Atmospheric
Chemistry
and Physics
Discussions

1 A Comparative Study to Reveal the Influence of Typhoons on the
2 Transport, Production and Accumulation of O_3 in the Pearl River
3 Delta, China

4 Kun Qu[1,2], Xuesong Wang[1,2], Yu Yan[1,2], Jin Shen[3], Teng Xiao[1,2], Huabin Dong[1,2], Limin Zeng[1,2], and
5 Yuanhang Zhang[1,2,4,5]

6 [1]State Key Joint Laboratory of Environmental Simulation and Pollution Control, College of Environmental Sciences and Engineering,
7 Peking University, Beijing 100871, China
8 [2]International Joint Laboratory for Regional Pollution Control, Ministry of Education, Beijing, 100816, China
9 [3]State Key Laboratory of Regional Air Quality Monitoring, Guangdong Key Laboratory of Secondary Air Pollution Research, Guangdong
10 Environmental Monitoring Center, Guangzhou 510308, China
11 [4]Beijing Innovation Center for Engineering Science and Advanced Technology, Peking University, Beijing 100871, China
12 [5]CAS Center for Excellence in Regional Atmospheric Environment, Chinese Academy of Sciences, Xiamen 361021, China

13 *Correspondence to*: Xuesong Wang (xswang@pku.edu.cn) and Yuanhang Zhang (yhzhang@pku.edu.cn)

14 **Abstract.** The Pearl River Delta (PRD) region in South China is faced with severe ambient O_3 pollution in autumn and summer,

15 which mostly coincides with the occurrence of typhoons above the Northwest Pacific. With increasingly severe O_3 pollution

16 in the PRD under the influence of typhoons, it is necessary to gain a comprehensive understanding of the impact of typhoons

17 on O_3 transport, production and accumulation for efficient O_3 reduction. In this study, we analysed the general influence of

18 typhoons on O_3 pollution in the PRD via systematic comparisons of meteorological conditions, O_3 processes and sources on

19 O_3 pollution days with and without typhoon occurrence (denoted as the typhoon-induced and no-typhoon scenarios,

20 respectively), and also examined the differences in these influences in autumn and summer. The results show that the approach

21 of typhoons was accompanied by higher wind speeds and strengthened downdrafts in autumn as well as the inflows of more

22 polluted air masses in summer, suggesting favourable O_3 transport conditions in the typhoon-induced scenario in both seasons.

23 However, the effect of typhoons on the production and accumulation of O_3 were distinct. Typhoons led to reduced cloud cover,

24 and thus stronger solar radiation in autumn, which accelerated O_3 production, but the shorter residence time of local air masses

25 was unfavourable for the accumulation of O_3 within the PRD. In contrast, in summer, typhoons increased cloud cover, and

26 weakened solar radiation, thus restraining O_3 formation, but the growing residence time of local air masses favoured O_3

27 accumulation. The modelling results using the Community Multiscale Air Quality (CMAQ) model for the typical O_3 pollution

28 days suggest increasing contributions from the transport processes as well as sources outside the PRD for O_3 pollution,

29 confirming enhanced O_3 transport under typhoon influence in both seasons. The results of the process analysis in CMAQ

30 suggest that the chemical process contributed more in autumn but less in summer in the PRD. Since O_3 production and

31 accumulation cannot be enhanced at the same time, the proportion of O_3 contributed by emissions within the PRD was likely

32 to decrease in both seasons. The difference in the typhoon influence on O_3 processes in autumn and summer can be attributed

33 to the seasonal variation of the East Asian monsoon. From the "meteorology-process-source" perspective, this study revealed

34   the complex influence of typhoons on O_3 pollution in the PRD and their seasonal differences. To alleviate O_3 pollution under

35   typhoon influence, emission control is needed on a larger scale, rather than only within the PRD.

1 Introduction

37   Tropospheric ozone (O_3) serves as a secondary pollutant in ambient air and is detrimental for human health and crop

38   production (Wang et al., 2017; Liu et al., 2018; Mills et al., 2018). Ambient O_3 is produced from its precursors, i.e., nitrogen

39   oxides ($NO_x = NO + NO_2$) and volatile organic compounds (VOCs), through chemical reactions in the presence of sunlight.

40   This O_3 can accumulate locally, or be transported to downwind regions. Under unfavourable meteorological conditions,

41   enhanced transport, production and/or accumulation of O_3 can all contribute to the O_3 pollution within a region (National

42   Research Council, 1991).

43

44   As the largest city cluster in South China, the Pearl River Delta (PRD) region is faced with frequent ambient O_3 pollution,

45   especially in autumn and summer (Li et al., 2014; Wang et al, 2017; Lu et al, 2018). Along with the continuous increasing of

46   O_3 levels in recent years (Li et al., 2019), O_3 has become the primary contributor to the deterioration of air quality in this

47   region (Feng et al., 2019). The occurrence of O_3 pollution in the PRD is predominantly related to the influence of typhoons

48   (or tropical cyclones) above the Northwest Pacific (Gao et al., 2018; Deng et al., 2019; Lin et al., 2019). According to Gao et

49   al. (2018), seven out of the nine most severe O_3 episodes (regional-mean maximum 8-h average O_3 concentrations of > 240

50   µg/m^3) during 2014–2016 coincided with the approach of typhoons. The changes in the track and intensity of typhoons may

51   contribute to the growing trend of O_3 levels recently and in future (Lam, 2018; Lam et al., 2018). Therefore, a

52   comprehensive understanding of the influence of typhoons on the transport, production and accumulation of O_3 has

53   important implications for efficient and strategic O_3 reduction in the PRD.

54

55   Analyses of typhoon-related O_3 episodes in the PRD have been extensively reported in previous publications. The effect of

56   typhoons on O_3 pollution is closely linked to meteorological conditions that are conducive to the transport, production and/or

57   accumulation of O_3. Stagnation caused by typhoons, characterised by low wind speeds, has been reported during many

58   episodes, and it promotes the accumulation of locally formed O_3 within the PRD (Wang et al., 1998; So and Wang, 2003;

59   Wang and Kwok, 2003; Huang et al., 2005; Lam et al., 2005; Jiang et al., 2008; Zhang et al., 2014; Chow et al., 2019).

60   Strong north or west winds were observed or simulated during several episodes, suggesting the potentially strengthened

61   transport of pollutants under typhoon influence (Wang et al., 2001; Yang et al., 2012; Wang et al., 2015; Wei et al., 2016).

62   Downdrafts on the outskirts of typhoons may promote downward O_3 transport and contribute to near-ground O_3 pollution as

63   well (Lam, 2018), but its appearance in the PRD has only been examined in a few studies. Cloudless conditions and strong

64   solar radiation enhance O_3 production, which is another important cause of O_3 pollution (Wang et al., 1998; Wang and

65   Kwok, 2003; Li et al., 2018; Yue et al., 2018; Chow et al., 2019). In a more direct way, several studies have utilised

Atmospheric
Chemistry
and Physics
Discussions

66 chemical transport models, along with the Process Analysis (PA) tool and source apportionment (SA) methods, to quantify

67 and compare the contributions of various O_3 processes (e.g., transport and the chemical process) and sources (e.g., local

68 emissions, outside emissions and background) during these episodes. Based on reports by Huang et al. (2005), Lam et al.

69 (2005), Jiang et al. (2008), Wang et al. (2010), Li (2013), Wang et al. (2015), Wei et al. (2016) and Chen et al. (2018),

70 horizontal/vertical transport and chemical production may both be the main contributing process for typhoon-induced O_3

71 pollution in different parts of the PRD. The SA results revealed that emissions within the PRD contributed 40–80% of O_3

72 during typhoon-related O_3 episodes (Li et al., 2012; Li, 2013; Chen et al., 2015), suggesting the potentially important role of

73 O_3 accumulation for O_3 pollution here. However, despite massive episode-based studies, several important questions still

74 remain: Are O_3 transport, production and accumulation within the PRD all enhanced at the same time by typhoons? Do both

75 O_3 pollution seasons (autumn and summer) experience similar impact of typhoons on O_3 pollution? More thorough

76 investigations are needed to answer these questions.

77

78 In this study, we present systematic comparisons between O_3 pollution in the typhoon-induced and no-typhoon scenarios

79 (definitions given in Sect. 2.2) to elucidate the influence of typhoons on O_3 transport, production and accumulation in the PRD

80 and to reveal their seasonal differences. October and July in 2014–2018 were selected as the representative months for autumn

81 and summer, respectively. Multiple datasets, including the ERA-Interim re-analysis, the routine monitoring datasets,

82 trajectories calculated by the Hysplit model and the modelling results of typical O_3 pollution days using the Community

83 Multiscale Air Quality (CMAQ) model, were used in the comparisons. A detailed introduction of these datasets is presented

84 in Sect. 2. The comparisons were conducted from the perspectives of meteorological conditions (Sect. 3), O_3 processes and

85 sources (Sect. 4), and the conclusions about the influence of typhoons on the causes of ambient O_3 pollution in the PRD in the

86 two seasons are illustrated in Sect. 5.

87 **2 Methods**

88 **2.1 Datasets**

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

90 • **Re-analysis datasets**: We mainly used the ERA-Interim re-analysis product in the analyses due to its more available

91 parameters and high spatial coverage (available at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-

92 interim, last accessed: March 2020; Dee et al., 2011; Berrisford et al., 2011). Specifically, meteorological parameters

93 used in the comparisons include the following three categories: (1) near-surface parameters from the analysis fields,

94 including air temperature (at a height of 2 m), relative humidity (RH, at 1000 hPa), horizontal wind speeds (at a height

95 of 10 m; zonal and meridional wind speeds were also involved in the comparisons), and low (for the height at which

96 pressure/surface pressure > 0.8), medium (for the height at which 0.45 < pressure/surface pressure < 0.8), high (for the

97 height at which pressure/surface pressure < 0.45) and total cloud covers; (2) near-surface parameters from the forecast

98 fields, including plenary boundary layer (PBL) height and net surface solar radiation; and (3) upper air parameters at

99 multiple heights, including horizontal and vertical wind speeds, cloud water content and O_3 mixing ratio. The focus of

100 this study is O_3 pollution during the daytime, and therefore, only the parameters at 14:00 local time (LT) were selected

101 for the analyses (except for net surface solar radiation, which was averaged within 8:00–17:00 LT).

102 • **Surface meteorological routine monitoring datasets**: The routine monitoring meteorological data collected at 29

103 national meteorological sites within the PRD (locations shown in Fig. S1a) were also used to explore the

104 meteorological features under the impact of typhoons. The parameters include air temperature, RH, and wind speed and

105 direction (also transformed to zonal and meridional wind speeds in the comparisons) at 14:00 LT.

106 • **Typhoon information**: The times, locations and intensities of typhoons were provided by the Chinese Meteorological

107 Administration Best Track Dataset of tropical cyclones (Ying et al., 2014). The tracks of all typhoons that potentially

108 contributed to O_3 pollution in the PRD during the study period (October and July in 2014–2018) are shown in Fig. S2

109 and S3.

110 • **O_3 concentrations**: Hourly O_3 concentration data, which were originally released by the China National Environmental

111 Monitoring Centre, were downloaded from http://beijingair.sinaapp.com (last accessed: Dec. 2018). Based on the

112 hourly data, we calculated the maximum 1-hr concentrations (MDA1) and maximum 8-hr average concentrations

113 (MDA8) of O_3 in nine municipalities in the PRD (including Guangzhou, Shenzhen, Zhuhai, Foshan, Jiangmen,

114 Zhaoqing, Huizhou, Dongguan and Zhongshan) to identify O_3 pollution days that served as samples in the comparisons.

2.2 Definition and classification of O_3 pollution days

116 In this study, O_3 pollution days were defined as the days when the MDA1 exceeds 200 μg/m³ or the MDA8 exceeds 160

117 μg/m³ for O_3 (both are the Grade-II thresholds of the Chinese National Ambient Air Quality Standard (NAAQS), GB 3095-

118 2012) in any of the nine municipalities in the PRD. According to these criteria, there were 78 and 55 O_3 pollution days

119 (given in Table S1 and S2) during October and July in 2014–2018, respectively. The information about these O_3 pollution

120 days in the two representative months is listed in Table 1 (overall) and S3 (monthly), including the numbers of days, their

121 proportions in the month, and the corresponding mean O_3 concentrations (MDA8 and MDA1, highest values among nine

122 municipalities in the PRD). Although there were more O_3 pollution days in October than in July, O_3 pollution days under

123 typhoon influence accounted for ~30% of all days in both months. Higher O_3 MDA1 and MDA8 values can be generally

124 found with the appearance of typhoons in comparison with days without typhoons, further indicating the important role of

125 typhoons in O_3 pollution in the PRD.

126

127 The differing locations of typhoons can result in the diverse effect of typhoons on O_3 pollution (Chow et al., 2018). To

128 determine the general influence of typhoons on O_3 pollution in the PRD, it was necessary to further select O_3 pollution days

129 coinciding with typhoons with similar directions and distances from the PRD. First, we removed five O_3 pollution days in

130 July with typhoons located to the due north or southwest of the PRD from the analyses. As is shown in Fig. 1, the remaining

131 days, including all O_3 pollution days in October and most O_3 pollution days in July under typhoon influence, were associated

132 with typhoons to the east of the PRD, which were more likely to cause O_3 pollution (Chow et al., 2018). After this, based on

133 the distances between typhoon centres and the PRD (at 14:00 LT), we classified the pollution days in each season into three

134 categories: close typhoon (lowest 20% of distances), typhoon (20–80% intervals of distances), and far typhoon (longest 20%

135 of distances)-induced days. The typhoon-induced days represent O_3 pollution days with general typhoon influence, and they

136 were compared with those without the appearance of typhoons (hereafter denoted as the no-typhoon days). It should be noted

137 that the distances between typhoon centres and the PRD on the typhoon-induced days were overall larger in autumn (1400–

138 2800 km, at 14:00 LT) than in summer (700–2000 km, at 14:00 LT), which may be the consequence of the different

139 characteristics of typhoon paths in the two seasons: most typhoons in autumn travel northwest initially and then turn

140 northward in the areas east of the Philippines (Fig. S2), whereas they are more likely to end up landing in Southeast China in

141 summer (Fig. S3). Since the influence of typhoons on O_3 pollution may be different when typhoons come close enough to

142 the PRD (Lam et al., 2005; Li, 2013), the close typhoon-induced days were considered to be a special scenario in the

143 comparisons of meteorological conditions (Sect. 3.5). Owing to the less apparent effect of typhoons over the PRD, we did

144 not include the far typhoon-induced days in the discussions.

145

146 **Table 1.** The numbers and proportions of O_3 pollution days, and O_3 concentrations for various scenarios.

Parameter	October, 2014–2018	July, 2014–2018
Number (proportion) of O_3 pollution days	78 (50.3%)	55 (35.5%)
With typhoons	49 (31.6%)	45 (29.0%)
Typhoon-induced days	30 (19.4%)	24 (15.5%)
Close typhoon-induced days	10 (6.5%)	8 (5.2%)
Without typhoons (no-typhoon days)	29 (18.7%)	10 (6.5%)
Mean PRD-max O_3 MDA8 ($\mu g/m^3$)		
With typhoons	195.0	205.3
Typhoon-induced days	199.5	205.4
Close typhoon-induced days	184.6	225.7
Without typhoons (no-typhoon days)	189.8	187.8
Mean PRD-max O_3 MDA1 ($\mu g/m^3$)		
With typhoons	230.4	259.8
Typhoon-induced days	235.2	260.0
Close typhoon-induced days	219.2	277.1
Without typhoons (no-typhoon days)	231.5	246.5

Atmospheric
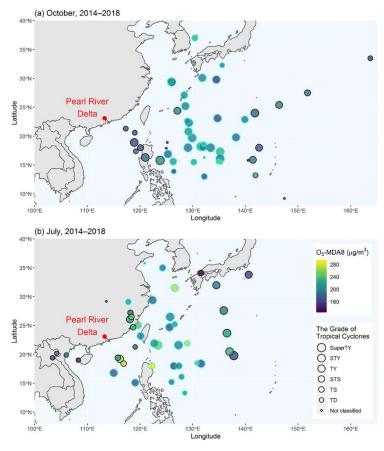Chemistry
and Physics
Discussions

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.

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 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

6

Atmospheric
Chemistry
and Physics
Discussions

Open Access

EGU

163 points was set as 100 m above the ground, which is close to the height of emissions. The start times were set as 2:00, 8:00,

164 14:00 and 20:00 LT for all O_3 pollution days. Afterwards, the length of time each trajectory remained within the administration

165 borders of the PRD, i.e., APRT, was calculated. The APRT values of all points were averaged for each scenario and were

166 interpolated to obtain field results.

167 **2.4 CMAQ modelling: basic setups and modelling methods**

168 We utilised the widely used 3D chemical transport model, the CMAQ model (version 5.0.2), to investigate the effect of

169 typhoons on O_3 processes and sources. October 2015 and July 2016 featured the most severe O_3 pollution under typhoon

170 influence among all representative months of the two seasons (Table S3), and thus, they were chosen as the period in the

171 CMAQ modelling (because there was no severe O_3 pollution during the first 10 days of October 2015 and 3–5 November can

172 be classified as the no-typhoon O_3 pollution days, we adjusted the modelling period in autumn to 11 October–10 November

173 2015) and all O_3 pollution days in these two months served as representative O_3 pollution days under multiple scenarios. In

174 detail, there were four typhoon-induced O_3 pollution days (14–16 and 21 October 2015) and four no-typhoon O_3 pollution days

175 (28 October and 3–5 November 2015) in October 2015, whereas there were four and six typhoon-induced and no-typhoon

176 days in July 2016, respectively (typhoon-induced: 7–8 and 30–31 July 2016; and no-typhoon: 22–26 and 29 July 2016). The

177 results of the daytime (9:00–17:00 LT) O_3 PA and SA on the above O_3 pollution days were averaged for each scenario and

178 were used in the comparisons.

179

180 The main setups of the CMAQ modelling are presented as follows. Two-nested modelling domains with the resolutions of 36

181 and 12 km (denoted as d01 and d02, respectively) were set in this study (Fig. 2). Specifically, d02 covers the whole East and

182 Central China (EC-China), enabling us to evaluate the contribution of emissions in these areas to O_3 pollution in the PRD.

183 There were 19 vertical layers in the CMAQ modelling, with about 10 layers within the PBL (about 0–1 km in heights; Guo et

184 al., 2016). The Weather Research and Forecasting (WRF) model (version 3.2) provided the meteorological fields used as inputs.

185 SMOKE (version 2.5) and MEGAN (version 2.10) were used to process the anthropogenic and biogenic emission files,

186 respectively. The anthropogenic emission inventory used in this study consisted of the following three parts: (1) emissions in

187 the PRD, which were provided by the Guangdong Environmental Monitoring Centre; (2) emissions in other areas of mainland

188 China, which were extracted from the MEIC inventory (He, 2012); and (3) emissions in other countries and regions in Asia,

189 which were extracted from the MIX inventory (Li et al., 2017). The initial and boundary conditions of the d01 modelling were

190 obtained from the same-period results of the MOZART-4 global model (available at https://www.acom.ucar.edu/wrf-

191 chem/mozart.shtml, last accessed: Dec. 2019), and those of the d02 modelling were extracted from the d01 modelling results.

192 The SAPRC07 gas-phase chemistry mechanism (Carter, 2010) and the AERO6 aerosol scheme were set in the CMAQ

193 modelling. In addition, the simulations of the two months were both started 10 days ahead to minimise the disturbance of the

194 bias of the initial conditions. The modelling performances of CMAQ and WRF were determined to be acceptable based on the

195 comparisons between the observational and modelling series of meteorological parameters, O_3 MDA8, daily NO_2

196 concentrations and the mixing ratios of non-methane hydrocarbons (NMHCs) in the PRD (for details, refer to Sect. 1 of the

197 Supplement Information), which ensures the validity of the further analyses.

198

199

200 **Figure 2.** Two-nested modelling domain, noted as d01 and d02. The black boxes indicate the WRF modelling domains, and the nested
201 areas are the CMAQ modelling domains.

202 The PA tool in CMAQ was implemented to quantify the hourly contributions of O_3 processes (or integrated process rate, IPR),

203 which includes vertical/horizontal transport (convection+diffusion), chemical process (net O_3 production), dry deposition and

204 cloud process. To explore the overall effect of typhoons on O_3 transport and production in the region, the mean PA results

205 within the administration boundaries of the PRD were calculated and compared.

206

207 We used the classic Brute Force Method (BFM) to identify the contributions of emissions (including anthropogenic and

208 biogenic emissions) in the PRD and other regions in the d02 (mainly EC-China), as well as regions outside the d02 (the

209 boundary conditions of the d02) for O_3 pollution in the PRD (hereafter denoted as the contributions of PRD, EC-China and

210 BCON, or S_{PRD}, $S_{EC\text{-}China}$ and S_{BCON}, respectively). For a pollutant, the contribution of a specific emission, E_i, can be calculated

211 in two ways: (1) the difference between the modelled concentrations of the base case (all emissions involved) and the sensitivity

212 case where E_i is zeroed out (i.e., top-down BFM); (2) the difference between two sensitivity cases where emissions expect E_i

213 and all of the emissions are zeroed out, respectively (i.e., bottom-up BFM). Owing to the non-linearity between O_3 and its

214 precursors, biases may occur between the results of two types of BFM methods (Clappier et al., 2017). Therefore, the average

215 of the top-down and bottom-up BFM results was treated as the quantified contributions of the concerned sources. Four

216 simulation cases were run in this study, including (the modelled O_3 concentration in each case was also marked in brackets):

217 • the base case (C_{base});

218 • the PRD-cut case (C_{PRD_cut}), where emissions within the PRD were zeroed out;

219 • the PRD-only case (C_{PRD_only}), where emissions outside the PRD (within d02) were zeroed out; and

220 • the zero-emission case (C_0), where all emissions within the d02 were zeroed out.

221   Afterwards, the S_{PRD}, $S_{EC\text{-}China}$ and S_{BCON} values (in concentrations) in the polluted areas of the PRD (where modelled daytime

222   O_3 concentrations > 160 μg/m^3, the Grade-II O_3 MDA8 thresholds of the Chinese NAAQS) were calculated using the following

223   equations,

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

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

$$S_{BCON} = C_0. \tag{R3}$$

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

225   **3 Comparison of meteorological conditions**

226   **3.1 Overview: comparison of meteorological parameters in the PRD**

227   First, we compared near-ground meteorological parameters in the PRD on the typhoon-induced and no-typhoon O_3 pollution

228   days. The parameters from the ERA-Interim re-analysis (including the parameters of the first and second categories in Sect.

229   2.1) and the routine monitoring datasets (including air temperature, RH, wind speed, zonal and meridional wind speeds)

230   were used in the comparison. The Mann-Whitney U test was applied to determine whether the above parameters were

231   significantly different ($p < 0.05$) in the two types of O_3 pollution scenarios.

232

233   As is listed in Table 2, statistically significant differences between the typhoon-induced and no-typhoon scenarios existed for

234   most of the parameters, such as meridional (south-north) wind speed, cloud covers within various height ranges and net

235   surface solar radiation — in both seasons, these parameters were significantly different for the two scenarios. It indicates that

236   the causes of O_3 pollution may vary on typhoon-induced and no-typhoon O_3 pollution days. Note that air temperature, one of

237   the parameters most closely related to O_3 pollution in the PRD (Zhao et al., 2019), was not significantly different in the two

238   scenarios. We also found that the comparison in autumn and summer did not produce the same results: the typhoon-induced

239   days in autumn featured lower RH, stronger winds (especially north wind), reduced cloud cover (low, medium, high and

240   total) and stronger surface solar radiation, whereas in summer, these days had higher RH, weaker south winds, more cloud

241   cover (medium, high and total), weaker surface solar radiation and lower PBL heights. Therefore, the impact of typhoons on

242   O_3 pollution differs in the two seasons, as well. In order to reveal the impact of typhoons on O_3 transport, production, and

243   accumulation in the PRD, more detailed comparisons of the corresponding meteorological indicators are presented in the

244   following sections.

Atmospheric
Chemistry
and Physics
Discussions

245 **Table 2.** The comparisons of meteorological parameters (all at 14:00 LT except for net surface solar radiation, which is the average value
246 for 9:00–17:00 LT) in the PRD for the three scenarios (no-typhoon, typhoon-induced, close typhoon-induced) in two seasons (autumn,
247 summer). RM, routine measurement; ERA, ERA-Interim re-analysis. All of the parameters are presented as "the mean value ± standard
248 deviation". The differences between parameters in the typhoon-induced or close typhoon-induced scenarios and the corresponding
249 typhoon-induced scenarios for the same season are given in parentheses, and "*" indicates $p < 0.05$, or statistically significant differences
250 between these parameters when the Mann-Whitney U test is used.

Parameters	Data Source	Autumn (October, 2014–2018)			Summer (July, 2014–2018)		
		No-typhoon	Typhoon-induced	Close Typhoon-induced	No-typhoon	Typhoon-induced	Close Typhoon-induced
Air Temperature (℃)	RM	29.1 ±2.2	29.3 ±1.8 (+0.2)	29.6 ±1.5 (+0.5, *)	33.7 ±2.0	33.9 ±2.0 (+0.2)	35.0 ±1.5 (+1.3, *)
	ERA	29.2 ±2.1	29.3 ±1.6 (+0.1)	29.6 ±1.5 (+0.4, *)	33.4 ±1.8	33.5 ±1.4 (+0.1)	34.6 ±1.4 (+1.2, *)
RH (%)	RM	52.4 ±10.2	44.8 ±10.4 (-7.6, *)	51.4 ±12.4 (-1.0)	57.0 ±9.3	58.3 ±9.7 (+1.3)	56.9 ±6.4 (-0.1)
	ERA	54.0 ±9.8	48.3 ±11.2 (-5.7, *)	52.2 ±12.4 (-1.8, *)	62.6 ±10.8	66.4 ±9.4 (+3.8, *)	62.5 ±9.4 (+0.1)
Wind Speed (m/s)	RM	2.33 ±1.18	2.58 ±1.23 (+0.25, *)	2.96 ±1.40 (+0.63, *)	2.46 ±1.33	2.30 ±1.20 (-0.16)	2.53 ±1.16 (+0.07)
	ERA	2.39 ±1.30	2.54 ±0.99 (+0.15, *)	3.53 ±1.11 (+1.14, *)	2.41 ±0.99	2.18 ±1.18 (-0.23, *)	2.61 ±1.05 (+0.20)
Zonal (East-West) Wind Speed (m/s)	RM	-0.83 ±1.72	-0.59 ±1.70 (+0.24, *)	-0.13 ±1.74 (+0.70, *)	-0.41 ±2.05	-0.03 ±1.94 (+0.38)	0.73 ±1.98 (+1.14, *)
	ERA	-1.41 ±1.43	-1.07 ±1.04 (+0.34, *)	-0.87 ±0.79 (+0.54, *)	0.22 ±1.73	-0.02 ±1.81 (-0.24)	0.29 ±2.45 (+0.07)
Meridional (South-North) Wind Speed (m/s)	RM	-0.36 ±1.74	-1.49 ±1.66 (-1.13, *)	-2.21 ±1.66 (-1.85, *)	0.79 ±1.69	0.01 ±1.72 (-0.78, *)	-0.69 ±1.68 (-1.48, *)
	ERA	-0.27 ±1.82	-1.97 ±1.16 (-1.70, *)	-3.27 ±1.29 (-3.00, *)	1.61 ±1.09	0.64 ±1.58 (-0.97, *)	-0.68 ±1.19 (-2.29, *)
Low Cloud Cover (%)	ERA	17.2 ±22.7	4.2 ±11.9 (-13.0, *)	15.5 ±23.9 (-1.7, *)	8.7 ±9.4	7.1 ±9.5 (-1.6, *)	5.2 ±5.0 (-3.5, *)
Medium Cloud Cover (%)	ERA	22.2 ±26.5	10.4 ±19.7 (-11.8, *)	9.5 ±14.5 (-12.7, *)	8.7 ±11.1	15.4 ±15.1 (+6.7, *)	21.5 ±15.5 (+12.8, *)
High Cloud Cover (%)	ERA	12.1 ±23.1	7.2 ±16.3 (-4.9, *)	34.6 ±35.6 (+22.5, *)	32.2 ±30.0	44.9 ±29.3 (+12.7, *)	51.0 ±34.2 (+18.8, *)
Total Cloud Cover (%)	ERA	43.5 ±32.3	20.5 ±25.7 (-23.0, *)	51.9 ±33.1 (+8.4, *)	43.7 ±26.7	58.3 ±22.7 (+14.6, *)	67.5 ±21.0 (+23.7, *)
Net Surface Solar Radiation (W/m²)	ERA	456.9 ±78.4	516.6 ±66.7 (+59.7, *)	516.5 ±62.8 (+59.6, *)	560.3 ±93.1	523.2 ±74.4 (-37.1, *)	541.9 ±54.0 (-18.4, *)
PBL Height (m)	ERA	1471 ±315	1473 ±348 (+2)	1349 ±227 (-122, *)	1268 ±383	1037 ±289 (-231, *)	1196 ±300 (-72, *)

251 **3.2 O₃ transport conditions: comparison of wind speeds, backward trajectories and vertical air motions**

252 The higher wind speeds and/or O_3 levels in the transported air masses are, the more likely O_3 transport plays an increasingly
253 important role in O_3 pollution. In the PRD, O_3 levels are closely linked to the type of air masses influencing the region, which
254 can be identified based on backward trajectories. According to Zheng et al. (2010), there are generally three types of air masses

255 that are transported into the PRD along different paths and contribute to O_3 pollution here, namely, the continental, coastal and

256 marine air masses (Fig. 3a). The continental and coastal air masses can bring O_3 from EC-China to the PRD, and thus, they

257 are typically recognised as being polluted and contributing to relatively high O_3 levels in the PRD. In contrast, the marine air

258 masses, originated from the South China Sea, are much cleaner. In this section, we studied the influence of typhoons on O_3

259 transport by comparing wind speeds and 72-h backward trajectories in various scenarios.
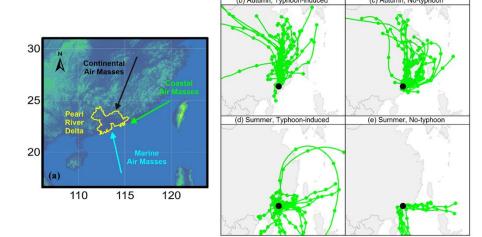
260

261

262 **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,
263 typhoon-induced; (c) autumn, no-typhoon; (d) summer, typhoon-induced; and (e) summer, no-typhoon. The black dots indicate the end
264 point of all trajectories, i.e., where the Modiesha site in the central PRD is located.

265 As is displayed in Fig. 3b–c, we identified the influence of continental air masses on the typhoon-induced O_3 pollution days

266 in autumn, as well as mixed contributions from the continental and coastal air masses on the corresponding no-typhoon days.

267 However, for the former scenario, significantly increased wind speeds (Table 2) ensure more favourable conditions for the

268 transport of O_3. In summer, the three types of air masses may all have affected O_3 pollution in the typhoon-induced scenario,

269 while only the marine air masses influenced the PRD in the no-typhoon scenario (Fig. 3d–e). Since wind speeds did not vary

270 significantly (Table 2), the inflows of much more polluted air masses resulted in that typhoons also tended to increase the

271 contribution of transport to O_3 pollution in the PRD in summer. In addition, the influence of different air masses was also

272 accompanied with variations in the prevailing winds in the PRD, that is, north winds and easterlies in the typhoon-induced and

273 no-typhoon scenario in autumn, respectively, and southwest winds in the no-typhoon scenario in summer (indicated by wind

274 roses in Fig. S5). For the typhoon-induced scenario in summer, the dominate wind direction is hard to determine. These

275 variations in the local wind fields potentially result in the different spatial distribution of O_3 concentrations in various scenarios.

276

277 Downdrafts are typically considered to be an important cause of typhoon-induced O_3 pollution (Lam, 2018), but in which

278 scenarios downdrafts influence the PRD remains unclear. Thus, we explored the overall features of vertical air motions from
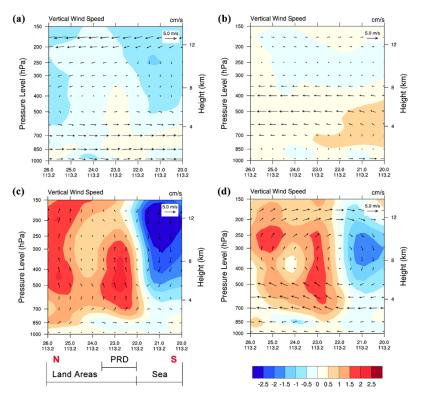
279   the surface layer to the tropopause in four scenarios, and the ERA-Interim reanalysis dataset (including the parameters of the

280   third category in Sect. 2.1) was utilised in the comparisons. The contours in Fig. 4 show the cross section of vertical wind

281   speed 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

282   occurred over large areas above the PRD, especially above a height of ~4 km. Although updrafts can still be found near the

283   sea surface in this scenario, vertical wind speeds tended to be lower compared with those on the no-typhoon days in autumn,

284   which also suggests the enhancement of downdrafts caused by typhoons. In summer, the influence of downdrafts was found

285   over the PRD under 850 hPa on the typhoon-induced O_3 pollution days. However, overall, updrafts prevailed above the land

286   areas and downdrafts prevailed above the sea in both the typhoon-induced and no-typhoon scenarios in summer, which is

287   recognised as the structure of the East Asian summer monsoon cell (Chen et al., 1964; Jin et al., 2013; Ding et al., 2018). For

288   both updrafts and downdrafts, the absolute values of vertical wind speeds in the typhoon-induced scenario in summer were

289   overall higher than these in the corresponding no-typhoon scenario. Therefore, the approach of typhoons did not break the

290   structure of the summer monsoon cell, but rather they further strengthened the vertical motions above both land areas and sea.

291   These analyses suggest that typhoons do not necessarily lead to downdrafts during O_3 pollution periods in the PRD and its

292   adjacent areas; and in summer, vertical air motions affected by typhoons are more complicated than expected owing to the

293   existence of the East Asian summer monsoon.

294

295   We also explored the regions where downdrafts and updrafts occurred on a larger scale and their potential connections with

296   O_3 levels. As is shown in Fig. 5, though updrafts appeared in the PRD at 850 hPa on the typhoon-induced days in autumn,

297   downdrafts dominated in the region at 700 and 500 hPa. For the areas to the north of the PRD, the important role of downdrafts

298   was found at all three heights. In contrast to the no-typhoon days in autumn, downdrafts tended to cover much larger areas in

299   this scenario. Moreover, these areas at 850 and 700 hPa generally featured higher O_3 mixing ratios as well as lower RH (Fig.

300   S6) than others, which is a sign of possible direct downward O_3 transport (Roux et al., 2020; Wang et al., 2020). This part of

301   O_3 can notably aggravate near-ground O_3 pollution in the PRD. In contrast, in summer, updrafts dominated the PRD at various

302   heights in both scenarios. Besides the PRD, most of the regions near the coast were characterised by updrafts above the land

303   as well as downdrafts offshore, further indicating the ubiquity of the summer monsoon cell. By comparing the two scenarios

304   in summer, we found that typhoons resulted in more areas being influenced by updrafts. The areas with high O_3 levels did not

305   coincide with the downdraft-affected areas, and therefore, O_3 transported from the upper air may play a less significant role in

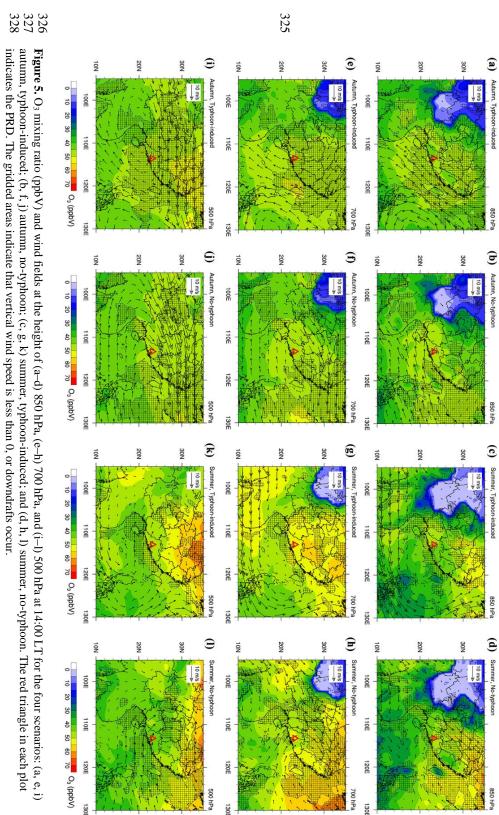306   the typhoon-induced O_3 pollution in summer.

Figure 4. The cross sections of mean vertical wind field 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 are 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), and the contours indicate vertical wind speed (cm/s). PRD, the Pearl River Delta.
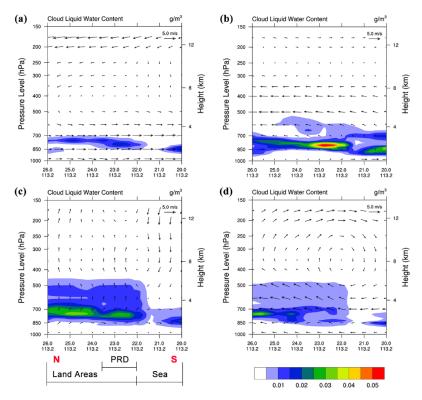
3.3 O₃ production conditions: comparison of clouds

Clouds efficiently reflect solar radiation (Liou, 1976), and therefore, they have a notable impact on the local formation of O_3. The comparison of cloud liquid water content in the cross section (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 at the heights of 2–5 km 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. O₃ mixing ratio (ppbV) and wind fields at the height of (a–d) 850 hPa, (e–h) 700 hPa, and (i–l) 500 hPa at 14:00 LT for the four scenarios: (a, e, i) autumn, typhoon-induced; (b, f, j) autumn, no-typhoon; (c, g, k) summer, typhoon-induced; and (d, h, l) summer, no-typhoon. The red triangle in each plot indicates the PRD. The gridded areas indicate that vertical wind speed is 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 are 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.
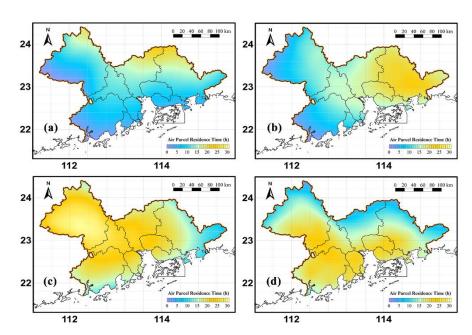
3.4 O$_3$ accumulation conditions: comparison of APRTs

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 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 offset the influence of weakened O$_3$ formation to some extent. In both seasons, typhoons did not cause more favourable conditions for O$_3$ production and accumulation simultaneously in the PRD, potentially

15

346 resulting in a less important role of local contributions in O_3 pollution here. More quantitative evaluations of the contributions

347 from multiple O_3 sources are discussed in Sect. 4.

348

349

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

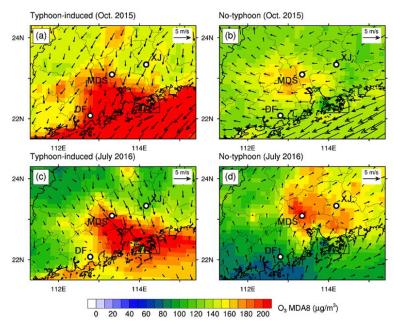352 **3.5 Meteorological conditions on the close typhoon-induced days**

353 On the close typhoon-induced days in the two seasons, stronger north winds prevailed and total cloud cover was higher than

354 that on the no-typhoon days (Table 2), suggesting better conditions for the transport of O_3 but less favourable conditions for

355 O_3 production. As displayed in Fig. S7, the APRT values were significantly lower on the close typhoon-induced days (mean

356 = 6.6 hours, 12.9 hours in autumn and summer, respectively) than on the no-typhoon days, making it even harder for locally

357 sourced O_3 to accumulate within the PRD. Therefore, close typhoons are concluded to promote the transport of O_3 from the

358 outside and to reduce the contributions of O_3 produced from local emissions in a more notable way. In addition, close typhoons

359 led to stronger downdrafts in autumn and updrafts in summer than other scenarios in the same season (Fig. S8). It should be

360 noted that the structure of the summer monsoon cell near the PRD was destroyed in the close typhoon-induced scenario in

361 summer, indicating the stronger influence of typhoons on regional wind fields. The dominant role of O_3 transport during O_3

362 pollution days in this special scenario agrees well with the reported episode-based analyses (Lam et al., 2005; Li, 2013).

363 **4 Comparisons of O₃ processes and sources**

364 The comparisons of meteorological conditions served as qualitative evidence to determine the general influence of typhoons

365 on O₃ transport, production and accumulation in autumn and summer. Based on the comparison between the CMAQ modelling

366 results on typical O₃ pollution days in October 2015 and July 2016, more quantitative evidence can be presented. Figure 8

367 displays modelled mean O₃ MDA8 concentrations and wind fields (at 14:00 LT) in the four scenarios. Large standard-

368 exceedance (> 160 μg/m³) areas were distributed in the PRD on most days, and the typhoon-induced days of both seasons

369 generally featured higher O₃ levels. The distinct wind fields for these scenarios, which were consistent with those in the longer

370 timespan (Fig. S5), indeed led to different spatial distributions of O₃. Generally, the most severe O₃ pollution occurred in the

371 downwind areas, such as the central and southern parts of the PRD on the typhoon-induced days in October 2015, the central

372 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

373 typhoon-induced days in July 2016, high levels of O₃ accumulated around the PRE. In this section, we discuss the different

374 contributions of various O₃ processes and sources on these days to better understand the effect of typhoons on O₃ pollution in
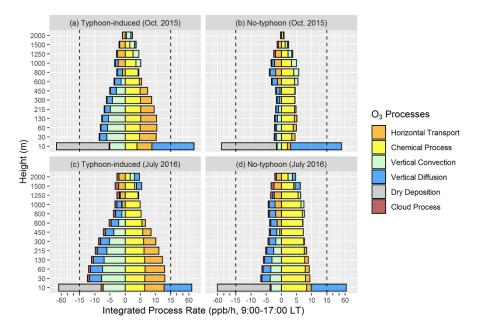
375 the PRD.

376

377

378 **Figure 8.** Modelling mean O₃ MDA8 concentrations (μg/m³) and wind vectors (at 14:00 LT) on the representative O₃ pollution days: (a)
379 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
380 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
381 and 29 July 2016). Three representative sites in the PRD are shown as black circles in the plots: XJ, Xijiao; MDS, Modiesha; DF,
382 Duanfen.

Atmospheric
Chemistry
and Physics
Discussions

4.1 O₃ 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 four 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.
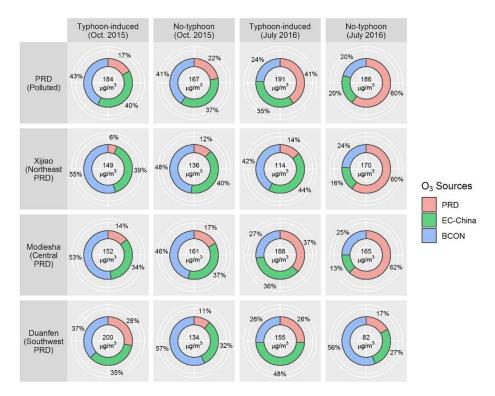

Figure 9. The daytime-mean (9:00–17:00 LT) hourly contributions of O_3 processes within the PRD in vertical layers 1–13 on representative O_3 pollution days: (a) the typhoon-induced days in October 2015 (14–16 and 21 October 2015); (b) the no-typhoon days in October 2015 (28 October and 3–5 November 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).

Atmospheric
Chemistry
and Physics
Discussions

Open Access

EGU

4.2 O₃ sources: local sources vs regional sources

The contributions of various sources to O$_3$ within the PRD are determined by the combined impact of O$_3$ transport, production and accumulation. The results for the daytime (9:00–17:00 LT) O$_3$ SA near the ground (about 0–80 m in height) in four scenarios are illustrated in Fig. 10. For polluted regions within the PRD, stronger O$_3$ production under typhoons did not lead to a higher proportion of local contributions to O$_3$ 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 O$_3$ SA results is more apparent for the summer scenarios, that is, typhoons resulted in growing contributions from O$_3$ transported from other regions (from 40% to 59%) but decreased local contributions (from 60% to 41%) in July 2016. More favourable O$_3$ accumulation conditions (indicated by higher APRTs on the representative typhoon-induced O$_3$ pollution days in summer (Fig. S9)) were far from sufficient to compensate for the effect of weakened O$_3$ production on the high contributions of local sources.

Figure 10. The O$_3$ SA near the ground (about 0–80 m in height) on representative O$_3$ pollution days for the four scenarios (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 O$_3$ SA in different parts of the PRD may differ from the regional ones. For instance, while the comparisons of O$_3$ SA in the Xijiao and Modiesha site (located in the northeast

422 and central part of the PRD, respectively) agree well with those in the polluted regions of the PRD, higher contributions of

423 PRD emissions for O_3 can be found in the Duanfen site (located in the southwest part of the PRD) on the typhoon-induced

424 days of two months in comparison to these on the corresponding no-typhoon days (Fig. 10). Since the site was located in the

425 downwind region in the typhoon-induced scenario in October 2015 (Fig. 8a), enhanced O_3 production led by typhoons from

426 the massive emissions of O_3 precursors in the central PRD (Zheng et al., 2009) contributed to higher local contributions for O_3

427 pollution here (the highest local contribution in the PRD occurred in areas near the Duanfen site and almost reached 40% in

428 this scenario, which was even higher than that in the corresponding no-typhoon scenario (33%)). In the no-typhoon scenario

429 in July 2016, the site was located in the upwind regions under the prevailing of southwest winds, limiting the contributions of

430 local emissions for O_3 at the site (Fig. 8d). Thus, higher local contributions can also be found in the typhoon-induced scenario

431 in this month.

432 **5 Discussion and conclusions**

433 The significance of typhoons on O_3 pollution in the PRD calls for thorough evaluations of the different causes of O_3 pollution

434 with the appearance of typhoons in the Northwest Pacific. In this study, we revealed the different impacts of typhoons on O_3

435 transport, production and accumulation in the PRD (as summarised in Fig. 11) through systematic comparisons of

436 meteorological conditions, the contributions of various O_3 processes and sources in the typhoon-induced and no-typhoon

437 scenarios. We found that typhoons tended to promote O_3 transport towards the PRD, but failed to provide more favourable O_3

438 production and accumulation conditions simultaneously, which limited the contribution of local emissions to O_3 pollution.

439 Furthermore, there were also differences between the influence of typhoons on O_3 pollution in autumn and summer. More

440 favourable transport conditions occurred in the typhoon-induced scenario in autumn, which was characterised by higher wind

441 speeds and the increased influence of downdrafts. In summer, the mixed types of air masses in the typhoon-induced scenario

442 were likely to bring more O_3 into the PRD than the clean marine air masses in the no-typhoon scenario, also suggesting

443 enhanced O_3 transport under the influence of typhoons. Generally, typhoons led to cloudless conditions, stronger solar radiation,

444 and thus more rapid O_3 production in autumn, but shorter APRTs (5–10 hours) suggest that locally sourced O_3 was hard to

445 accumulate within the PRD. As a result, the contributions in percentage of local emissions to O_3 pollution decreased (slightly

446 by ~5% for the polluted regions of the PRD in October 2015). In contrast, in summer, intensified updrafts associated with

447 typhoons strengthened cloud formation, weakened solar radiation, and thus restrained local O_3 production. Longer APRTs (>

448 20 hour) under typhoon influence were far from sufficient to maintain high contributions of local emissions for O_3 pollution

449 (which decreased by ~20% for the polluted regions of the PRD in July 2016). However, due to the variations of wind fields

450 under different scenarios, the changes of local and transport contributions for O_3 led by typhoons were different in the

451 southwest part of the PRD, that is, higher contribution from emissions within the PRD and reduced transport contribution

452 occurred in the typhoon-induced scenarios in both seasons. As for the close typhoon-induced scenario, O_3 transport was further

453   strengthened, but meteorological conditions in the PRD became less favourable for both the production and accumulation of

454   O_3.

455

456

Figure 11. The summary of the causes of O_3 pollution in the PRD under typhoon influence in autumn and summer.

458   The East Asian monsoon, changing with seasons, has a pronounced impact on local meteorological conditions as well as the

459   characteristics of O_3 pollution in East China (He et al., 2008). The seasonal behaviour of the East Asian monsoon is likely to

460   result in the seasonally varied effect of typhoons on O_3 pollution in the PRD. In October, the summer monsoon has almost

461   finished its retraction and the winter monsoon is beginning (Ding, 1994). Thus, there are not many obstacles to the southward

462   movement of typhoon periphery and the transport of O_3 towards the PRD by the continental and coastal air masses. Large

463   downdraft-influenced areas in Central and South China occur in this scenario, and high O_3 levels and low RH in these areas

464   indicate the potentially important role of directly downward O_3 transport. In July, the summer monsoon reaches its strongest

465   (Ding, 1994). The interaction between typhoon periphery and the summer monsoon results in stagnation and enhanced updrafts

466   above the land areas of the PRD and its surroundings. Only when typhoon is close enough to the PRD is the stagnation

467   terminated and the structure of the summer monsoon cell broken. This also explains why some summertime typhoon-induced

468   O_3 episodes in the PRD can be typically divided into two periods, as stagnation leads to the accumulation of locally produced

469   O_3 in the first phase and strong northerly winds strengthen O_3 transport before the landing of typhoons (Lam et al., 2005; Li,

470   2013). It should be noted that updrafts, rather than downdrafts, prevailed on the typhoon-induced O_3 pollution days in summer.

471   High levels of O_3 did not necessarily occur in the regions dominated by downdrafts in this scenario, suggesting a less notable

472   connection between downdrafts and summertime O_3 pollution in the PRD. Further investigations are required to trace the

473   detailed process of downward O_3 transport, including the stratosphere-troposphere exchange (Stohl et al., 2003), in each

474   scenario, and quantify their contributions to near-ground O_3 pollution.

475

476 Some limitations remain in this study. We chose O_3 pollution days as individual samples, ignoring the influence of O_3 pollution
477 on the previous days. Thus, more detailed full-episode analyses are required. Moreover, owing to the small sampling size, the
478 influence of typhoons on O_3 pollution in the PRD is still not fully understood, including, for instance, the detailed connections
479 between the features of typhoons (intensity, position) and O_3 pollution. However, the comparisons of meteorological conditions,
480 O_3 processes and sources in different scenarios and seasons demonstrate the complex causes of typhoon-induced O_3 pollution
481 in the PRD — typhoons tend to enhance O_3 transport into the PRD in both seasons, but their impacts on the production and
482 accumulation of O_3 are completely different. As a result, emissions within (outside of) the PRD are likely to contribute less
483 (more) on the typhoon-induced O_3 pollution days than on the no-typhoon days, and more attention should be paid to controlling
484 anthropogenic emissions of O_3 precursors on a larger scale under typhoon influence. This study also suggests that a thorough
485 evaluation of O_3 transport, production and accumulation conditions can be applied to understand the causes of regional O_3
486 pollution not only in the PRD, but also in other regions.

487

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

489

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

494

495 *Competing interests.* The authors declare no conflict of interest.

496

500

References

Berrisford, P., Dee, D., Poli, P., Brugge, R., Fielding, K., Fuentes, M., Kallberg, P., Kobayashi, S., Uppala, S., and Simmons, A.: The ERA-Interim archive Version 2.0, ERA report series, 1, 1–16, 2011.

Carter, W. P. L.: Development of the SAPRC-07 chemical mechanism, Atmos. Environ., 44, 5324–5335, https://doi.org/10.1016/j.atmosenv.2010.01.026, 2010.

Chen, H., Wang, X., Shen, J., Lu, K., and Zhang, Y.: Ozone source apportionment of typical photochemical pollution episodes in the Pearl River Delta in autumn, Acta Scientiarum Naturalium Universitatis Pekinensis (in Chinese), 51, 620–630, https://doi.org/10.13209/j.0479-8023.2015.089, 2015.

Chen, Q., Miao, J., and Li, W.: A comparison of mean wind field and mean meridional circulation between south-west monsoon area in Southeast Asia and Pacific trade wind area in July, 1958, Acta Meteorologica Sinica (in Chinese), 34(1), 51–61, https://doi.org/10.11676/qxxb1964.006, 1964.

Chen, X., Liu, Y., Lai, A., Han, S., Fan, Q., Wang, X., Ling, Z., Huang, F., and Fan, S.: Factors dominating 3-dimensional ozone distribution during high tropospheric ozone period, Environ. Pollut., 232, 55–64, https://doi.org/10.1016/j.envpol.2017.09.017, 2018.

Chow, E. C., Li, R. C., and Zhou, W.: Influence of tropical cyclones on Hong Kong air quality, Adv. Atmos. Sci., 35(9), 1177–1188, https://doi.org/10.1007/s00376-018-7225-4, 2018.

Chow, E. C., Wen, M., Li, L., Leung, M. Y., Cheung, P. K., and Zhou, W.: Assessment of the Environmental and Societal Impacts of the Category-3 Typhoon Hato, Atmosphere, 10(6), 296. https://doi.org/10.3390/atmos10060296, 2019.

Clappier, A., Belis, C. A., Pernigotti, D., and Thunis, P.: Source apportionment and sensitivity analysis: two methodologies with two different purposes, Geosci. Model Dev., 10, 4245–4256, https://doi.org/10.5194/gmd-10-4245-2017, 2017.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beijaars, A.C.M., van de Berg, L., Bidiot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hólm, E.V., Isaksen, L., Isaksen, L., Källberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, Thépaut, J.-N., and Vitart, F.: The ERA−Interim reanalysis: Configuration and performance of the data assimilation system, Q. J. Roy. Meteor. Soc., 137(656), 553–597, https://doi.org/10.1002/qj.828, 2011.

Deng, T., Wang, T., Wang, S., Zou, Y., Yin, C., Li, F., Liu, L., Wang, N., Song, L., Wu, C., and Wu, D.: Impact of typhoon periphery on high ozone and high aerosol pollution in the Pearl River Delta region, Sci. Total Environ., 668, 617–630, https://doi.org/10.1016/j.scitotenv.2019.02.450, 2019.

Ding, Y. H.: Monsoons over China, Kluwer Academic Publishers, Dordrecht/Boston/London, 1994.

Ding, Y., Si, D., Liu, Y., Wang, Z., Li, Y., Zhao, L., and Song, Y.: On the Characteristics, Driving Forces and Inter-decadal Variability of the East Asian Summer Monsoon, Chinese Journal of Atmospheric Sciences (in Chinese), 42(3), 533–558, https://doi.org/10.3878/j.issn.1006-9895.1712.17261, 2018.

534 Feng, Y., Ning, M., Lei, Y., Sun, Y., Liu, W., and Wang, J.: Defending blue sky in China: Effectiveness of the "Air
535   Pollution Prevention and Control Action Plan" on air quality improvements from 2013 to 2017, J. Environ. Manage.,
536   252, 109603, https://doi.org/10.1016/j.jenvman.2019.109603, 2019.

537 Gao, X., Deng, X., Tan, H., Wang, C., Wang, N., and Yue, D.: Characteristics and analysis on regional pollution process and
538   circulation weather types over Guangdong Province, Acta Scientiae Circumstantiae (in Chinese), 38(5), 1708–1716,
539   https://doi.org/10.13671/j.hjkxxb.2017.0473, 2018.

540 Guo, J., Miao, Y., Zhang, Y., Liu, H., Li, Z., Zhang, W., He, J., Lou, M., Yan, Y., Bian, L., and Zhai, P.: The climatology of
541   planetary boundary layer height in China derived from radiosonde and reanalysis data, Atmos. Chem. Phys., 16, 13309–
542   13319, https://doi.org/10.5194/acp-16-13309-2016, 2016.

543 He, K.: Multi-resolution Emission Inventory for China (MEIC): model framework and 1990-2010 anthropogenic emissions,
544   American Geophysical Union, Fall Meeting 2012, San Francisco, the United States of America, 3–7 December 2012,
545   A32B-05, 2012.

546 He Y. J., Uno, I., Wang, Z. F., Pochanart, P., Li, J., and Akimoto, H.: Significant impact of the East Asia monsoon on ozone
547   seasonal behavior in the boundary layer of Eastern China and the west Pacific region, Atmos. Chem. Phys., 8, 7543–
548   7555, https://doi.org/10.5194/acp-8-7543-2008, 2008.

549 Huang, J. P., Fung, J. C., Lau, A. K., and Qin, Y: Numerical simulation and process analysis of typhoon-related ozone
550   episodes in Hong Kong, J. Geophys. Res.-Atmos., 110(D5), https://doi.org/10.1029/2004JD004914, 2005.

551 Huang, Y., Yao, T., Fung, J. C., Lu, X., and Lau, A. K.: Application of air parcel residence time analysis for air pollution
552   prevention and control policy in the Pearl River Delta region, Sci. Total Environ., 658, 744–752,
553   https://doi.org/10.1016/j.scitotenv.2018.12.205, 2019.

554 Jin, Q., Yang, X. Q., Sun, X. G., and Fang, J. B.: East Asian summer monsoon circulation structure controlled by feedback
555   of condensational heating, Clim. Dynam., 41(7-8), 1885–1897, https://doi.org/10.1007/s00382-012-1620-9, 2013.

556 Jiang, F., Wang, T., Wang, T., Xie, M., and Zhao, H.: Numerical modeling of a continuous photochemical pollution episode
557   in Hong Kong using WRF–chem, Atmos. Environ., 42(38), 8717–8727,
558   https://doi.org/10.1016/j.atmosenv.2008.08.034, 2008.

559 Lam, K. S., Wang, T. J., Wu, C. L., and Li, Y. S.: Study on an ozone episode in hot season in Hong Kong and transboundary
560   air pollution over Pearl River Delta region of China, Atmos. Environ., 39(11), 1967–1977,
561   https://doi.org/10.1016/j.atmosenv.2004.11.023, 2005.

562 Lam, Y. F.: Climate change and air quality in Southeastern China: Hong Kong study, in: Climate change and air pollution,
563   edited by: Akhtar R., and Palagiano C., Springer, Cham, 181–196, https://doi.org/10.1007/978-3-319-61346-8_12,
564   2018.

565 Lam, Y. F., Cheung, H. M., and Ying, C. C.: Impact of tropical cyclone track change on regional air quality, Sci. Total
566   Environ., 610, 1347–1355, https://doi.org/10.1016/j.scitotenv.2017.08.100, 2018.

567 Li, J., Lu, K., Lv, W., Li, J., Zhong, L., Ou, Y., Chen, D., Huang, X., and Zhang, Y.: Fast increasing of surface ozone
568   concentrations in Pearl River Delta characterized by a regional air quality monitoring network during 2006–2011, J.
569   Environ. Sci., 26(1), 23–36, https://doi.org/10.1016/S1001-0742(13)60377-0, 2014.

570 Li, M., Jiang, S., Gan, Q., Chen, F., Zeng, D., Li, J., Fan, S., and Zhu, W.: Characteristics of ozone pollution and analysis of
571   typical pollution processes in summer and autumn in Huizhou, Acta Scientiarum Naturalium Universitatis Sunyatseni
572   (in Chinese), 57(5), 29, https://doi.org/10.13471/j.cnki.acta.snus.2018.05.004, 2018.

573 Li, M., Zhang, Q., Kurokawa, J.-I., Woo, J.-H., He, K., Lu, Z., Ohara, T., Song, Y., Streets, D. G., Carmichael, G. R., Cheng,
574   Y., Hong, C., Huo, H., Jiang, X., Kang, S., Liu, F., Su, H., and Zheng, B.: MIX: a mosaic Asian anthropogenic emission
575   inventory under the international collaboration framework of the MICS-Asia and HTAP, Atmos. Chem. Phys., 17, 935–
576   963, https://doi.org/10.5194/acp-17-935-2017, 2017.

577 Li, K., Jacob, D. J., Liao, H., Shen, L., Zhang, Q., and Bates, K. H.: Anthropogenic drivers of 2013–2017 trends in summer
578   surface ozone in China, P. Natl. Acad. Sci. USA, 116(2), 422–427, https://doi.org/10.1073/pnas.1812168116, 2019.

579 Li, Y.: The evolution characteristics and source analysis of the secondary pollutants in summer over Pearl River Delta, Ph.D.
580   thesis, College of Environmental Science and Engineering, Peking University, China, 160 pp., 2013.

581 Li, Y., Lau, A. K. H., Fung, J. C. H., Zheng, J.Y., Zhong, L. J., and Louie, P. K. K.: Ozone source apportionment (OSAT) to
582   differentiate local regional and super-regional source contributions in the Pearl River Delta region, China, J. Geophys.
583   Res.-Atmos., 117, D15305, http://doi.org/10.1029/2011JD017340, 2012.

584 Liou, K. N.: On the absorption, reflection and transmission of solar radiation in cloudy atmospheres, J. Atmos. Sci., 33(5),
585   798–805, https://doi.org/10.1175/1520-0469(1976)033<0798:OTARAT>2.0.CO;2, 1976.

586 Lin, X., Yuan, Z., Yang, L., Luo, H., and Li, W.: Impact of extreme meteorological events on ozone in the Pearl River Delta,
587   China, Aerosol Air Qual. Res., 19(6), 1307–1324, https://doi.org/10.4209/aaqr.2019.01.0027, 2019.

588 Liu, H., Liu, S., Xue, B., Lv, Z., Meng, Z., Yang, X., Xue, T., Yu, Q., and He, K.: Ground-level ozone pollution and its
589   health impacts in China, Atmos. Environ., 173, 223–230, https://doi.org/10.1016/j.atmosenv.2017.11.014, 2018.

590 Lu, X., Hong, J., Zhang, L., Cooper, O. R., Schultz, M. G., Xu, X., Wang, T., Gao, M., Zhao, Y., and Zhang, Y.: Severe
591   surface ozone pollution in China: A global perspective, Environ. Sci. Tech. Let., 5(8), 487–494,
592   https://doi.org/10.1021/acs.estlett.8b00366, 2018.

593 Mills, G., Sharps, K., Simpson, D., Pleijel, H., Broberg, M., Uddling, J., Jaramillo, F., Davies, W. J., Dentener, F., Van den
594   Berg, M., Agrawal, M., Agrawal, S. B., Ainsworth, E. A., Büker, P., Emberson, L., Feng, Z., Harmens, H., Hayes, F.,
595   Kobayashi, K., Paoletti, E., and Van Dingenen, R.: Ozone pollution will compromise efforts to increase global wheat
596   production, Glob. Change Biol., 24, 3560–3574, https://doi.org/10.1111/gcb.14157, 2018.

597 National Research Council: Rethinking the Ozone Problem in Urban and Regional Air Pollution, Natl. Acad. Press,
598   Washington, D. C., USA, 1991.

599 Roux, F., Clark, H., Wang, K.-Y., Rohs, S., Sauvage, B., and Nédélec, P.: The influence of typhoons on atmospheric

600   composition deduced from IAGOS measurements over Taipei, Atmos. Chem. Phys., 20, 3945–3963,

601   https://doi.org/10.5194/acp-20-3945-2020, 2020.

602 So, K. L. and Wang, T.: On the local and regional influence on ground-level ozone concentrations in Hong Kong, Environ.

603   Pollut., 123(2), 307–317, https://doi.org/10.1016/S0269-7491(02)00370-6, 2003.

604 Stein, A. F., Draxler, R. R., Rolph, G. D., Stunder, B. J., Cohen, M. D., and Ngan, F.: NOAA's HYSPLIT atmospheric

605   transport and dispersion modeling system, B. Am. Meteorol. Soc., 96(12), 2059–2077, https://doi.org/10.1175/BAMS-

606   D-14-00110.1, 2015.

607 Stohl, A., Bonasoni, P., Cristofanelli, P., Collins, W., Feichter, J., Frank, A., Forster, C., Gerasopoulos, E., Gaggeler, H.,

608   James, P., Kentarchos, T., Kromp-Kolb, H., Kruger, B., Land, C., Meloen, J., Papayannis, A., Priller, A., Seibert, P.,

609   Sprenger, M., Roelofs, G. J., Scheel, H. E., Schnabel, C., Siegmund, P., Tobler, L., Trickl, T., Wernli, H., Wirth, V.,

610   Zanis, P., and Zerefos, C.: Stratosphere-troposphere exchange: A review, and what we have learned from STACCATO,

611   J. Geophys. Res., 108, 8516, https://doi.org/10.1029/2002JD002490, 2003.

612 Wang, H., Wang, W., Huang, X., and Ding A.: Impacts of stratosphere-to-troposphere-transport on summertime surface

613   ozone over eastern China, Sci. Bull., 65, 276–279, https://doi.org/10.1016/j.scib.2019.11.017, 2020.

614 Wang, N., Guo, H., Jiang, F., Ling, Z. H., and Wang, T.: Simulation of ozone formation at different elevations in

615   mountainous area of Hong Kong using WRF-CMAQ model, Sci. Total Environ., 505, 939–951,

616   https://doi.org/10.1016/j.scitotenv.2014.10.070, 2015.

617 Wang, T. and Kwok, J. Y: Measurement and analysis of a multiday photochemical smog episode in the Pearl River Delta of

618   China, J. Appl. Meteorol., 42(3), 404–416, https://doi.org/10.1175/1520-0450(2003)042<0404:MAAOAM>2.0.CO;2,

619   2003.

620 Wang, T., Lam, K. S., Lee, A. S., Pang, S. W., and Tsui, W. S.: Meteorological and chemical characteristics of the

621   photochemical ozone episodes observed at Cape D'Aguilar in Hong Kong, J. Appl. Meteorol., 37(10), 1167–1178,

622   https://doi.org/10.1175/1520-0450(1998)037<1167:MACCOT>2.0.CO;2, 1998.

623 Wang, T., Wu, Y. Y., Cheung, T. F., and Lam, K. S.: A study of surface ozone and the relation to complex wind flow in

624   Hong Kong, Atmos. Environ., 35(18), 3203–3215, https://doi.org/10.1016/S1352-2310(00)00558-6, 2001.

625 Wang, T., Xue, L., Brimblecombe, P., Lam, Y. F., Li, L., and Zhang, L.: Ozone pollution in China: A review of

626   concentrations, meteorological influences, chemical precursors, and effects, Sci. Total Environ., 575, 1582–1596,

627   https://doi.org/10.1016/j.scitotenv.2016.10.081, 2017.

628 Wang, X., Zhang, Y., Hu, Y., Zhou, W., Lu, K., Zhong, L., Zeng, L., Shao, M., Hu, M., and Russell, A. G.: Process analysis

629   and sensitivity study of regional ozone formation over the Pearl River Delta, China, during the PRIDE-PRD2004

630   campaign using the Community Multiscale Air Quality modeling system, Atmos. Chem. Phys., 10, 4423–4437,

631   https://doi.org/10.5194/acp-10-4423-2010, 2010.

632 Wei, X., Lam, K. S., Cao, C., Li, H., and He, J.: Dynamics of the typhoon Haitang related high ozone episode over Hong
633   Kong, Adv. Meteorol., 2016, https://doi.org/10.1155/2016/6089154, 2016.

634 Yang, J. X., Lau, A. K. H., Fung, J. C. H., Zhou, W., and Wenig, M.: An air pollution episode and its formation mechanism
635   during the tropical cyclone Nuri's landfall in a coastal city of south China, Atmos. Environ., 54, 746–753,
636   https://doi.org/10.1016/j.atmosenv.2011.12.023, 2012.

637 Ying, M., Zhang, W., Yu, H., Lu, X., Feng, J., Fan, Y., Zhu, Y., and Chen, D.: An overview of the China Meteorological
638   Administration tropical cyclone database, J. Atmos. Ocean Tech., 31(2), 287–301, https://doi.org/10.1175/JTECH-D-
639   12-00119.1, 2014.

640 Yue, H., Gu, T., Wang, C., Wu, D., Deng, X., Huang, J., and Wang, Y.: Influence of typhoon Nida process on ozone
641   concentration in Guangzhou, Acta Scientiae Circumstantiae (in Chinese), 38(12), 4565–4572,
642   https://doi.org/10.13671/j.hjkxxb.2018.0319, 2018.

643 Zhang, X., Liu, Y., Deng, X., Chen, P., Feng, Y., and Fan, Q.: Analysis of summertime typical pollution in Pearl River Delta
644   region——numerical simulation of meteorological field, Meteorological and Environmental Research, 59(4), 9–18,
645   2014.

646 Zhao, W., Gao, B., Liu, M., Lu, Q., Ma, S., Sun, S., Sun, J. Chen, L., and Fan, S.: Impact of meteorological factors on the
647   ozone pollution in Hong Kong, Huan jing ke xue= Huanjing kexue (in Chinese), 40(1), 55–66,
648   https://doi.org/10.13227/j.hjkx.201803151, 2019.

649 Zheng, J., Zhang, L., Che, W., Zheng, Z., and Yin, S.: A highly resolved temporal and spatial air pollutant emission
650   inventory for the Pearl River Delta region, China and its uncertainty assessment, Atmos. Environ., 43(32), 5112–5122,
651   https://doi.org/10.1016/j.atmosenv.2009.04.060, 2009.

652 Zheng, J., Zhong, L., Wang, T., Louie, P. K. K., and Li, Z.: Ground-level ozone in the Pearl River Delta region: Analysis of
653   data from a recently estabilished regional air quality monitoring network, Atmos. Environ., 44(6), 814–823,
654   https://doi.org/10.1016/j.atmosenv.2009.11.032, 2010.