et al., 2018):

$$F_{htrans} = \int_0^H c_{O_3} u L dz dt \quad (1)$$

165 where H is the ABL height, c_{O_3} denotes the O_3 concentration in the upwind grid, u is the wind speed perpendicular to the interface, and L is the interface length.

(ii) Vertical exchange through the ABL top (ABLex), consisting of the processes driven by temporal variations in ABL height (ABLex-H) and by advection perpendicular to the ABL top and its slope (ABLex-A). The total vertical exchange flux (F_{ABLex}) over a time interval dt can be generally expressed as (Sinclair et al., 2010; Lee, 2018; Jin et al., 2021):

$$F_{ABLex} = c_{O_3,h} \frac{\partial H}{\partial t} S dt + c_{O_3,h} \left(u_h \frac{\partial H}{\partial x} + v_h \frac{\partial H}{\partial y} - w_h \right) S dt \quad (2)$$

170 where $c_{O_3,h}$ denotes the O_3 concentration near the ABL top, S is the grid-cell area, and u_h , v_h and w_h separately represent wind components near the ABL top in the x-, y- and z-directions, respectively. The two terms on the right side correspond to the fluxes of ABLex-H and ABLex-A, respectively.

(iii) Other non-transport processes, including gas-phase chemistry, cloud processes (e.g., aqueous-phase chemistry and below-/in-cloud mixing; Liu et al., 2011) and dry deposition.

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The calculations were based on meteorological variables simulated by WRF, O_3 concentrations simulated by CMAQ, and IPR outputs from the CMAQ Process Analysis module. Detailed descriptions of the calculation procedures are provided in Qu et al. (2023), and the corresponding codes are documented in Qu et al. (2022).

2.4 Source apportionment

180 To further identify the source regions of O_3 fluxes contributed by different processes, the O_3 mass budget was combined with source apportionment analyses based on the Brute Force Method (BFM). This approach separates process-related O_3 fluxes into contributions from emissions within the PRD, emissions outside the PRD but within d02, and sources outside d02 (represented by the chemical boundary conditions of d02), hereafter denoted as local, regional and background contributions, respectively. By attributing process-induced O_3 fluxes to these source regions, this approach provides additional insights into
 185 the impacts of transport on O_3 pollution. In particular, local contributions to O_3 transport fluxes can indicate the effects of pollutant recirculation, whereby O_3 produced from local emissions is transported out of the region and subsequently re-enters. In contrast, non-local contributions to chemically produced O_3 can reflect the influence of transported precursors on local O_3 production.



190 In this study, O₃ mass variations induced by horizontal transport, vertical exchange and gas-phase chemistry were attributed to local, regional and background contributions. Following the BFM framework applied in Qu et al. (2023), four simulation cases were designed for source apportionment:

- Base case: All emissions within d02 were included.
- PRD-cut case: Emissions within the PRD were set to zero.
- 195 • PRD-only case: Emissions outside the PRD but within d02 were set to zero.
- Zero-emission case: All emissions within d02 were set to zero.

Supposing that the hourly O₃ fluxes induced by the process i in the above four cases are $F_{base,i}$, $F_{PRD_cut,i}$, $F_{PRD_only,i}$ and $F_{0,i}$, respectively. The local, regional and background contributions (denoted as $S_{local,i}$, $S_{regional,i}$ and $S_{background,i}$, respectively) were calculated as follows:

$$S_{local,i} = \frac{1}{2} [(F_{base,i} - F_{PRD_cut,i}) + (F_{PRD_only,i} - F_{0,i})] \quad (3)$$

$$S_{regional,i} = \frac{1}{2} [(F_{base,i} - F_{PRD_only,i}) + (F_{PRD_cut,i} - F_{0,i})] \quad (4)$$

$$S_{background,i} = F_{0,i} \quad (5)$$

The local and regional contributions were estimated by averaging the top-down and bottom-up BFM results. The top-down BFM estimates source contributions by removing the targeted emissions from the base case, corresponding to the terms $F_{base,i} - F_{PRD_cut,i}$ in Eq. (3) and $F_{base,i} - F_{PRD_only,i}$ in Eq. (4), whereas the bottom-up BFM estimates contributions by adding the targeted emissions to the zero-emission case, corresponding to the terms $F_{PRD_only,i} - F_{0,i}$ in Eq. (3) and $F_{PRD_cut,i} - F_{0,i}$ in Eq. (4) (Clappier et al., 2017; Qu et al., 2023). Averaging the two estimates provides an equal allocation of the interactive effects between local and regional emissions to the local and regional contributions, while ensuring that the sum of all three contributions equals the corresponding O₃ fluxes in the base simulation ($S_{local,i} + S_{regional,i} + S_{background,i} = F_{base,i}$).

2.5 Identifying contributions of transported precursor groups to O₃

210 A series of sensitivity simulations was performed to assess the contributions of transport of different precursor groups, including NO_x, HCs, APNs and OVOCs, to O₃ pollution in the PRD. These precursor groups contribute to O₃ production through distinct chemical pathways (Fig. 1) representing different mechanisms through which cross-regional transport influences local photochemistry. In particular, APNs (e.g., peroxyacetyl nitrate, PAN) act as reactive nitrogen reservoirs and can enhance downwind O₃ production through thermal decomposition that releases NO_x (Jiang et al, 2016). OVOCs influence O₃ formation through their involvement in radical chemistry via oxidation by OH and/or photolysis that generates HO₂ radicals. In contrast, transported NO_x and HCs can directly participate in local O₃ production after entering the region.



The subdomain d03 (Fig. S1) with the same 12 km horizontal resolution as d02 but confined to the PRD was used for these simulations. Seven simulation cases, including one base case and six sensitivity cases (Table 1), were designed. The chemical boundary conditions for the base case were derived from the corresponding d02 simulations. In sensitivity cases S1-S4, the concentrations of individual precursor groups in the chemical boundary conditions were set to zero, thereby removing the inflow of the corresponding precursor groups from outside the simulation domain. The resulting change in O₃ concentrations relative to the base case was interpreted as the contribution of transport of the corresponding precursor group to O₃ pollution in the PRD. An additional sensitivity case (S5) with all four precursor groups simultaneously zeroed out was designed to evaluate potential interactions among these groups. If the combined contribution estimated from S5 is close to the sum of the individual contributions estimated from S1-S4, the interaction effects among different transported precursor groups can be considered relatively small. Moreover, a sensitivity case (S6) with O₃ concentrations set to zero in the chemical boundary conditions was included to provide a reference for the influence of direct O₃ transport. Comparisons among these simulations allow the influences of individual precursor groups to be quantified and evaluated relative to direct O₃ transport.

Table 1. Setup of the base and sensitivity cases used to quantify the influence of transported precursor groups on O₃ in the PRD.

Case ID	Case name	Species zeroed out in the chemical boundary conditions
/	base	None
S1	APNs_cut	APNs, including PAN, PAN2, PBZN and MAPAN in SAPRC07
S2	NO _x _cut	NO _x , including NO and NO ₂
S3	OVOCs_cut	OVOCs (detailed SAPRC07 species listed in Table S4)
S4	HCS_cut	HCS (methane excluded; detailed SAPRC07 species listed in Table S4)
S5	precursor_cut	APNs, NO _x , OVOCs and HCS (methane excluded)
S6	O ₃ _cut	O ₃

2.6 Chemical indicators for O₃ production

Changes in transport pathways, precursor transport and local meteorological conditions may all influence the characteristics of O₃ production under typhoon-induced and no-typhoon conditions. To characterize these responses, several chemical indicators were quantified based on outputs from the CMAQ Process Analysis module (Gipson and Young, 1999). It provides the IPR and Integrated Reaction Rate (IRR), which quantify the hourly contributions of individual atmospheric processes to targeted species and the rates of individual chemical reactions, respectively.

The chemical indicators applied in this study include: (1) the O₃ production rate (P(O₃)); (2) the efficiency of HO_x and NO_x cycling in O₃ production, separately represented by the OH chain length (L_{OH}) and ozone production efficiency (OPE); (3) the contributions of different VOC species groups to OH reactivity (k_{OH}); and (4) the sensitivity of O₃ production to precursor emissions, characterized by the relative incremental reactivity (RIR) of NO_x and VOCs derived from simulations with 25%



reductions in the respective emissions. Detailed calculation methods for these indicators based on CMAQ simulations are summarized in Table 2.

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Table 2. Calculation methods of chemical indicators for O₃ production based on CMAQ simulations.

Indicator	Description	CMAQ module	Calculation method
P(O ₃)	Net O ₃ production rate	IPR	Contributions of the chemical process to O ₃ in the IPR output
L _{OH}	OH chain length	IRR	Ratio of HO ₂ -to-OH conversion rate to the primary OH production rate (Emmerson et al., 2007)
OPE	O ₃ production efficiency	IPR	Ratio between the contributions of the chemical process to O ₃ and oxidized nitrogen species (NO _x , including NO ₃ , N ₂ O ₅ , HONO, HNO ₃ , particle nitrates, HNO ₄ and organic nitrates) in the IPR output (Wang et al., 2010) Contributions of different VOC groups (biogenic VOCs, alkanes, alkenes, aromatics and OVOCs; VOCs species corresponding to each group are listed in Table S4) to the total OH reactivity, defined as:
k _{OH}	OH reactivity	IRR	$k_{OH} = \sum_i (k_i c_i)$, where k_i is the rate constant for the oxidation of VOC species i by OH and c_i is the concentration of VOC species i (Yang et al., 2016). The IRR output provides the reaction rates of OH oxidation for individual VOC species, expressed as $k_i c_i [OH]$
RIR	Relative incremental reactivity	IPR	Relative changes in simulated daytime-mean P(O ₃) in response to a 25% reduction in NO _x and VOC emissions (from both anthropogenic and biogenic sources) within the PRD, quantified as (Cardelino and Chameides, 1995): $RIR = \frac{[P(O_3)_0 - P(O_3)_{sens}]/P(O_3)_0}{25\%}$ where $P(O_3)_0$ and $P(O_3)_{sens}$ are the simulated O ₃ production rates in the base case and in the sensitivity simulation after emission reduction, respectively

3 Results

3.1 Typhoon-induced changes in O₃ transport pathways (horizontal transport and vertical exchange)

O₃ can be transported into a region through two major pathways, horizontal transport and vertical exchange, whose relative importance may vary under different meteorological conditions. In addition, identifying the source regions of transported O₃ can further clarify where the enhanced O₃ influx originates. In this section, O₃ mass budgets under typhoon-induced and no-typhoon conditions are compared to investigate how typhoons modify these transport pathways, while source apportionment is additionally used to identify changes in the source contributions to transported O₃. These analyses provide a process-level perspective on the enhanced transport contributions to O₃ pollution identified in our previous study (Qu et al., 2021).

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Mean O_3 mass budgets for all pollution days during the same periods were presented in Qu et al. (2023). Here, we focus on the differences between typhoon-induced and no-typhoon pollution days (Fig. 2). Overall, the diurnal evolution of the budgets is similar under different conditions. Total O_3 mass increases in the morning until around 14:00 local time (LT), decreases in the afternoon and remains relatively stable at night, generally following the diurnal evolution of the ABL. These variations are dominated by transport processes, particularly vertical exchange (ABLex-H), which largely controls the morning increase and afternoon decrease in O_3 mass. Horizontal transport contributes throughout both daytime and nighttime with a smaller but non-negligible magnitude. Gas-phase chemistry also contributes to the O_3 mass budget, with its relative contribution differing among scenarios, as discussed in detail in Sect. 3.3. The following analyses focus on how typhoons modify the two transport pathways and their associated source contributions.

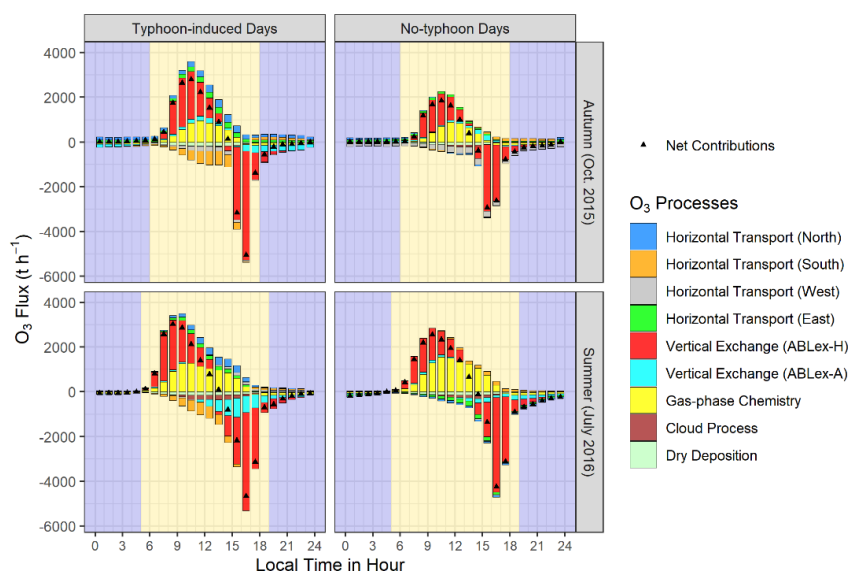


Figure 2. Mean diurnal changes of O_3 mass budget on the typhoon-induced (left panels) and no-typhoon (right panels) pollution days of the representative months in autumn (October 2015; upper panels) and summer (July 2016; lower panels) within the atmospheric boundary layer of the Pearl River Delta. The unit is $t h^{-1}$. Backgrounds in yellow and dark blue indicate daytime and nighttime periods, respectively.

(1) Vertical exchange. Vertical exchange is the dominant transport pathway contributing to O_3 pollution in the PRD and it exhibits substantial responses to typhoon influence. Compared to no-typhoon conditions, typhoons markedly enhanced vertical exchange in both autumn and summer, as characterized by stronger O_3 influxes in the morning and outfluxes in the afternoon (Fig. 3). The enhancement was dominated by changes in ABLex-H, whose morning and afternoon O_3 fluxes both increased by over 50% in autumn and by 37% and 14%, respectively, in summer. In contrast, the response of ABLex-A exhibited clear seasonal differences: Its fluxes increased under typhoon influence in autumn, whereas in summer, typhoons reversed the morning transport direction from downward to upward and further strengthened upward transport in the afternoon, consistent with the intensified updrafts associated with summer typhoons reported by Qu et al. (2021).

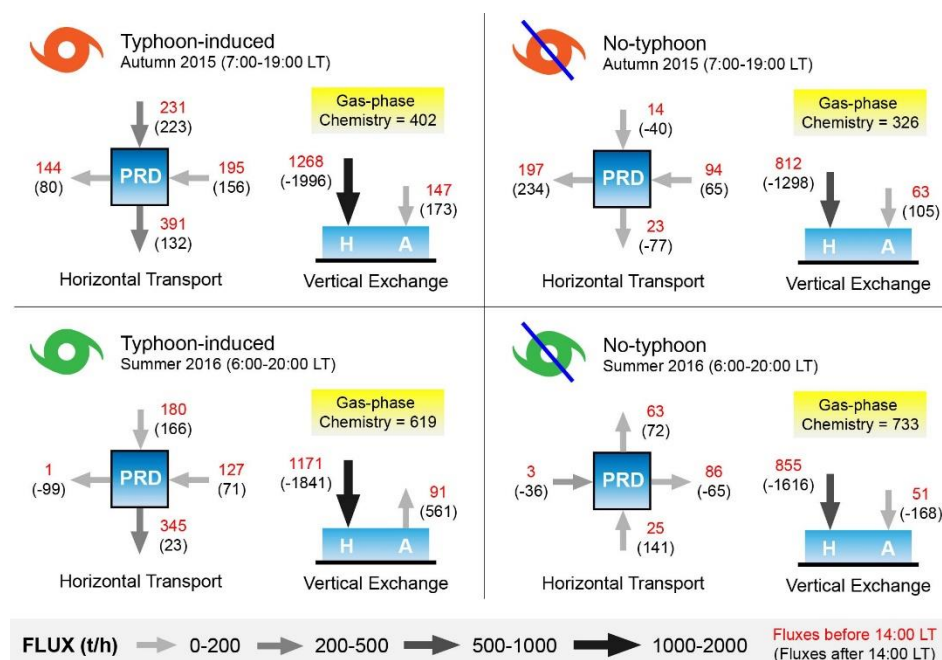


Figure 3. Mean daytime contributions to O₃ mass variation (fluxes) within the atmospheric boundary layer of the Pearl River Delta (PRD) from horizontal transport, vertical exchange and gas-phase chemistry in the typhoon-induced and no-typhoon scenarios of autumn (October 2015) and summer (July 2016). Numbers in red denote mean daytime transport fluxes before 14:00 local time (LT), whereas numbers in parentheses denote mean daytime transport fluxes after 14:00 LT. Negative values indicate transport in the opposite direction to that indicated by the arrows. Contributions of gas-phase chemistry represent daytime-mean values. H and A denote two vertical exchange processes, ABLex-H and ABLex-A, respectively.

Source apportionment further reveals that enhanced vertical exchange under typhoons is associated with increased transport of non-local O₃ (Fig. 4a-d). For O₃ influxes, regional contributions increased slightly from 35% to 38% in autumn and more notably from 27% to 46% in summer, indicating a stronger influence of O₃ transport from upwind regions. Background contributions also increased markedly in autumn, by over 50% in absolute O₃ mass, but only slightly in summer (~12%). This enhancement in background contributions agrees well with the stronger subsidence identified under autumn typhoon-induced conditions in our previous study (Qu et al., 2021), which could enhance downward O₃ transport from the upper troposphere and lower stratosphere. In contrast, local contributions remained low in autumn (4-5%) but decreased from 28% to 16% in summer, indicating a less important role of O₃ recirculation in vertical exchange. To summarize, typhoons substantially enhanced vertical exchange in the PRD by increasing the influx of regionally transported O₃ in both seasons and background O₃ mainly in autumn.

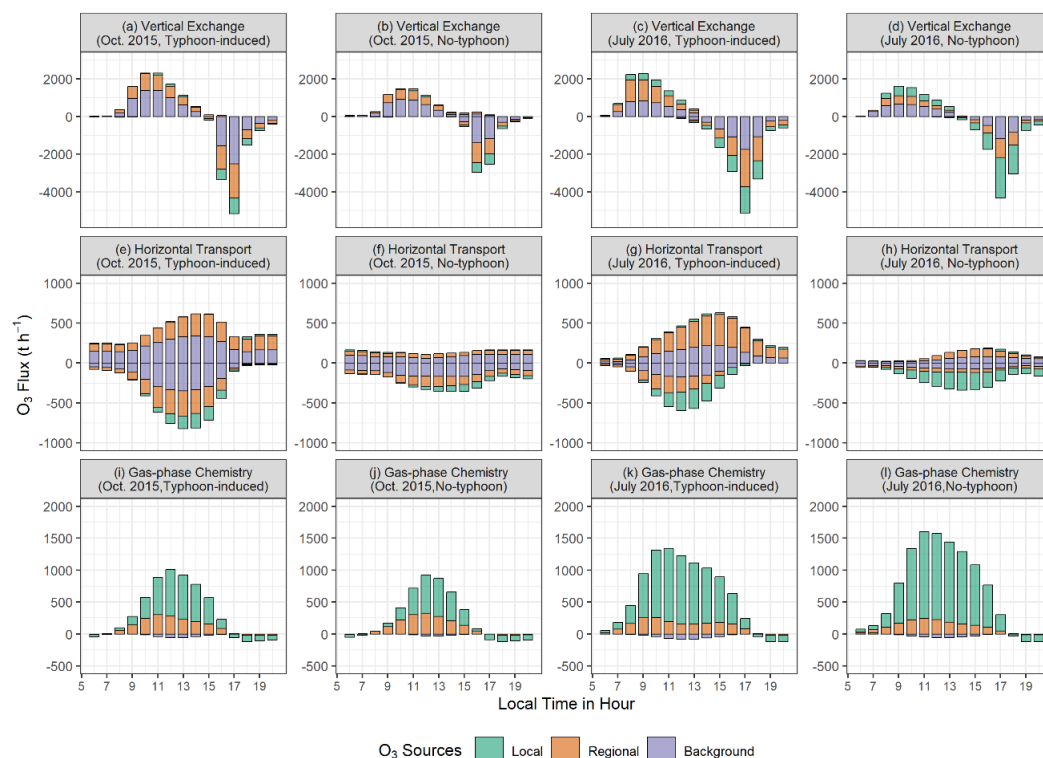


Figure 4. Regional source contributions of hourly O_3 fluxes in the Pearl River Delta, associated with (a-d) vertical exchange, (e-h) horizontal transport and (i-l) gas-phase chemistry, during the daytime of (a, e, i) typhoon-induced days in autumn (October 2015), (b, f, j) no-typhoon days in autumn (October 2015), (c, g, k) typhoon-induced days in summer (July 2016), and (d, h, l) no-typhoon days in summer (July 2016).

(2) Horizontal transport. Horizontal transport was also substantially modified by typhoons. In both seasons, typhoons led to overall higher horizontal O_3 transport fluxes, particularly in the north-south direction (Fig. 3). In addition, typhoons modified the directions of horizontal O_3 transport. During typhoon-induced pollution days, strong O_3 transport persisted throughout the daytime with consistent directions, characterized by inflow from the north and east boundaries of the PRD and outflow toward the south and west boundaries. In contrast, in the no-typhoon scenarios, O_3 transport across the south boundaries became evident in the afternoon, reflecting the development of sea breezes under relatively stagnant synoptic conditions. Source apportionment further shows that O_3 horizontally transported into the PRD was dominated by regional and background sources, together accounting for over 95% of the total influxes (Fig. 4e-h). Under typhoon influence, O_3 influxes from both sources increased substantially, confirming enhanced O_3 transport toward the PRD.

Based on these results, we found that typhoons substantially reshape O_3 transport in the PRD by enhancing both vertical exchange and horizontal transport. The enhanced O_3 influxes are linked to increased non-local contributions, including regionally transported O_3 in both seasons and background O_3 mainly in autumn. Together, these findings reveal that typhoons



enhance O_3 transport through both vertical and horizontal pathways, accompanied by changes in the source contributions to transported O_3 , providing a more detailed explanation of the enhanced transport effects identified in Part I.

3.2 Typhoon-induced changes in transported precursor influences

315 In addition to direct O_3 transport, precursor transport can also contribute to O_3 pollution. Through a series of sensitivity simulations, we quantify the contributions of different transported precursor groups (NO_x , HCs, APNs and OVOCs) to O_3 in the PRD, and examine how these contributions respond to typhoon influence.

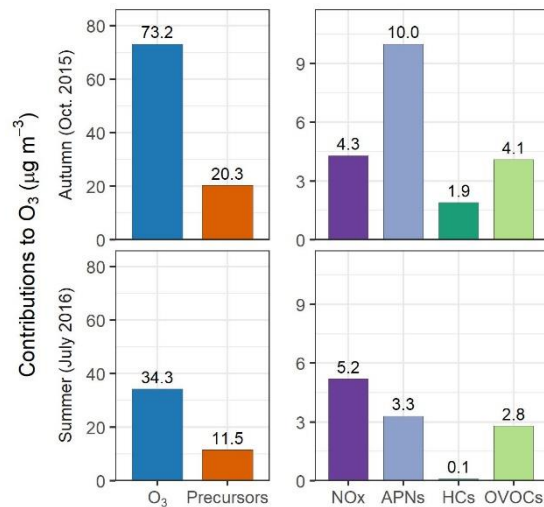
Figure 5 summarizes the mean contributions of directly transported O_3 and transported precursor groups to surface O_3 in the PRD on pollution days. Transported precursors contributed 20.3 and 11.5 $\mu g\ m^{-3}$ of O_3 in autumn and summer, respectively, corresponding to ~30% of direct transport contributions in both seasons. These contributions are also supported by the source apportionment of O_3 associated with gas-phase chemistry in Fig. 4i-l, which reveals considerable regional contributions to chemically produced O_3 within the PRD. Together, these results demonstrate that cross-regional transport influences O_3 pollution in the PRD not only through direct transport of O_3 itself, but also through transported precursor species that
 325 subsequently contribute to local photochemical production. Given that the PRD is often influenced by transported air masses from more polluted North and Central China, precursor transport can act as an important process through which cross-regional transport influences local O_3 production and pollution in the PRD.

The relative importance of individual precursor groups exhibited clear seasonal differences (Fig. 5). The sum of the contributions from the four precursor groups closely matched the total contribution obtained by zeroing out all precursor groups, suggesting a limited influence of non-linear interactions among these precursor groups on O_3 concentrations. In autumn, APNs were the dominant transported precursor group, contributing 10.0 $\mu g\ m^{-3}$ of O_3 . This result indicates that the well-established mechanism whereby transported APNs decompose to release NO_x and subsequently enhance downwind O_3 production (Jiang et al., 2016) also plays an important role in autumn O_3 pollution in the PRD. Transported NO_x and OVOCs
 335 contributed 4.3 and 4.1 $\mu g\ m^{-3}$ of O_3 , respectively, whereas HCs showed the smallest contribution among all precursor groups. In contrast, transported NO_x showed the largest contribution to O_3 in summer (5.2 $\mu g\ m^{-3}$), followed by APNs (3.3 $\mu g\ m^{-3}$) and OVOCs (2.8 $\mu g\ m^{-3}$). The contribution of transported HCs was negligible, likely because reactive HCs were largely oxidized during transport under stronger summertime photochemical conditions.

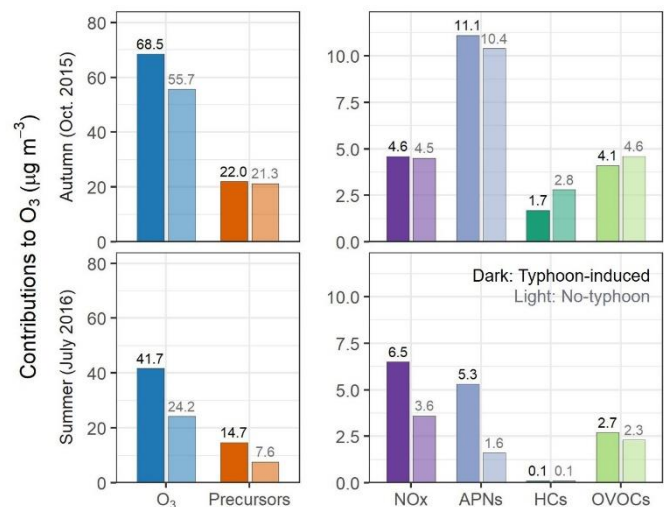
340 We further compared the contributions of directly transported O_3 and transported precursor groups on the typhoon-induced and no-typhoon pollution days, as displayed in Fig. 6. In both seasons, typhoons enhanced the contributions of both direct O_3 transport and precursor transport, although the enhancement was more pronounced for the former. These changes are consistent with the enhanced transport fluxes identified in Sect. 3.1. The contributions of transported precursors increased only slightly in autumn but nearly doubled in summer, indicating a much stronger response to typhoon influence associated with the reversal



345 of prevailing winds in summer. Source apportionment of O₃ associated with gas-phase chemistry (Fig. 4i-l) also shows increased regional contributions (by 5% in autumn and 13% in summer for absolute O₃ mass), providing further evidence of enhanced precursor transport contributions to local O₃ production and pollution under typhoon influence.



350 **Figure 5.** Contributions of directly transported O₃ and transported precursor groups to daytime-mean (9:00–17:00 LT) surface O₃ concentrations (μg m⁻³) in the PRD, averaged over all O₃ pollution days during the simulation periods in autumn and summer. APNs, acyl peroxy nitrates; HCs, hydrocarbons; OVOCs, oxygenated VOCs.



355 **Figure 6.** Contributions of transported O₃ and precursor groups to daytime-mean (9:00–17:00 LT) surface O₃ concentrations (μg m⁻³) in the PRD, averaged over typhoon-induced (dark colors) and no-typhoon (light colors) O₃ pollution days during the simulation periods in autumn and summer. APNs, acyl peroxy nitrates; HCs, hydrocarbons; OVOCs, oxygenated VOCs.



The responses of individual precursor groups differed considerably between the two seasons (Fig. 6). In autumn, the contributions of all four groups showed relatively small changes under typhoon influence, with slight increases in NO_x and APNs and decreases in HCs and OVOCs. APNs remained the dominant contributor under both conditions. In contrast, more pronounced changes occurred in summer, particularly for transported NO_x and APNs, whose contributions increased from 3.6 to 6.5 $\mu\text{g m}^{-3}$ and from 1.6 to 5.3 $\mu\text{g m}^{-3}$, respectively, under typhoon influence. Notably, the contribution of APNs increased by over 200%, approaching that of NO_x , possibly reflecting an enhanced influence of polluted air masses from the north. Meanwhile, the contribution of OVOCs changed only slightly, while that of HCs remained nearly negligible under both conditions. Overall, typhoons enhanced the contributions of precursor transport to O_3 in both seasons; while APNs and NO_x remained major contributors to O_3 among the transported precursor groups, they were also the main species responsible for the typhoon-induced enhancement in precursor contributions.

3.3 Typhoon-induced changes in local O_3 photochemistry

Previous studies have shown that typhoons modify not only O_3 transport but also its chemical production. These chemical responses are expected to arise from combined changes in meteorological conditions and transported air masses under typhoon influence, thereby altering the local photochemical environment. To better understand these responses, we further examine the chemical characteristics of O_3 production under typhoon-induced and no-typhoon conditions. Specifically, we analyze the O_3 production rate and efficiency, VOC contributions to OH reactivity and O_3 sensitivity to NO_x and VOCs, with the results as follows.

3.3.1 Changes in O_3 production rate and efficiency

The net O_3 production rate, denoted as $P(\text{O}_3)$, quantifies the intensity of local O_3 formation through gas-phase chemistry. Simulated daytime $P(\text{O}_3)$, averaged over the height range of 0-1 km under the four scenarios, is shown in Fig. 7a-d. Generally, high $P(\text{O}_3)$ values occurred in the central PRD, where anthropogenic emissions are intensive, and extended towards the downwind regions. In summer, daytime $P(\text{O}_3)$ reached 10-25 ppb h^{-1} in the central PRD, substantially higher than that in autumn (5-15 ppb h^{-1}). These simulated values are generally consistent with previous observation- and model-based studies in the PRD (Lu et al., 2010; Wang et al., 2010; Ling et al., 2014; Tan et al., 2019; see Table S5 for a summary).

Typhoon influences on $P(\text{O}_3)$ exhibited clear seasonal differences in the PRD. The regional mean $P(\text{O}_3)$ increased from 5.1 to 5.5 ppb h^{-1} in autumn but decreased from 8.3 to 6.9 ppb h^{-1} in summer. These responses agree well with the comparison of O_3 mass budgets (Fig. 4i-l), which suggests consistent seasonal responses in the contribution of gas-phase chemistry. As discussed in our previous study (Qu et al., 2021), these contrasting seasonal responses mainly reflect different meteorological effects of typhoons. In autumn, reduced cloud cover and stronger solar radiation generally favor O_3 production. In summer, however, stronger updrafts, increased clouds and weakened solar radiation tend to suppress photochemical production, while concurrent changes in transport patterns also led to a pronounced spatial redistribution of $P(\text{O}_3)$.



O₃ production results from the coupled HO_x and NO_x chemical cycles (Fig. 1), and becomes more efficient when fewer HO_x radicals or less NO_x is required to produce a given amount of O₃. Two indicators are commonly used to characterize the efficiencies of these cycles: (i) the OH chain length (L_{OH}; Emmerson et al., 2007), representing the average number of times an OH radical is recycled within the HO_x cycles before termination, and (ii) the ozone production efficiency (OPE; Xu et al., 2009), defined as the amount of O₃ produced per unit NO_x consumed. Simulated daytime (9:00-17:00 LT) L_{OH} and OPE, averaged over the 0-1 km layer, are shown in Fig. 7e-h and i-l, respectively.

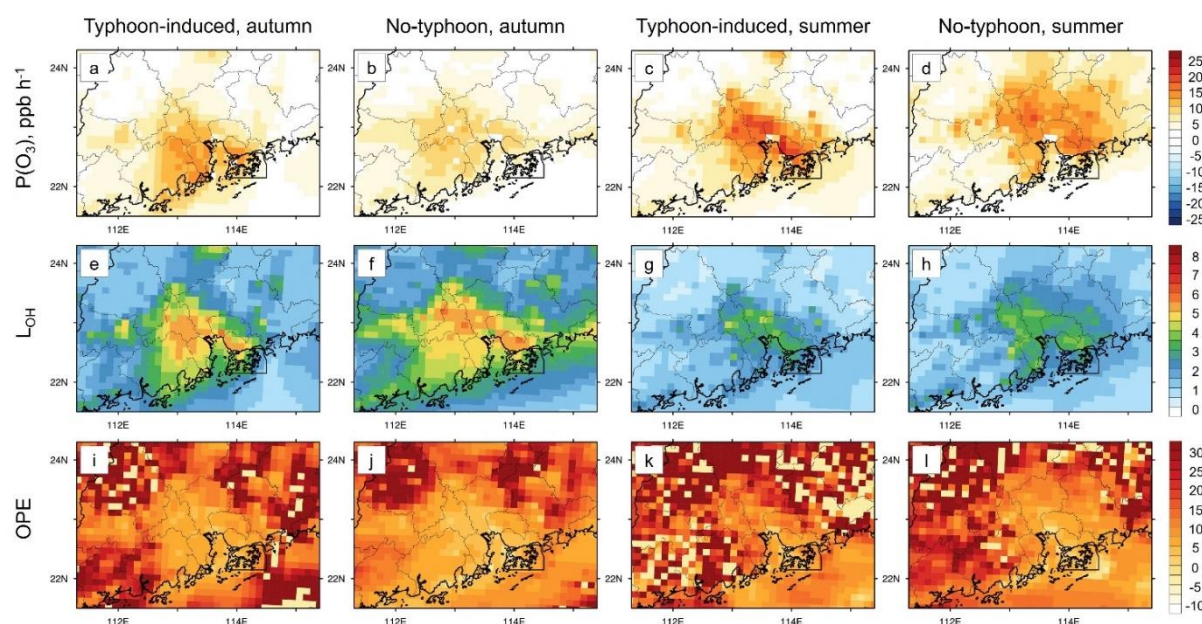


Figure 7. Distribution of simulated daytime-mean (9:00–17:00 LT) $P(O_3)$ (ppb h^{-1} ; a-d), L_{OH} (e-h) and OPE (i-l) on represented O₃ pollution days, averaged over the height range of 0-1 km: (a,e,i) typhoon-induced days in autumn 2015; (b,f,j) no-typhoon days in autumn 2015; (c,g,k) typhoon-induced days in summer 2016; (d,h,l) no-typhoon days in summer 2016.

Similar to $P(O_3)$, elevated L_{OH} values mainly occurred in the central PRD, ranging within 4-6 in autumn and 2-4 in summer. These values are comparable to those reported by Liu et al. (2010), Lu et al. (2010) and Ling et al. (2014) for the same region (Table S5). Typhoons reduced L_{OH} in both seasons, with its regional-mean values declining from 3.5 to 2.7 in autumn and from 1.9 to 1.6 in summer, indicating less efficient HO_x cycling under typhoons. This reduction is likely associated with enhanced transport of aged air masses. As shown in Fig. S3, L_{OH} is positively correlated with the NO_x/NO_y ratio (NO_x = NO + NO₂; NO_y = NO_x + NO_z), a widely used indicator of photochemical age (Mendoza and Carrillo, 2015). Higher NO_x/NO_y ratios represent relatively fresh air masses, whereas lower ratios indicate more aged air parcels with a larger fraction of NO_x converted to reservoir species. Under typhoon influence, strengthened cross-regional transport reduced the NO_x/NO_y ratios (from 0.29 to 0.23 in autumn and from 0.33 to 0.23 in summer at representative sites; Fig. S3). Meanwhile, OH recycling efficiency also decreased.



410 Unlike L_{OH} , OPE exhibited relatively lower values in the central PRD and higher values in the surrounding suburban regions. Negative OPE values were also found in some suburban areas, indicating the decomposition of oxidized nitrogen species, such as APNs. This spatial pattern is consistent with previous studies in the PRD (Lu et al., 2010; Wang et al., 2010). No pronounced seasonal differences in OPE were observed. Typhoons generally increased OPE in both seasons, with the regional-mean OPE rising from 6.3 to 7.6 in autumn and from 8.2 to 10.6 in summer, suggesting more efficient utilization of NO_x for O_3 production

415 under typhoon influence. This increase is also linked to enhanced transport of aged air masses. As discussed above, typhoons reduced the NO_x/NO_y ratios, indicating more aged air masses in which a larger fraction of NO_x had already been converted to reservoir species during transport. Under such conditions, a larger fraction of the remaining NO_x might contribute to O_3 formation rather than being converted to reservoir species, potentially contributing to the higher OPE.

420 To summarize, typhoons resulted in more rapid O_3 production in autumn but slower production in summer, consistent with both the O_3 mass budgets and our previous study (Qu et al., 2021). Enhanced transport of aged air masses under typhoons, characterized by lower NO_x/NO_y ratios in the PRD, also modified the efficiencies of O_3 production. Specifically, typhoons reduced the efficiency of HO_x cycling, as indicated by lower L_{OH} , but enhanced the efficiency of NO_x utilization for O_3 production, as reflected by higher OPE.

425 3.3.2 Changes in VOC contributions to OH reactivity

VOCs promote O_3 production primarily by sustaining the HO_x cycle through their oxidation by OH (Fig. 1). The IRR output from CMAQ provides the reaction rates of OH oxidation for individual VOC species, which can also be expressed as the product of k_{OH} and OH concentration ($[OH]$). By comparing the contributions of different VOCs to $k_{OH} \times [OH]$, their relative importance to VOC oxidation by OH can be identified (Pfister et al., 2019). In this study, the contributions of five VOC groups

430 (biogenic VOCs, alkanes, alkenes, aromatics and OVOCs), together with selected important species or sub-categories, were compared under various scenarios. The analyses are based on daytime-mean results at three representative sites, namely Xijiao (regional), Daxuecheng (urban) and Heshan (suburban), whose locations are shown in Fig. S4.

Before further analysis, the simulated near-surface contributions of multiple VOC groups to k_{OH} were compared with available

435 observation-based estimates for the PRD, including measurements at the Backgarden site during summer 2006 (Lou et al., 2010) and at the Daxuecheng site during autumn 2018 (Liu et al., 2019). Owing to different study periods, these comparisons are intended to identify potential substantial biases rather than provide a direct model validation. As shown in Fig. S5, both simulations and observations indicate considerable contributions of hydrocarbons to k_{OH} (30-40% in VOC-related k_{OH}). Differences exist for individual VOC groups, which may reflect uncertainties in VOC emission speciation and possible changes

440 in VOC emissions. Both observation-based studies also reported substantial fractions of missing or unresolved k_{OH} (~40% in VOC-related k_{OH}), which may arise from the limited capability of current measurement techniques to quantify many OVOC



species (Yang et al., 2016). If so, the contribution of OVOCs inferred from the observations would be closer to the simulation results. Overall, no evident systematic biases are found in the simulated contributions of the major VOC groups to k_{OH} , although more comprehensive observations, particularly of OVOCs, are still required for a more rigorous validation.

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The relative contributions of different VOC groups to k_{OH} at the three sites are displayed in Fig. 8, while their absolute contributions to the OH+VOCs reaction rates ($k_{OH} \times [OH]$) are presented in Fig. S6. OVOCs acted as the dominant contributors to k_{OH} at all three sites, accounting for 50-75% at 50 m and even larger fractions at higher altitudes. Throughout the ABL, their contributions generally exceeded those of the other four VOC groups. The dominance of OVOCs highlights their important role in sustaining O_3 photochemistry in the PRD, a receptor region strongly influenced by regional transport. For hydrocarbon groups, their contributions exhibited more pronounced seasonal and spatial variability. Biogenic VOCs contributed more strongly in summer than in autumn and were more important at the regional site (Xijiao) than at the urban and suburban sites (Daxuecheng and Heshan), whereas anthropogenic hydrocarbons, particularly alkanes and aromatics, showed the opposite pattern. Vertically, the contributions of biogenic VOCs, alkenes and aromatics decreased with altitude, while those of alkanes remained relatively stable.

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We further assessed the impacts of typhoons on VOC contributions by comparing typhoon-induced and no-typhoon scenarios. In autumn, although typhoons led to higher OH+VOCs reaction rates within the PRD (Fig. S6), the relative contributions of different VOC groups remained nearly unchanged. The only notable response was a slight increase in the contribution of biogenic VOCs at the regional site (Xijiao), likely associated with nearly doubled biogenic VOC emissions within the region under typhoon influence. In contrast, more pronounced and site-dependent responses occurred in summer, reflecting typhoon-related changes in the regional wind field. As the prevailing wind shifted from southerly to northerly, the regional site in the northeastern PRD (Xijiao) became upwind, reducing the influence of transported anthropogenic VOCs and their oxidation products. Consequently, the contributions of alkanes and OVOCs decreased, whereas that of biogenic VOCs increased. In contrast, slightly higher OVOC contributions and lower biogenic VOC contributions can be found at the urban and suburban sites in the central and southern PRD (Daxuecheng and Heshan).

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Overall, OVOCs remained the dominant VOC group contributing to k_{OH} under all scenarios, highlighting their important role in sustaining O_3 photochemistry in this downwind region. Although typhoons modified the relative contributions of individual VOC groups through changes in biogenic emissions and transport patterns, the overall contribution pattern remained largely unchanged, with OVOCs consistently dominating the VOC contribution to OH reactivity. To further identify the key species responsible for the simulated VOC group contributions, we also extended the analyses to 16 individual VOC species or sub-categories at the three sites, with the detailed results presented in Figs. S7–S10 and Text S1 of the Supplementary Information.

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3.3.3 Changes in O₃ sensitivity to precursors

O₃ sensitivity to its precursors is another key chemical characteristic of O₃ production and provides useful information for developing effective emission control strategies. The relative incremental reactivity (RIR; Cardelino and Chameides, 1995) quantifies the response of simulated P(O₃) to changes in precursor emissions. By comparing the RIR values of NO_x and VOCs, the O₃ sensitivity regime can be diagnosed as NO_x-limited or VOC-limited when one RIR is substantially higher than the other, and transitional when their values are comparable. Here, the simulated RIR values under typhoon-induced and no-typhoon conditions are compared to assess how typhoons modify O₃ sensitivity to its precursors.

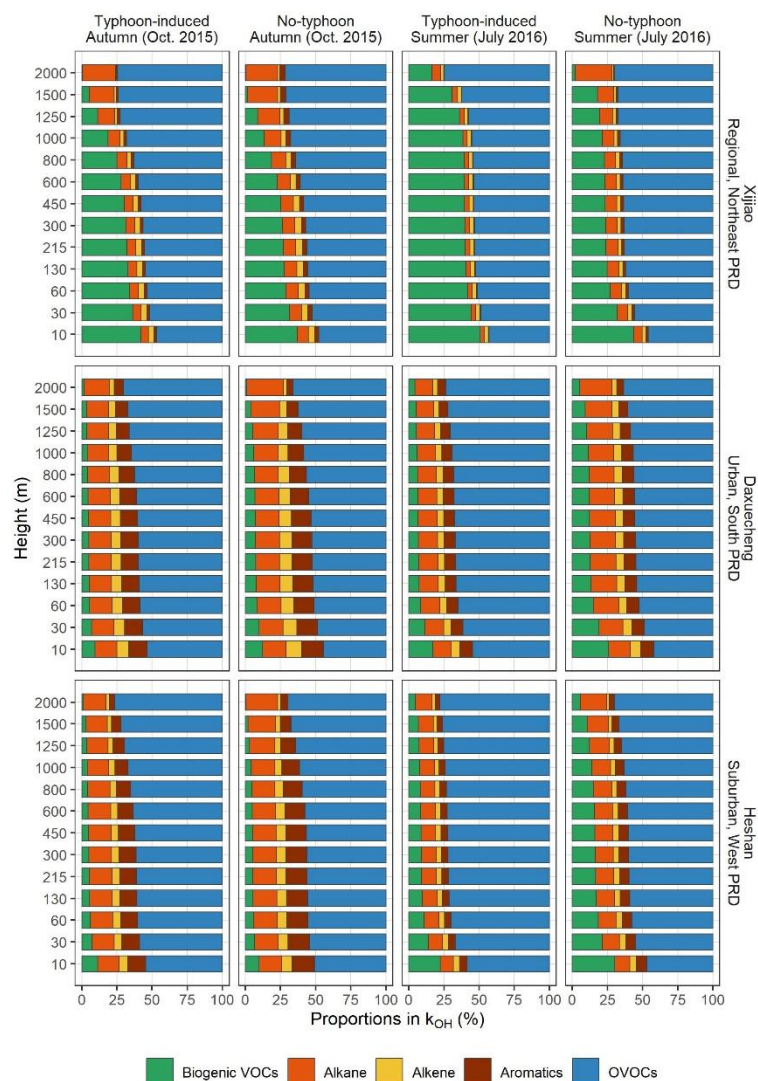


Figure 8. Proportional contributions of VOC groups to daytime-mean (9:00–17:00 LT) kOH (or OH+VOCs reaction rates) at the Xijiao, Daxuecheng and Heshan sites, shown for multiple heights on the typhoon-induced and no-typhoon O₃ pollution days of two seasons.



Before further analysis, the CMAQ-derived RIR values were compared with those quantified using observation-based models (OBM) at five representative sites with VOC measurements during the same period (Jiang, 2018; locations shown in Fig. S4). The same RIR calculation framework was applied in both analyses. Although the OBM- and CMAQ-based RIRs were derived using 20% and 25% emission reductions, respectively, both perturbations fall within a moderate range and are not expected to substantially influence the diagnosed O₃ sensitivity regimes. As shown in Fig. S11, the pollution-day mean RIR values from the two approaches are generally consistent. Both methods indicate VOC-limited regimes at the two urban sites (Modiesha and Daxuecheng) and transitional regimes at the other sites, suggesting no evident systematic biases in the simulated O₃ sensitivity patterns. The main discrepancy is that CMAQ tends to predict higher RIR(NO_x) in summer, which is likely related to differences in spatial representation and NO_x perturbation treatment between the two approaches (Xu et al., 2022). In OBM, NO_x perturbations are constrained by local concentration measurements and mainly represent local-scale emission changes. In contrast, CMAQ accounts for the combined influence of NO_x emissions across broader areas, allowing regional transport and chemistry to influence the perturbation response. As a result, CMAQ generally predicts larger changes in P(O₃) following NO_x emission reductions, leading to higher RIR(NO_x) values.

The RIR(NO_x) and RIR(VOCs) at three representative sites, Daxuecheng (urban), Heshan (suburban) and Xijiao (regional), and at various altitudes are shown in Fig. 9. In general, RIR(NO_x) increased with altitude, whereas RIR(VOCs) decreased, indicating a transition toward more NO_x-limited regimes aloft. O₃ production was generally NO_x-limited at the regional site (Xijiao) and VOC-limited at the urban site (Daxuecheng), while the regime at the suburban site (Heshan) varied among scenarios. In addition, RIR(NO_x) was generally higher in summer than in autumn, suggesting a stronger constraint of NO_x availability on O₃ production in summer. These spatial and seasonal variations in O₃ sensitivity are consistent with the current understanding of O₃ chemistry (Lu et al., 2019b).

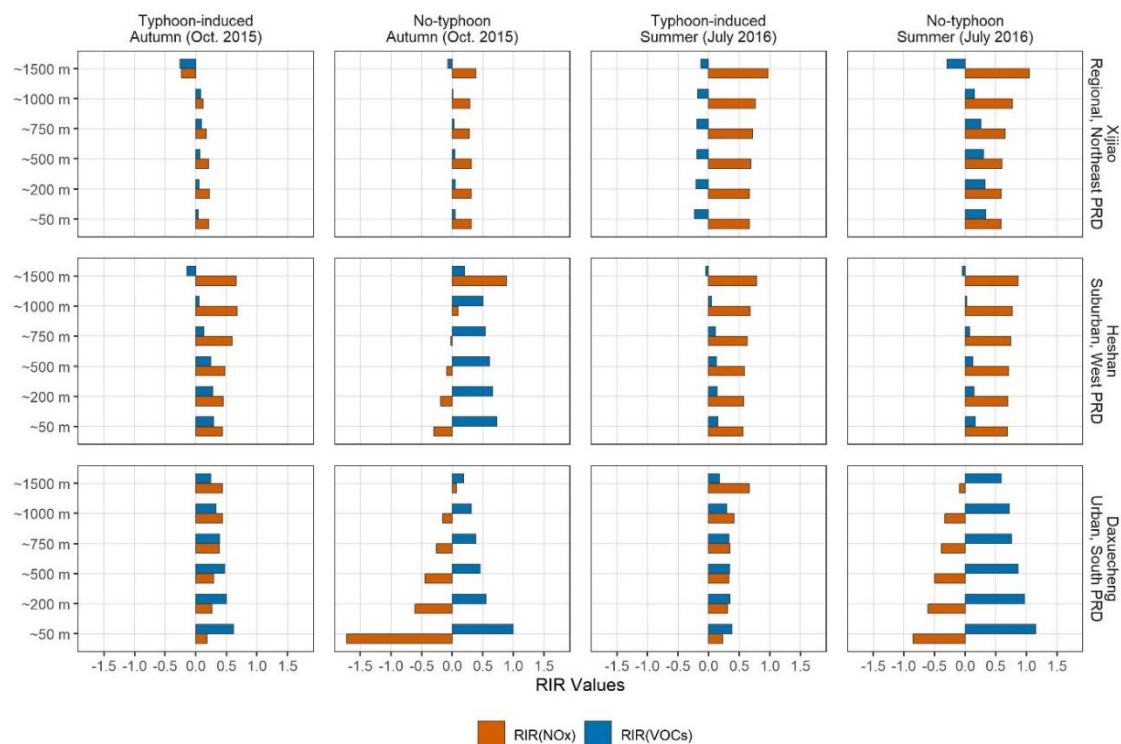


Figure 9. Daytime-mean (9:00–17:00 LT) RIR(NO_x) and RIR(VOCs) values at the Xijiao, Daxuecheng and Heshan sites, shown for multiple heights on the typhoon-induced and no-typhoon O₃ pollution days of two seasons.

Typhoon influences on O₃ sensitivity differed between autumn and summer, reflecting their distinct impacts on regional transport patterns (Fig. S12). In autumn, typhoons generally shifted O₃ production toward a more NO_x-limited regime. While the regional site (Xijiao) remained NO_x-limited, the downwind suburban and urban sites (Heshan and Daxuecheng) exhibited increased RIR(NO_x) and reduced RIR(VOCs) under typhoon influence. In particular, the transition of RIR(NO_x) from negative to positive values in the lower layers indicates weakened O₃ titration, consistent with more effective precursor mixing under enhanced transport. In contrast, summer responses were more spatially heterogeneous because typhoons reversed the prevailing wind direction from southerly to northerly. Consequently, the regional site (Xijiao) became more NO_x-limited owing to the reduced influence of NO_x-rich urban plumes from the southern PRD, whereas the urban site (Daxuecheng) became less VOC-limited along with enhanced precursor transport within the region. The suburban site (Heshan) showed comparatively smaller changes in O₃ sensitivity. Overall, typhoons tended to shift O₃ production in the PRD toward a more NO_x-limited and less VOC-limited regime, although the underlying mechanisms differed between seasons: the change in autumn was mainly associated with enhanced precursor mixing, while that in summer was more strongly influenced by the redistribution of precursor transport following wind reversal.



4 Conclusions and applications

Although the important role of typhoons in O₃ pollution over the coastal regions of the Northwest Pacific has been widely recognized, the specific responses of O₃ transport and photochemistry to typhoon influence remain insufficiently understood. In this study, we conducted systematic process-oriented analyses based on WRF-CMAQ simulations to characterize typhoon-induced changes in O₃ transport pathways, transported precursor contributions and local photochemical processes in the PRD, South China, with the main findings summarized as follows (also in Table S6):

- **Typhoons enhance O₃ transport through both vertical and horizontal pathways.** Vertical exchange remained the dominant transport pathway, with morning O₃ import associated with boundary-layer height changes increasing by over 50% in autumn and ~37% in summer. Horizontal transport was also enhanced in both seasons, accompanied by a shift from southerly to northerly transport in summer. The enhanced transport was associated with increased O₃ contributions from upwind regional emissions in both seasons and background sources mainly in autumn. These findings indicate that typhoons enhance both O₃ transport pathways accompanied by changes in regional wind fields and O₃ source contributions, rather than simply through stronger winds.
- **Typhoons enhance the contributions of transported O₃ precursors, further strengthening the influence of cross-regional transport on local O₃ pollution.** Transported precursors contributed 20.3 and 11.5 µg m⁻³ of O₃ in autumn and summer, respectively, equivalent to ~30% of direct O₃ transport contributions in both seasons. Among the precursor groups, APNs and NO_x dominated in autumn and summer, respectively. Typhoons further enhanced the overall contributions of transported precursors in both seasons, with a slight increase in autumn and a nearly twofold increase in summer, primarily driven by increased contributions from NO_x and APNs. These findings highlight the considerable contribution of precursor transport to local O₃ production and pollution in the PRD, as well as its enhanced influence under typhoon conditions.
- **Typhoons modify different aspects of local photochemistry, with distinct responses in O₃ production rates, chemical efficiencies, VOC contributions to OH reactivity and precursor sensitivity.** Under typhoon influence, O₃ production rates increased in autumn but decreased in summer, consistent with the contrasting seasonal changes in local O₃ production conditions and net chemical contributions reported in Part I. Meanwhile, HO_x cycling efficiency decreased while O₃ production efficiency increased in both seasons, potentially reflecting the enhanced influence of aged air masses. Typhoons also modified the contributions of individual VOC groups to OH reactivity through changes in biogenic emissions and transport patterns, although OVOCs remained the dominant VOC contributors under all conditions. In addition, O₃ production generally shifted toward a more NO_x-limited regime in both seasons, associated with changes in precursor mixing and transport within the region. These findings suggest that typhoon-induced changes in O₃ chemistry reflect not only changes in local O₃ production conditions, but also the influences of enhanced transport, changing wind patterns and emissions on the photochemical environment.



In Part I (Qu et al., 2021), meteorological analyses and quantification of net process contributions identified enhanced O₃ transport as the dominant contributor to typhoon-induced O₃ pollution in the PRD, South China, in both autumn and summer. Meanwhile, local O₃ production and accumulation exhibited contrasting responses to typhoons: O₃ production was enhanced in autumn but weakened in summer, whereas O₃ accumulation showed the opposite pattern. These findings provided an overall understanding of typhoon-induced O₃ pollution mechanisms, but the specific transport and chemical processes underlying these net contributions remained less well characterized. This limitation also applies more broadly to many previous studies. The present study further develops the “weather-process-pollution” analysis by resolving changes in individual transport pathways, transported precursor contributions and photochemical characteristics. We show that enhanced O₃ transport involves both horizontal and vertical pathways, accompanied by considerable and increasing contributions from transported precursors to O₃ pollution. For local photochemistry, typhoon-related changes in O₃ production rates are consistent with the responses of net chemical contributions identified in Part I, while further diagnostics reveal distinct changes in chemical efficiencies, VOC contributions to OH reactivity and precursor sensitivity, reflecting the influences of enhanced transport, changing wind patterns and emissions. Together, these findings strengthen the mechanistic explanation of how typhoon-related meteorological changes affect O₃ transport and chemistry and ultimately lead to regional O₃ pollution.

Beyond typhoons, extreme weather conditions such as heat waves and stagnation can also modify atmospheric transport, precursor emissions and distributions, and local photochemical environments, leading to complex O₃ pollution responses. The findings of this study highlight that resolving specific atmospheric processes and their connections is essential for understanding how extreme weather affects O₃ pollution, as meteorological changes and overall process contributions alone may not fully explain the underlying mechanisms. Applying such process-oriented analyses to different weather systems and regions could help identify both commonalities and differences in atmospheric process responses and pollution mechanisms under varying transport, accumulation and production conditions. A clearer understanding of these process responses could also provide a stronger scientific basis for assessing O₃ pollution risks and supporting local and regional air quality management strategies under extreme weather conditions.

Several limitations should nevertheless be acknowledged. Although available observations and observation-based analyses were used to evaluate key simulated characteristics, additional evidence from more comprehensive datasets is required to better constrain O₃ transport and chemistry. In particular, vertically resolved measurements of meteorological variables, O₃ and key precursors, such as APNs and OVOCs, would be valuable for further evaluation. In addition, potential changes in dry deposition under typhoon influence were not explicitly investigated, and further studies considering dynamic land-surface and deposition processes could help clarify their contributions to typhoon-induced O₃ pollution. Finally, this study focused primarily on O₃-related processes within the PRD, while the chemical evolution of O₃ and its precursors in upwind regions and during transport remains less well characterized. Future studies integrating comprehensive observations with process-oriented modeling over broader regions could help address these uncertainties. Despite these limitations, our findings reveal



that typhoons affect regional O₃ pollution through complex changes in multiple transport pathways, transported precursor contributions and local photochemical characteristics, providing further process-level evidence for understanding the mechanisms underlying typhoon-induced O₃ pollution.

Data availability. The main datasets and codes used for this study are as follows:

- The China Meteorological Administration best-track typhoon dataset (Ying et al., 2014);
- WRF meteorological model, version 3.2 (<https://doi.org/10.5065/D68S4MVH>, last access: 13 July 2023; Skamarock et al., 2008);
- CMAQ chemical transport model, version 5.0.2 (<https://doi.org/10.5281/zenodo.1079898>, last access: 13 July 2023; US EPA Office of Research and Development, 2014);
- Chemical initial and boundary conditions for CMAQ simulations – derived from MOZART-4 simulations (<https://www.acom.ucar.edu/wrf-chem/mozart.shtml>, last access: 4 December 2019);
- MEIC emission inventory for mainland China, version 1.3 (http://meicmodel.org/?page_id=560, last access: 10 August 2021; Li et al., 2017a, Zheng et al., 2018);
- MIX emission inventory for Asia, version 1.1 (http://meicmodel.org.cn/?page_id=87&lang=en, last access: 31 March 2019; Li et al., 2017b);
- East Asian shipping emissions (http://meicmodel.org.cn/?page_id=1916&lang=en, last access: 19 April 2019; Liu et al., 2016);
- FINN biomass burning emission inventory, version 1.5 (<https://www.acom.ucar.edu/Data/fire/>, last access: 25 June 2019; Wiedinmyer et al., 2011);
- MEGAN model to quantify biogenic emissions (<https://bai.ess.uci.edu/megan/data-and-code>, last access: 3 May 2017; Guenther et al., 2012);
- Regional O₃ mass budget calculation tool (<https://doi.org/10.5281/zenodo.6259253>; Qu et al., 2022, 2023).

Other observational data within the Pearl River Delta are available from the corresponding author upon request.

Author contributions. KQ, XW and YZ designed the study. KQ, XW, YY and TX conducted the simulations using the WRF/CMAQ model. JS, LZ and YZ provided observational results for model validation. XW, YY, XJ, XC and YZ provided support for the quantification of regional O₃ mass budget. MJ, ZT, XM, KL and YZ provided the results of observation-based RIR values. MV, MK, JD, GB and ND supported the quantifications of chemical indicators based on simulation results. KQ, XW, YY and YZ did the other analyses. KQ, XW, MV, MK, GB, ND and YZ wrote and/or revised this paper, with critical feedbacks from all the other co-authors.

Competing interests. At least one of the (co-)authors is a member of the editorial board of Atmospheric Chemistry and Physics. The authors declare no other conflict of interest.



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