A Comparative Study to Reveal the Influence of Typhoons on the Transport, Production and Accumulation of O₃ in the Pearl River Delta, China

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Abstract. The Pearl River Delta (PRD) region in South China is faced with severe ambient O₃ pollution in autumn and summer, which mostly coincides with the occurrence of typhoons above the Northwest Pacific. With increasingly severe O₃ pollution in the PRD under the influence of typhoons, it is necessary to gain a comprehensive understanding of the impact of typhoons on O₃ transport, production and accumulation for efficient O₃ reduction. In this study, we analysed the general influence of typhoons on O₃ pollution in the PRD via systematic comparisons of meteorological conditions, O₃ processes and sources on O₃ pollution days with and without typhoon occurrence (denoted as the typhoon-induced and no-typhoon scenarios, respectively), and also examined the differences in these influences in autumn and summer. The results show that the approach of typhoons was accompanied by higher wind speeds and strengthened downdrafts in autumn as well as the inflows of more polluted air masses in summer, suggesting favourable O₃ transport conditions in the typhoon-induced scenario in both seasons. However, the effect of typhoons on the production and accumulation of O₃ were distinct. Typhoons led to reduced cloud cover, and thus stronger solar radiation in autumn, which accelerated O₃ production, but the shorter residence time of local air masses was unfavourable for the accumulation of O₃ within the PRD. In contrast, in summer, typhoons increased cloud cover, and weakened solar radiation, thus restraining O₃ formation, but the growing residence time of local air masses favoured O₃ accumulation. The modelling results using the Community Multiscale Air Quality (CMAQ) model for the typical O₃ pollution days suggest increasing contributions from the transport processes as well as sources outside the PRD for O₃ pollution, confirming enhanced O₃ transport under typhoon influence in both seasons. The results of the process analysis in CMAQ suggest that the chemical process contributed more in autumn but less in summer in the PRD. Since O₃ production and accumulation cannot be enhanced at the same time, the proportion of O₃ contributed by emissions within the PRD was likely to decrease in both seasons. The difference in the typhoon influence on O₃ processes in autumn and summer can be attributed to the seasonal variation of the East Asian monsoon. From the “meteorology-process-source” perspective, this study revealed...
the complex influence of typhoons on O₃ pollution in the PRD and their seasonal differences. To alleviate O₃ pollution under typhoon influence, emission control is needed on a larger scale, rather than only within the PRD.

1 Introduction

Tropospheric ozone (O₃) serves as a secondary pollutant in ambient air and is detrimental for human health and crop production (Wang et al., 2017; Liu et al., 2018; Mills et al., 2018). Ambient O₃ is produced from its precursors, i.e., nitrogen oxides (NOₓ = NO + NO₂) and volatile organic compounds (VOCs), through chemical reactions in the presence of sunlight. This O₃ can accumulate locally, or be transported to downwind regions. Due to the relatively long lifetime of O₃ (~22 days; Stevenson et al., 2006), it can accumulate locally, or be transported to downwind regions. Under unfavourable meteorological conditions, enhanced transport, production and/or accumulation of O₃ can all contribute to the O₃ pollution within a region (National Research Council, 1991).

As the largest city cluster in South China, the Pearl River Delta (PRD) region is faced with frequent ambient O₃ pollution, especially in autumn and summer (Li et al., 2014; Wang et al, 2017; Lu et al, 2018). Along with the continuous increasing of O₃ levels in recent years (Li et al., 2019), O₃ has become the primary contributor to the deterioration of air quality in this region (Feng et al., 2019). The occurrence of O₃ pollution in the PRD is predominantly related to the influence of typhoons (or tropical cyclones) above the Northwest Pacific (Gao et al., 2018; Deng et al., 2019; Lin et al., 2019). According to Gao et al. (2018), seven out of the nine most severe O₃ episodes (regional-mean maximum 8-h average O₃ concentrations > 240 μg/m³) during 2014–2016 coincided with the approach of typhoons. The changes in the track and intensity of typhoons may contribute to the growing trend of O₃ levels recently and in future (Lam, 2018; Lam et al., 2018). Therefore, a comprehensive understanding of the influence of typhoons on the transport, production and accumulation of O₃ has important implications for efficient and strategic O₃ reduction in the PRD.

Analyses of typhoon-related O₃ episodes in the PRD have been extensively reported in previous publications. The effect of typhoons on O₃ pollution is closely linked to meteorological conditions that are conducive to the transport, production and/or accumulation of O₃. Stagnation caused by typhoons, characterised by low wind speeds, has been reported during many episodes, and it promotes the accumulation of locally formed O₃ within the PRD (Wang et al., 1998; So and Wang, 2003; Wang and Kwok, 2003; Huang et al., 2005; Lam et al., 2005; Jiang et al., 2008; Zhang et al., 2014; Chow et al., 2019). Strong north or west winds were observed or simulated during several episodes, suggesting the potentially strengthened transport of pollutants under typhoon influence (Wang et al., 2001; Yang et al., 2012; Wang et al., 2015; Wei et al., 2016). Downdrafts on the outskirts of typhoons may promote downward O₃ transport and contribute to near-ground O₃ pollution as well (Lam, 2018), but its appearance in the PRD has only been examined in a few studies. Cloudless conditions and strong solar radiation enhance O₃ production, which is another important cause of O₃ pollution (Wang et al., 1998; Wang and
In a more direct way, several studies have utilised chemical transport models, along with the Process Analysis (PA) tool and source apportionment (SA) methods, to quantify and compare the contributions of various O₃ processes (e.g., transport and the chemical process) and sources (e.g., local emissions, outside emissions and background) during these episodes. Based on reports by Huang et al. (2005), Lam et al. (2005), Jiang et al. (2008), Wang et al. (2010), Li (2013), Wang et al. (2015), Wei et al. (2016) and Chen et al. (2018), horizontal/vertical transport and chemical production may both be the main contributing process for typhoon-induced O₃ pollution in different parts of the PRD. The SA results revealed that emissions within the PRD contributed 40–80% of O₃ during typhoon-related O₃ episodes (Li et al., 2012; Li, 2013; Chen et al., 2015), suggesting the potentially important role of O₃ accumulation for O₃ pollution here. However, despite massive episode-based studies, several important questions still remain: Are O₃ transport, production and accumulation within the PRD all enhanced at the same time by typhoons? Do both O₃ pollution seasons (autumn and summer) experience similar impact of typhoons on O₃ pollution? More thorough investigations are needed to answer these questions.

In this study, we present systematic comparisons between O₃ pollution in the typhoon-induced and no-typhoon scenarios (definitions given in Sect. 2.2) to elucidate the influence of typhoons on O₃ transport, production and accumulation in the PRD and to reveal their seasonal differences. October and July in 2014–2018 were selected as the representative months for autumn and summer, respectively. Multiple datasets, including the ERA-Interim re-analysis, the routine monitoring datasets, trajectories calculated by the Hysplit model and the modelling results of typical O₃ pollution days using the Community Multiscale Air Quality (CMAQ) model, were used in the comparisons. A detailed introduction of these datasets is presented in Sect. 2. The comparisons were conducted from the perspectives of meteorological conditions (Sect. 3), O₃ processes and sources (Sect. 4), and the conclusions about the influence of typhoons on the causes of ambient O₃ pollution in the PRD in the two seasons are illustrated in Sect. 5.

### 2 Methods

#### 2.1 Datasets

The detailed information for the datasets utilised in the comparison of meteorological conditions is presented below:

- **Re-analysis datasets**: We mainly used the ERA-Interim re-analysis product in the analyses due to its more available parameters and high spatial coverage (available at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim, last accessed: March 2020; Dee et al., 2011; Berrisford et al., 2011). Specifically, meteorological parameters used in the comparisons include the following three categories: (1) near-surface parameters from the analysis fields, including air temperature (at a height of 2 m), relative humidity (RH, at 1000 hPa), horizontal wind speeds (at a height of 10 m; zonal and meridional wind speeds were also involved in the comparisons), and low (for the height at which pressure/surface pressure > 0.8), medium (for the height at which 0.45 < pressure/surface pressure < 0.8), high (for the...
height at which pressure/surface pressure < 0.45) and total cloud covers; (2) near-surface parameters from the forecast fields, including plenary boundary layer (PBL) height and net surface solar radiation; and (3) upper air parameters at multiple heights, including horizontal and vertical wind speeds, cloud water content and O₃ mixing ratio. The focus of this study is O₃ pollution during the daytime, and therefore, only the parameters at 14:00 local time (LT) were selected for the analyses (except for net surface solar radiation, which was averaged within 8:00–17:00 LT).

- **Surface meteorological routine monitoring datasets**: The routine monitoring meteorological data collected at 29 national meteorological sites within the PRD (locations shown in Fig. S1a) were also used to explore the meteorological features under the impact of typhoons. The parameters include air temperature, RH, and wind speed and direction (also transformed to zonal and meridional wind speeds in the comparisons) at 14:00 LT.

- **Typhoon information**: The times, locations and intensities of typhoons were provided by the Chinese Meteorological Administration Best Track Dataset of tropical cyclones (Ying et al., 2014). The tracks of all typhoons that potentially contributed to O₃ pollution in the PRD during the study period (October and July in 2014–2018) are shown in Fig. S2 and S3.

- **O₃ concentrations**: Hourly O₃ concentration data, which were originally released by the China National Environmental Monitoring Centre, were downloaded from http://beijingair.sinaapp.com (last accessed: Dec. 2018). Based on the hourly data, we calculated the maximum 1-hr concentrations (MDA1) and maximum 8-hr average concentrations (MDA8) of O₃ in nine municipalities in the PRD (including Guangzhou, Shenzhen, Zhuhai, Foshan, Jiangmen, Zhaoqing, Huizhou, Dongguan and Zhongshan) to identify O₃ pollution days that served as samples in the comparisons.

**2.2 Definition and classification of O₃ pollution days**

In this study, O₃ pollution days were defined as the days when the MDA1 exceeds 200 μg/m³ or the MDA8 exceeds 160 μg/m³ for O₃ (both are the Grade-II thresholds of the Chinese National Ambient Air Quality Standard (NAAQS), GB 3095-2012) in any of the nine municipalities in the PRD. According to these criteria, there were 78 and 55 O₃ pollution days (given in Table S1 and S2) during October and July in 2014–2018, respectively. The information about these O₃ pollution days in the two representative months is listed in Table 1 (overall) and S3 (monthly), including the numbers of days, their proportions in the month, and the corresponding mean O₃ concentrations (MDA8 and MDA1, highest values among nine municipalities in the PRD). Although there were more O₃ pollution days in October than in July, O₃ pollution days under typhoon influence accounted for ~30% of all days in both months. O₃ pollution under typhoon influence occurred on ~30% days of both months. Higher O₃ MDA1 and MDA8 values can be generally found with the appearance of typhoons in comparison with days without typhoons in July, whereas these values are similar in October, further indicating the important role of typhoons in O₃ pollution in the PRD.

The differing locations of typhoons can result in the diverse effect of typhoons on O₃ pollution (Chow et al., 2018). To determine the general influence of typhoons on O₃ pollution in the PRD, it was necessary to further select O₃ pollution days
coinciding with typhoons with similar directions and distances from the PRD. First, we removed five O$_3$ pollution days in July with typhoons located to the due north or southwest of the PRD from the analyses. As is shown in Fig. 1, the remaining days, including all O$_3$ pollution days in October and most O$_3$ pollution days in July under typhoon influence, were associated with typhoons to the east of the PRD, which were more likely to cause O$_3$ pollution (Chow et al., 2018). In order to minimize the disturbance of typhoon directions in the comparisons, we removed the remaining five O$_3$ pollution days in July with typhoons located to the due north or southwest of the PRD from the analyses. After this, based on the distances between typhoon centres and the PRD (at 14:00 LT), we classified the pollution days with typhoons in each season into three categories: close typhoon (lowest 20% of distances), typhoon (20–80% intervals of distances), and far typhoon (longest 20% of distances)-induced days. The typhoon-induced days represent O$_3$ pollution days with general typhoon influence, and they were compared with those without the appearance of typhoons (hereafter denoted as the no-typhoon days). It should be noted that the distances between typhoon centres and the PRD on the typhoon-induced days were overall larger in autumn (1400–2800 km, at 14:00 LT) than in summer (700–2000 km, at 14:00 LT), which may be the consequence of the different characteristics of typhoon paths in the two seasons: most typhoons in autumn travel northwest initially and then turn northward in the areas east of the Philippines (Fig. S2), whereas they are more likely to end up landing in Southeast China in summer (Fig. S3). Since the influence of typhoons on O$_3$ pollution may be different when typhoons come close enough to the PRD (Lam et al., 2005; Li, 2013), the close typhoon-induced days were considered to be a special scenario in the comparisons of meteorological conditions (Sect. 3.5). Owing to the less apparent effect of typhoons over the PRD, we did not include the far typhoon-induced days in the discussions.

Table 1. The numbers and proportions of O$_3$ pollution days, and O$_3$ concentrations for various scenarios.

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<tr>
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<tbody>
<tr>
<td>Number (proportion) of O$_3$ pollution days</td>
<td>78 (50.3%)</td>
<td>55 (35.5%)</td>
</tr>
<tr>
<td>With typhoons</td>
<td>49 (31.6%)</td>
<td>45 (29.0%)</td>
</tr>
<tr>
<td>Typhoon-induced days</td>
<td>30 (19.4%)</td>
<td>24 (15.5%)</td>
</tr>
<tr>
<td>Close typhoon-induced days</td>
<td>10 (6.5%)</td>
<td>8 (5.2%)</td>
</tr>
<tr>
<td>Without typhoons (no-typhoon days)</td>
<td>29 (18.7%)</td>
<td>10 (6.5%)</td>
</tr>
<tr>
<td>Mean PRD-max O$_3$ MDA8 (µg/m$^3$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>With typhoons</td>
<td>195.0</td>
<td>205.3</td>
</tr>
<tr>
<td>Typhoon-induced days</td>
<td>199.5</td>
<td>205.4</td>
</tr>
<tr>
<td>Close typhoon-induced days</td>
<td>184.6</td>
<td>225.7</td>
</tr>
<tr>
<td>Without typhoons (no-typhoon days)</td>
<td>189.8</td>
<td>187.8</td>
</tr>
<tr>
<td>Mean PRD-max O$_3$ MDA1 (µg/m$^3$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>With typhoons</td>
<td>230.4</td>
<td>259.8</td>
</tr>
<tr>
<td>Typhoon-induced days</td>
<td>235.2</td>
<td>260.0</td>
</tr>
<tr>
<td>Close typhoon-induced days</td>
<td>219.2</td>
<td>277.1</td>
</tr>
<tr>
<td>Without typhoons (no-typhoon days)</td>
<td>231.5</td>
<td>246.5</td>
</tr>
</tbody>
</table>
Figure 1. The location and intensity of typhoons at 14:00 LT on all O$_3$ pollution days with typhoons, and the corresponding O$_3$ MDA8 concentrations (maximum values in the nine municipalities of the PRD) on the same days during (a) October and (b) July in 2014–2018. The points with cyan borders indicate the “typhoon-induced” O$_3$ pollution days used in the comparisons. The grades of tropical cyclones (Chinese National Standard, GB/T 19201-2006) are as follows: SuperTY - super typhoon; STY - severe typhoon; TY - typhoon; STS - severe tropical storm; TS - tropical storm; TD - tropical depression; others are grouped as “not classified”.

2.3 Calculation of the trajectories and air parcel residence time

To explore the potential effect of cross-regional transport on O$_3$ pollution in the PRD, we applied the Hysplit model (Stein et al., 2015) with the Global Data Assimilation System (GDAS) datasets as inputs to calculate 72-h backward trajectories reaching the PRD at 14:00 LT for all O$_3$ pollution days. The Modiesha site (23.1°N, 113.3°E; Fig. S1b), which is located in the central part of the PRD, was the endpoint of backward trajectories, with its height set as 500 m above the ground. Its height was set as 500 m above the ground to better represent the effect of long-range transport on O$_3$ pollution, as well as to minimize the disturbance of objects near the surface to the transport (Park et al., 2007).

Air parcel residence time (APRT), discussed by Huang et al. (2019), is the average number of hours that air parcels originated from one place stay within a pre-defined domain, and long APRTs can be used to indicate good accumulation conditions for
locally sourced pollutants. To calculate APRTs in the PRD, we designed a 21×15 point matrix (resolution: 0.2°×0.2°) that embraces the whole PRD (Fig. S4), and forward trajectories starting from these points were also calculated using the Hysplit model. The height of all points was set as 100 m above the ground, which is close to the height of emissions to represent the height of all local emissions and to reduce the disturbance of the surface, as well. The start times were set as 2:00, 8:00, 14:00 and 20:00 LT for all O₃ pollution days. Afterwards, the length of time each trajectory remained within the administration borders of the PRD, i.e., APRT, was calculated and attributed to its starting point. The APRT values of all points were averaged for each scenario and were interpolated to obtain field results. APRTs in each point were averaged, and these averaged APRT values in all points were interpolated using the Kriging method to obtain field results for the further comparisons.

2.4 CMAQ modelling: basic setups and modelling methods

We utilised the widely used 3D chemical transport model—the CMAQ model (version 5.0.2)—to investigate the effects of typhoons on O₃ processes and sources. October 2015 and July 2016 featured the most severe O₃ pollution under typhoon influence among all representative months of the two seasons (Table S3), and thus, they were chosen as the period in the CMAQ-modelling (because there was no severe O₃ pollution during the first 10 days of October 2015 and 3–5 November can be classified as the no-typhoon O₃ pollution days, we adjusted the modelling period in autumn to 11 October–10 November 2015) and all typhoon-induced and no-typhoon O₃ pollution days in these two months served as representative O₃ pollution days under multiple scenarios in the comparisons. In detail, there were four typhoon-induced O₃ pollution days (14–16 and 21 October 2015) and four no-typhoon O₃ pollution days (28 October and 3–5 November 2015) in October 2015, whereas there were four and six typhoon-induced and no-typhoon days in July 2016, respectively (typhoon-induced: 7–8 and 30–31 July 2016; and no-typhoon: 22–26 and 29 July 2016). The results of the daytime (9:00–17:00 LT) O₃ PA and SA on the above O₃ pollution days were averaged for each the typhoon-induced and no-typhoon scenarios in autumn (October 2015) and summer (July 2016) and were used in the comparisons.

The main setups of the CMAQ modelling are presented as follows. Two-nested modelling domains with the resolutions of 36 and 12 km (denoted as d01 and d02, respectively) were set in this study (Fig. 2). Specifically, d02 covers the whole East and Central China (EC-China), enabling us to evaluate the contribution of emissions in these areas to O₃ pollution in the PRD. There were 19 vertical layers in the CMAQ modelling, with about 10 layers within the PBL (about 0–1 km in heights; Guo et al., 2016). The Weather Research and Forecasting (WRF) model (version 3.2) provided the meteorological fields used as inputs. SMOKE (version 2.5) and MEGAN (version 2.10) were used to process the anthropogenic and biogenic emission files, respectively. The anthropogenic emission inventory used in this study consisted of the following three parts: (1) emissions in the PRD, which were provided by the Guangdong Environmental Monitoring Centre; (2) emissions in other areas of mainland China, which were extracted from the MEIC inventory (He, 2012); and (3) emissions in other countries and regions in Asia, which were extracted from the MIX inventory (Li et al., 2017). The initial and boundary conditions of the d01 modelling were obtained from the same-period results of the MOZART-4 global model (available at https://www.aoml.noaa.gov/wrf-
The SAPRC07 gas-phase chemistry mechanism (Carter, 2010) and the AERO6 aerosol scheme were set in the CMAQ modelling. In addition, the simulations of the two months were both started 10 days ahead to minimise the disturbance of the bias of the initial conditions. The modelling performances of CMAQ and WRF were determined to be acceptable based on the comparisons between the observational and modelling series of meteorological parameters, O$_3$ MDA8, daily NO$_2$ concentrations and the mixing ratios of non-methane hydrocarbons (NMHCs) in the PRD (for details, refer to Sect. 1 of in the Supplement Information), which ensures the validity of the further analyses.

![Figure 2](image_url)  **Figure 2.** Two-nested modelling domain, noted as d01 and d02. The black boxes indicate the WRF modelling domains, and the nested areas are the CMAQ modelling domains.

The PA tool in CMAQ was implemented to quantify the hourly contributions of O$_3$ processes (or integrated process rate, IPR), which includes vertical/horizontal transport (convection+diffusion), chemical process (net O$_3$ production through gas-phase reactions), dry deposition and cloud process. To explore the overall effect of typhoons on O$_3$ transport and production in the region, the mean PA results within the administration boundaries of the PRD were calculated and compared.

In order to identify the sources of all O$_3$ in the PRD, we used the classic Brute Force Method (BFM) to identify the contributions of emissions (including anthropogenic and biogenic emissions) in the PRD and other regions in the d02 (mainly EC-China), as well as regions outside the d02 (the boundary conditions of the d02) for O$_3$ pollution in the PRD (hereafter denoted as the contributions of PRD, EC-China and BCON, or $S_{PRD}$, $S_{EC-China}$ and $S_{BCON}$, respectively). For a pollutant, the contribution of a specific emission, E$_i$, can be calculated in two ways: (1) the difference between the modelled concentrations of the base case (all emissions involved) and the sensitivity case where E$_i$ is zeroed out (i.e., top-down BFM); (2) the difference between two sensitivity cases where emissions expect E$_i$ and all of the emissions are zeroed out, respectively (i.e., bottom-up BFM). Owing to the non-linearity between O$_3$ and its precursors, biases may occur between the results of two types of BFM methods, leading to the non-additivity of the results (Clappier et al., 2017). Therefore, the average of the top-down and bottom-
up BFM results was treated as the quantified contributions of the concerned sources. Four simulation cases were run in this study, including (the modelled O₃ concentration in each case was also marked in brackets):

- the base case ($C_{base}$);
- the PRD-cut case ($C_{PRD\_cut}$), where emissions within the PRD were zeroed out;
- the PRD-only case ($C_{PRD\_only}$), where emissions outside the PRD (within d02) were zeroed out; and
- the zero-emission case ($C_0$), where all emissions within the d02 were zeroed out.

Afterwards, the $S_{PRD}$, $S_{EC\_China}$ and $S_{BCON}$ values (in concentrations) in the polluted areas of the PRD (where modelled daytime O₃ concentrations > 160 µg/m³, the Grade-II O₃ MDA8 thresholds of the Chinese NAAQS) were calculated using the following equations,

$$S_{PRD} = \frac{1}{2} \left[ (C_{base} - C_{PRD\_cut}) + (C_{PRD\_only} - C_0) \right],$$  \hspace{1cm} (R1)

$$S_{EC\_China} = \frac{1}{2} \left[ (C_{base} - C_{PRD\_only}) + (C_{PRD\_cut} - C_0) \right],$$  \hspace{1cm} (R2)

$$S_{BCON} = C_0.$$  \hspace{1cm} (R3)

The percentage forms of these values were used in the comparisons.

3 Comparison of meteorological conditions

3.1 Overview: comparison of meteorological parameters in the PRD

First, we compared near-ground meteorological parameters in the PRD on the typhoon-induced and no-typhoon O₃ pollution days. The parameters from the ERA-Interim re-analysis (including the parameters of the first and second categories in Sect. 2.1) and the routine monitoring datasets (including air temperature, RH, wind speed, zonal and meridional wind speeds, measured at 14:00 LT of all O₃ pollution days at 29 national meteorological sites within the PRD (Fig. S1a) and the ERA-Interim re-analysis (including all near-surface parameters from the analysis and forecast fields introduced in Sect. 2.1, extracted at the same time and the locations of sites as these in routine monitoring datasets) were used in the comparison (since all O₃ pollution days in October and over 60% of O₃ pollution days in July were characterized with sunny, cloudy, or overcast weathers with no rainfall in the PRD (Table S4, represented by the weather in Guangzhou), precipitation was not considered in the comparisons). The Mann–Whitney U test was applied to determine whether the above parameters were significantly different ($p < 0.05$) in the two types of O₃-pollution scenarios between typhoon-induced and no-typhoon O₃ pollution days.

As is listed in Table 2, statistically significant differences between the typhoon-induced and no-typhoon scenarios existed for most of the parameters, such as meridional (south-north) wind speed, cloud covers within various height ranges and net surface solar radiation — in both seasons, these parameters were significantly different for the two scenarios. It indicates that the causes of O₃ pollution may vary on typhoon-induced and no-typhoon O₃ pollution days. Note that air temperature, one of
the parameters most closely related to O$_3$ pollution in the PRD (Zhao et al., 2019), was not significantly different in the two scenarios. We also found that the comparison in autumn and summer did not produce the same results: the typhoon-induced days in autumn featured lower RH, stronger winds (especially north wind), reduced cloud cover (low, medium, high and total) and stronger surface solar radiation, whereas in summer, these days had higher RH, weaker south winds, more cloud cover (medium, high and total), weaker surface solar radiation and lower PBL heights. Therefore, the impact of typhoons on O$_3$ pollution differs in the two seasons, as well. In order to reveal the impact of typhoons on O$_3$ transport, production, and accumulation in the PRD, more detailed comparisons of the corresponding meteorological indicators are presented in the following sections.
Table 2. The comparisons of meteorological parameters (all at 14:00 LT except for net surface solar radiation, which is the average value for 9:00–17:00 LT) in the PRD for the three scenarios (no-typhoon, typhoon-induced, close typhoon-induced) in two seasons (autumn, summer). RM, routine measurement; ERA, ERA-Interim re-analysis. All of the parameters are presented as “the mean value ± standard deviation”. The differences between parameters in the typhoon-induced or close typhoon-induced scenarios and the corresponding typhoon-induced scenarios for the same season are given in parentheses, and “*” indicates p < 0.05, or statistically significant differences between these parameters when the Mann-Whitney U test is used.

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<tr>
<td></td>
<td></td>
<td>No-typhoon</td>
<td>Typhoon-induced</td>
</tr>
<tr>
<td>Air Temperature (°C)</td>
<td>RM</td>
<td>29.1 ± 2.2</td>
<td>29.3 ± 1.8</td>
</tr>
<tr>
<td></td>
<td>ERA</td>
<td>29.2 ± 2.1</td>
<td>29.3 ± 1.6</td>
</tr>
<tr>
<td>RH (%)</td>
<td>RM</td>
<td>52.4 ± 10.2</td>
<td>44.8 ± 10.4</td>
</tr>
<tr>
<td></td>
<td>ERA</td>
<td>54.0 ± 9.8</td>
<td>48.3 ± 11.2</td>
</tr>
<tr>
<td>Wind Speed (m/s)</td>
<td>RM</td>
<td>2.33 ± 1.18</td>
<td>2.58 ± 1.23</td>
</tr>
<tr>
<td></td>
<td>ERA</td>
<td>2.39 ± 1.30</td>
<td>2.54 ± 0.99</td>
</tr>
<tr>
<td>Zonal (East-West) Wind Speed (m/s)</td>
<td>RM</td>
<td>-0.83 ± 1.72</td>
<td>-0.59 ± 1.70</td>
</tr>
<tr>
<td></td>
<td>ERA</td>
<td>-1.41 ± 1.43</td>
<td>-1.07 ± 1.04</td>
</tr>
<tr>
<td>Meridional (South-North) Wind Speed (m/s)</td>
<td>RM</td>
<td>-0.36 ± 1.74</td>
<td>-1.49 ± 1.66</td>
</tr>
<tr>
<td></td>
<td>ERA</td>
<td>-0.27 ± 1.82</td>
<td>-1.97 ± 1.16</td>
</tr>
<tr>
<td>Low Cloud Cover (%)</td>
<td>ERA</td>
<td>17.2 ± 22.7</td>
<td>4.2 ± 11.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-13.0, *)</td>
<td>(-1.7, *)</td>
</tr>
<tr>
<td>Medium Cloud Cover (%)</td>
<td>ERA</td>
<td>22.2 ± 26.5</td>
<td>10.4 ± 19.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-11.8, *)</td>
<td>(-12.7, *)</td>
</tr>
<tr>
<td>High Cloud Cover (%)</td>
<td>ERA</td>
<td>12.1 ± 23.1</td>
<td>7.2 ± 16.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-4.9, *)</td>
<td>(+22.5, *)</td>
</tr>
<tr>
<td>Total Cloud Cover (%)</td>
<td>ERA</td>
<td>43.5 ± 32.3</td>
<td>20.5 ± 25.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-23.0, *)</td>
<td>(+8.4, *)</td>
</tr>
<tr>
<td>Net Surface Solar Radiation (W/m²)</td>
<td>ERA</td>
<td>456.9 ± 78.4</td>
<td>516.6 ± 66.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(+59.7, *)</td>
<td>(+59.6, *)</td>
</tr>
<tr>
<td>PBL Height (m)</td>
<td>ERA</td>
<td>1471 ± 315</td>
<td>1473 ± 348</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(+2)</td>
<td>(-122, *)</td>
</tr>
</tbody>
</table>

3.2 O₃ transport conditions: comparison of wind speeds, backward trajectories and vertical air motions

The higher wind speeds and/or O₃ levels in the transported air masses are, the more likely O₃ transport plays an increasingly important role in O₃ pollution. In the PRD, O₃ levels are closely linked to the type of air masses influencing the region, which can be identified based on backward trajectories. According to Zheng et al. (2010), there are generally three types of air masses
that are transported into the PRD along different paths and contribute to O$_3$ pollution here, namely, the continental, coastal and marine air masses (Fig. 3a). The continental and coastal air masses can bring O$_3$ from EC-China to the PRD, and thus, they are typically recognised as being polluted and contributing to relatively high O$_3$ levels in the PRD. In contrast, the marine air masses, originated from the South China Sea, are much cleaner. In this section, we studied the influence of typhoons on O$_3$ transport by comparing wind speeds and 72-h backward trajectories in various the typhoon-induced and no-typhoon scenarios.

**Figure 3.** (a) Three O$_3$ transport paths towards the PRD. (b–e) Backward trajectories at 14:00 LT for the four scenarios: (b) autumn, typhoon-induced; (c) autumn, no-typhoon; (d) summer, typhoon-induced; and (e) summer, no-typhoon. The black dots indicate the end point of all trajectories, i.e., where the Modiesha site in the central PRD is located.

As is displayed in Fig. 3b–c, we identified the influence of continental air masses on the typhoon-induced O$_3$ pollution days in autumn, as well as mixed contributions from the continental and coastal air masses on the corresponding no-typhoon days. However, for the former scenario, significantly increased wind speeds (Table 2) ensure more favourable conditions for the transport of O$_3$. In summer, the three types of air masses may all have affected O$_3$ pollution in the typhoon-induced scenario, while only the marine air masses influenced the PRD in the no-typhoon scenario (Fig. 3d–e). Since wind speeds did not vary significantly (Table 2), the inflows of much more polluted air masses resulted in that typhoons also tended to increase the contribution of transport to O$_3$ pollution in the PRD in summer. The increasing influence of much more polluted air masses (continental and coastal air masses) led by typhoon ensured that more O$_3$ was transported to the PRD, thus typhoons also tended to increase the contribution of transport to O$_3$ pollution in the PRD in summer. In addition, the influence of different air masses was also accompanied with variations in the prevailing winds in the PRD, that is, north winds and easterlies in the typhoon-induced and no-typhoon scenarios in autumn, respectively, and southwest winds in the no-typhoon scenario in summer (indicated by wind roses in Fig. S5). For the typhoon-induced scenario in summer, the dominate wind direction is hard to determine. These variations in the local wind fields potentially result in the different spatial distribution of O$_3$ concentrations in various scenarios.
Downdrafts are typically considered to be an important cause of typhoon-induced O₃ pollution (Lam, 2018), but in which scenarios downdrafts influence the PRD remains unclear. Thus, we explored the overall features of vertical air motions from the surface layer to the tropopause in the typhoon-induced and no-typhoon scenarios, and the ERA-Interim reanalysis dataset (including all upper air parameters at multiple heights introduced in Sect. 2.1) was utilised in the comparisons. The contours in Fig. 4 show the cross sections of mean vertical wind speed at 14:00 LT of all O₃ pollution days corresponding to the typhoon-induced and no-typhoon scenarios of two seasons, which were made along the 113.2°E longitude line, from 26.0°N to 20.0°N along the 113.2°E longitude line (Fig. S4). On the typhoon-induced days in autumn, downdrafts occurred over large areas above the PRD, especially above a height of ~4 km~700 hPa. Although updrafts can still be found near the sea surface in this scenario, vertical wind speeds tended to be lower compared with those on the no-typhoon days in autumn, which also suggests the enhancement of downdrafts caused by typhoons. In summer, the influence of downdrafts was found over the PRD under 850 hPa on the typhoon-induced O₃ pollution days. However, overall, updrafts prevailed above the land areas and downdrafts prevailed above the sea in both the typhoon-induced and no-typhoon scenarios in summer, which is recognised as the structure of the East Asian summer monsoon cell (Chen et al., 1964; Jin et al., 2013; Ding et al., 2018). For both updrafts and downdrafts, the absolute values of vertical wind speeds in the typhoon-induced scenario in summer were overall higher than those in the corresponding no-typhoon scenario. Therefore, the approach of typhoons did not break the structure of the summer monsoon cell, but rather they further strengthened the vertical motions above both land areas and sea. These analyses suggest that typhoons do not necessarily lead to downdrafts during O₃ pollution periods in the PRD and its adjacent areas; and in summer, vertical air motions affected by typhoons are more complicated than expected owing to the existence of the East Asian summer monsoon.

We also explored the regions where downdrafts and updrafts occurred on a larger scale and their potential connections with O₃ levels. As is shown in Fig. 5, though updrafts appeared in the PRD at 850 hPa on the typhoon-induced days in autumn, downdrafts dominated in the region at 700 and 500 hPa. For the areas to the north of the PRD, the important role of downdrafts was found at all three heights. In contrast to the no-typhoon days in autumn, downdrafts tended to cover much larger areas in this scenario. Moreover, these areas at 850 and 700 hPa generally featured higher O₃ mixing ratios as well as lower RH (Fig. S6) than others, which is a sign of possible direct downward O₃ transport (Roux et al., 2020; Wang et al., 2020). This part of O₃ can notably aggravate near-ground O₃ pollution in the PRD. In contrast, in summer, updrafts dominated the PRD at various heights in both scenarios. Besides the PRD, most of the regions near the coast were characterised by updrafts above the land as well as downdrafts offshore, further indicating the ubiquity of the summer monsoon cell. By comparing the two scenarios in summer, we found that typhoons resulted in more areas being influenced by updrafts. The areas with high O₃ levels did not coincide with the downdraft-affected areas, and therefore, O₃ transported from the upper air may play a less significant role in the typhoon-induced O₃ pollution in summer.
3.3 O₃ production conditions: comparison of clouds

Clouds efficiently reflect solar radiation (Liou, 1976), and therefore, they have a notable impact on the local formation of O₃. Figure 6 displays the cross sections of mean ERA-Interim cloud liquid water contents (CLWC) at 14:00 LT of all O₃ pollution days corresponding to the typhoon-induced and no-typhoon scenarios of two seasons, which were also made along the 113.2°E longitude line, from 26.0°N to 20.0°N (Fig. S4). The comparison of cloud liquid water content CLWC in the cross sections (Fig. 6, derived from the ERA-Interim datasets) suggests that typhoons generally resulted in fewer clouds in autumn but more clouds in summer, which agrees well with the comparison of cloud covers in Table 2. The presence of fewer clouds on the typhoon-induced days in autumn can be attributed to two reasons: the influence of dry air masses (indicated by lower RH in Table 2 and Fig. S6) and/or the hindrance of cloud formation by downdrafts. In summer, the strengthened updrafts above the land caused by typhoons favoured cloud formation, which is demonstrated by higher cloud liquid water content CLWC at the heights of 2–5 km 500–850 hPa and increases in medium and high cloud covers. In areas above the PRD below 850 hPa, downdrafts led to slight decrease of clouds in the typhoon-induced scenario in summer, which is also indicated by reduced low cloud cover. As a consequence of varied cloud covers in each scenario, on average, net surface solar radiation increased by
13% and decreased by 7% on the typhoon-induced days in autumn and summer, respectively (Table 2), which promoted and hindered O$_3$ production in the PRD during these two seasons, respectively.
Figure 5. Ozone mixing ratio (ppbV) and vertical wind speed at 850 hPa, 700 hPa, and 500 hPa for the four scenarios: (a, c, e, i) autumn, typhoon-induced; (b, d, f, j) autumn, no-typhoon; (c, k) summer, typhoon-induced; and (d, l) summer, no-typhoon. The red triangle in each plot indicates the PRD. The gridded areas indicate vertical wind speed less than 0, or downdrafts occur.
Figure 6. The cross sections of mean cloud liquid water content (g/m$^3$) and wind vectors at 14:00 LT for the four scenarios: (a) autumn, typhoon-induced; (b) autumn, no-typhoon; (c) summer, typhoon-induced; and (d) summer, no-typhoon. Cross sections were made along the 113.2°E longitude line, from 26.0°N to 20.0°N along the 113.2°E longitude line (Fig. S4). The vectors indicate meridional wind speed (m/s) and vertical wind speed (cm/s). PRD, the Pearl River Delta.

3.4 O$_3$ accumulation conditions: comparison of APRTs

The longer APRTs are, the more likely that O$_3$ produced by local emissions accumulates within the targeted region and notably contributes to near-ground O$_3$ pollution. In order to study the effect of typhoons on O$_3$ accumulation, we calculated APRTs in the PRD in the four typhoon-induced and no-typhoon-scenarios (Fig. 7) for the further comparisons. On the typhoon-induced days in autumn, APRTs were typically 5–10 hours (mean = 9.5 hours) — shorter than those on the no-typhoon days in autumn (mean = 13.1 hours). In addition, lower APRT values occurred in the central part of the PRD, where high anthropogenic emissions of pollutants are distributed (Zheng et al., 2009). Despite more active O$_3$ chemistry discussed in the last section, locally sourced O$_3$ was less likely to accumulate within the PRD in this scenario, potentially limiting the contribution of local emissions for O$_3$. The comparison suggests opposite results in the summer scenarios, that is, APRTs on the typhoon-induced days (20–30 hours, mean = 21.0 hours) were overall higher than those on the no-typhoon days (15–25 hours, mean = 16.5 hours). This favoured the accumulation of locally sourced O$_3$ and, to some extent, offset the influence of weakened O$_3$ formation to some extent to maintain high contributions of local emissions to O$_3$ pollution. In both seasons, Based on the comparison of O$_3$ production conditions in the previous section and the comparison of O$_3$ accumulation conditions in this
section, typhoons did not provide more favourable conditions for O₃ production and accumulation simultaneously in the PRD in both autumn and summer, thus potentially resulting in a less important role of local contributions in O₃ pollution here. More quantitative evaluations of the contributions from multiple O₃ sources are discussed in Sect. 4.

Figure 7. The spatial distributions of APRTs in the PRD for each scenario: (a) autumn, typhoon-induced; (b) autumn, no-typhoon; (c) summer, typhoon-induced; and (d) summer, no-typhoon.

3.5 Meteorological conditions on the close typhoon-induced days

On the close typhoon-induced days in the two seasons, stronger north winds prevailed and total cloud cover was higher than that on the no-typhoon days (Table 2), suggesting better conditions for the transport of O₃ but less favourable conditions for O₃ production. As displayed in Fig. S7, the APRT values were significantly lower on the close typhoon-induced days (mean = 6.6 hours, 12.9 hours in autumn and summer, respectively) than on the no-typhoon days, making it even harder for locally sourced O₃ to accumulate within the PRD. Therefore, close typhoons are concluded to promote the transport of O₃ from the outside and to reduce the contributions of O₃ produced from local emissions in a more notable way. In addition, close typhoons led to stronger downdrafts in autumn and updrafts in summer than other scenarios in the same season (Fig. S8). It should be noted that the structure of the summer monsoon cell near the PRD was destroyed in the close typhoon-induced scenario in summer, indicating the stronger influence of typhoons on regional wind fields. The dominant role of O₃ transport during O₃ pollution days in this special scenario agrees well with the reported episode-based analyses (Lam et al., 2005; Li, 2013).
4 Comparisons of O$_3$ processes and sources

The comparisons of meteorological conditions served as qualitative evidence to determine the general influence of typhoons on O$_3$ transport, production and accumulation in autumn and summer. Based on the comparison between the CMAQ modelling results on typical O$_3$ pollution days in October 2015 and July 2016, more quantitative evidence can be presented. Figure 8 displays modelled mean O$_3$ MDA8 concentrations and wind fields (at 14:00 LT) on the typhoon-induced and no-typhoon O$_3$ pollution days of two seasons. Large standard-exceedance (> 160 μg/m$^3$) areas were distributed in the PRD on most days, and the typhoon-induced days of both seasons generally featured higher O$_3$ levels. The distinct wind fields for these scenarios, which were consistent with those in the longer timespan (Fig. S5), indeed led to different spatial distributions of O$_3$. Generally, the most severe O$_3$ pollution occurred in the downwind areas, such as the central and southern parts of the PRD on the typhoon-induced days in October 2015, the central PRD on the no-typhoon days in October 2015, and the northern and eastern PRD on the no-typhoon days in July 2016. On the typhoon-induced days in July 2016, high levels of O$_3$ accumulated around the PRE. In this section, we discuss the different contributions of various O$_3$ processes and sources on these days to better understand the effect of typhoons on O$_3$ pollution in the PRD.

Figure 8. Modelling mean O$_3$ MDA8 concentrations (μg/m$^3$) and wind vectors (at 14:00 LT) on the representative O$_3$ pollution days: (a) the typhoon-induced days in October 2015 (14–16 and 21 October 2015); (b) the no-typhoon days in October 2015 (28 October and 3–5 November 2015); (c) the typhoon-induced days in July 2016 (7–8 and 30–31 July 2016); and (d) the no-typhoon days in July 2016 (22–26 and 29 July 2016). Three representative sites in the PRD are shown as black circles in the plots: XJ, Xijiao; MDS, Modiesha; DF, Duanfen.
4.1 O$_3$ processes: transport vs chemical process

The PA tool in CMAQ was used to quantify the contributions of transport and chemical process to the O$_3$ variations on O$_3$ pollution days under various scenarios in October 2015 and July 2016. As is shown in Fig. 9, the daytime (9:00–17:00 LT) O$_3$ PA results within the PRD in all scenarios share similar characteristics. Dry deposition dominated O$_3$ removal near the surface, and it also led to high gradients of O$_3$ concentrations that promote downward O$_3$ diffusion. Within the PBL (about 0–1 km in height), O$_3$ was mainly contributed by horizontal transport and chemical process, and vertical convection led to the drop of O$_3$ concentrations. However, differences existed between the O$_3$ PA results in the typhoon-induced and no-typhoon scenarios, indicating the impact of typhoons on the transport and production of O$_3$. In both months, typhoons led to notably higher contribution of horizontal transport to O$_3$, especially in the lower and middle part of the PBL. Within the PBL, on average, it increased from -0.9 ppb/h, -0.8 ppb/h to 1.2 ppb/h, 2.0 ppb/h under typhoon influence in autumn and summer, respectively. The comparison of the contribution of chemical process (in absolute rates) suggests that they had opposite effects in the two months — under typhoons, the contribution increased in October 2015 (from 4.0 ppb/h to 4.5 ppb/h within the PBL, or by 11.4%), but it decreased in July 2016 (from 7.1 ppb/h to 5.7 ppb/h within the PBL, or by -20.8%). In other words, typhoons promoted and hindered O$_3$ production in autumn and summer, respectively. These results agree well with the comparisons of O$_3$ transport and production conditions in the previous section.

**Figure 9.** The daytime-mean (9:00–17:00 LT) hourly contributions of O$_3$ processes within the PRD in vertical layers 1–13 on representative O$_3$ pollution days: (a) the typhoon-induced days in October 2015 (14–16 and 21 October 2015); (b) the no-typhoon days in October 2015 (28 October and 3–5 November 2015); (c) the typhoon-induced days in July 2016 (7–8 and 30–31 July 2016); and (d) the no-typhoon days in July 2016 (22–26 and 29 July 2016).
4.2 O₃ sources: local sources vs regional sources

The contributions of various sources to O₃ within the PRD are determined by the combined impact of O₃ transport, production and accumulation. The results for the mean daytime (9:00–17:00 LT) O₃ SA near the ground (about 0–80 m in height) in four scenarios on typhoon-induced and no-typhoon O₃ pollution days are illustrated in Fig. 10. For polluted regions within the PRD, stronger O₃ production under typhoons did not lead to a higher proportion of local contributions to O₃ pollution in October 2015 — it even decreased from 22% (on the no-typhoon days) to 17% (on the typhoon-induced days). The contributions of EC-China emissions and BCON, in contrast, increased slightly from 37%, 41% to 40%, 43%, respectively. The distinction of the O₃ SA results is more apparent for the summer scenarios, that is, typhoons resulted in growing contributions from O₃ transported from other regions (from 40% to 59%) but decreased local contributions (from 60% to 41%) in July 2016. More favourable O₃ accumulation conditions (indicated by higher APRTs on the representative typhoon-induced O₃ pollution days in summer (Fig. S9)) were far from sufficient to compensate for the effect of weakened O₃ production on the high contributions of local sources.

**Figure 10.** The mean O₃ SA near the ground (about 0–80 m in height) on representative typhoon-induced and no-typhoon O₃ pollution days for the four scenarios in October 2015 and July 2016 (the average results of 9:00–17:00 LT). The locations of the three representative sites (Xijiao, Modiesha and Duanfen) are shown in Fig. 8. PRD, the Pearl River Delta; EC-China, East China and Central China; BCON, the boundary conditions of the d02 modelling.
Furthermore, owing to the variations of wind fields, the comparison results of O₃ SA in different parts of the PRD may differ from the regional ones. For instance, while the comparisons of O₃ SA in the Xijiao and Modiesha site (located in the northeast and central part of the PRD, respectively) agree well with those in the polluted regions of the PRD, higher contributions of PRD emissions for O₃ can be found in the Duanfen site (located in the southwest part of the PRD) on the typhoon-induced days of two months in comparison to these on the corresponding no-typhoon days (Fig. 10). Since the site was located in the downwind region in the typhoon-induced scenario in October 2015 (Fig. 8a), enhanced O₃ production led by typhoons from the massive emissions of O₃ precursors in the central PRD (Zheng et al., 2009) contributed to higher local contributions for O₃ pollution here (as the distribution of local contributions in percentage to daytime O₃ shown in Fig. S10, the highest local contribution in the PRD occurred in areas near the Duanfen site and almost reached 40% in this scenario, which was even higher than that in the corresponding no-typhoon scenario (33%)). In the no-typhoon scenario in July 2016, the site was located in the upwind regions under the prevailing of southwest winds, limiting the contributions of local emissions for O₃ at the site (Fig. 8d). Thus, higher local contributions can also be found in the typhoon-induced scenario in this month.

5 Discussion and conclusions

The significance of typhoons on O₃ pollution in the PRD calls for thorough evaluations of the different causes of O₃ pollution with the appearance of typhoons in the Northwest Pacific. In this study, we revealed the different impacts of typhoons on O₃ transport, production and accumulation in the PRD (as summarised in Fig. 11) through systematic comparisons of meteorological conditions, the contributions of various O₃ processes and sources in the typhoon-induced and no-typhoon scenarios. We found that typhoons tended to promote O₃ transport towards the PRD, but failed to provide more favourable O₃ production and accumulation conditions simultaneously, which limited the contribution of local emissions to O₃ pollution. Furthermore, there were also differences between the influence of typhoons on O₃ pollution in autumn and summer. More favourable transport conditions occurred in the typhoon-induced scenario in autumn, which was characterised by higher wind speeds and the increased influence of downdrafts. In summer, the mixed types of air masses in the typhoon-induced scenario were likely to bring more O₃ into the PRD than the clean marine air masses in the no-typhoon scenario, also suggesting enhanced O₃ transport under the influence of typhoons. Generally, typhoons led to cloudless conditions, stronger solar radiation, and thus more rapid O₃ production in autumn, but shorter APRTs (5–10 hours) suggest that locally sourced O₃ was hard to accumulate within the PRD. As a result, the contributions in percentage of local emissions to O₃ pollution decreased (slightly by ~5% for the polluted regions of the PRD in October 2015). In contrast, in summer, intensified updrafts associated with typhoons strengthened cloud formation, weakened solar radiation, and thus restrained local O₃ production. Longer APRTs (>20 hour) under typhoon influence were far from sufficient to maintain high contributions of local emissions for O₃ pollution (which decreased by ~20% for the polluted regions of the PRD in July 2016). However, due to the variations of wind fields under different scenarios, the changes of local and transport contributions for O₃ led by typhoons were different in the southwest part of the PRD, that is, higher contribution from emissions within the PRD and reduced transport contribution
occurred in the typhoon-induced scenarios in both seasons. As for the close typhoon-induced scenario, O₃ transport was further strengthened, but meteorological conditions in the PRD became less favourable for both the production and accumulation of O₃.

Figure 11. The summary of the causes of O₃ pollution in the PRD under typhoon influence in autumn and summer.

The East Asian monsoon, changing with seasons, has a pronounced impact on local meteorological conditions as well as the characteristics of O₃ pollution in East China (He et al., 2008). The seasonal behaviour of the East Asian monsoon is likely to result in the seasonally varied effect of typhoons on O₃ pollution in the PRD. In October, the summer monsoon has almost finished its retraction and the winter monsoon is beginning (Ding, 1994). Thus, there are not many obstacles to the southward movement of typhoon periphery and the transport of O₃ towards the PRD by the continental and coastal air masses. Large downdraft-influenced areas in Central and South China occur in this scenario, and high O₃ levels and low RH in these areas indicate the potentially important role of directly downward O₃ transport. In July, the summer monsoon reaches its strongest (Ding, 1994). The interaction between typhoon periphery and the summer monsoon results in stagnation and enhanced updrafts above the land areas of the PRD and its surroundings. Only when typhoon is close enough to the PRD is the stagnation terminated and the structure of the summer monsoon cell broken. This also explains why some summertime typhoon-induced O₃ episodes in the PRD can be typically divided into two periods, as stagnation leads to the accumulation of locally produced O₃ in the first phase and strong northerly winds strengthen O₃ transport before the landing of typhoons (Lam et al., 2005; Li, 2013). It should be noted that updrafts, rather than downdrafts, prevailed on the typhoon-induced O₃ pollution days in summer. High levels of O₃ did not necessarily occur in the regions dominated by downdrafts in this scenario, suggesting a less notable connection between downdrafts and summertime O₃ pollution in the PRD. Further investigations are required to trace the detailed process of downward O₃ transport, including the stratosphere-troposphere exchange (Stohl et al., 2003), in each scenario, and quantify their contributions to near-ground O₃ pollution.
Some limitations remain in this study. We chose O$_3$ pollution days as individual samples, ignoring the influence of O$_3$ pollution on the previous days. Thus, more detailed full-episode analyses are required. Moreover, owing to the small sampling size, the influence of typhoons on O$_3$ pollution in the PRD is still not fully understood, including, for instance, the detailed connections between the features of typhoons (intensity, position) and O$_3$ pollution. However, the comparisons of meteorological conditions, O$_3$ processes and sources in different scenarios and seasons demonstrate the complex causes of typhoon-induced O$_3$ pollution in the PRD — typhoons tend to enhance O$_3$ transport into the PRD in both seasons, but their impacts on the production and accumulation of O$_3$ are completely different. As a result, emissions within (outside of) the PRD are likely to contribute less (more) on the typhoon-induced O$_3$ pollution days than on the no-typhoon days, and more attention should be paid to controlling anthropogenic emissions of O$_3$ precursors on a larger scale under typhoon influence. In order to effectively alleviate O$_3$ pollution and to reduce the population exposure in the PRD, more attention should be paid to controlling anthropogenic emissions of O$_3$ precursors on a larger scale, rather than focusing on local emission, under typhoon influence. For air quality management, it is suggested to comprehensively evaluate the efficiency of fractional local and non-local emission reductions to reduce O$_3$ levels in the PRD in different scenarios (Thunis et al., 2019; Thunis et al., 2020). This study also suggests that a thorough evaluation of O$_3$ transport, production and accumulation conditions can be applied to understand the causes of regional O$_3$ pollution not only in the PRD, but also in other regions. The results will help find efficient strategies to alleviate regional O$_3$ pollution as well as to reduce its adverse effects.

Data availability. Data are available from the corresponding author upon request.

Author contributions. KQ, XW and YZ designed the study. KQ, XW, and TX did the simulation work, including the operation of the WRF, SMOKE and CMAQ models. JS, HD, LZ and YZ provided observational results of field campaigns and the routine monitoring datasets for the evaluation of model performance. KQ, XW, YY and YZ analysed the modelling results. KQ, XW, YY and YZ wrote and revised this paper, with critical feedbacks from all other authors.

Competing interests. The authors declare no conflict of interest.

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