A point to point response to the reviewers' comments

Thank you for the reviewers' comments on our manuscript entitled "Ozone affected by a succession of four landfall typhoons in the Yangtze River Delta, China: major processes and health impacts" (acp-2020-554). Those constructive comments are all valuable for revising and improving our manuscript, as well as the important guiding significance to our researches. We have studies those comments carefully and have made correction which we hope to meet with approval. Here are point to point responses (in blue colored). Accordingly, we also revised manuscript (in red colored).

Anonymous Referee #1:

General comments

This research is talking about an interesting topic. Ozone pollution episodes caused by the landfall typhoon were analyzed based on typical cases in the Yangtze River delta in China. This study provided an insight into the characteristics of the occurrence of ozone pollution and the changes in O3 concentrations during the special synoptic system. I think this paper is well-organized and presenting an important schematic diagram.

Response: we would like to express our great appreciation to you for your encouragement.

Specific comments

Here are some questions listed in the below, which need further addressing in the modified version:

Response: we thank the reviewer for the careful reading and the constructive comments, which are really important to improving our manuscript. We have carefully revised our manuscript based on the reviewer's comments.

1. Section 3.1, Figure2, since the influences of the typhoon cases are special in 2018, could the authors add summertime ozone concentrations in 2017 and 2019 (if the measurement data could be available) to compare with that in 2018 to show the roles clearer?

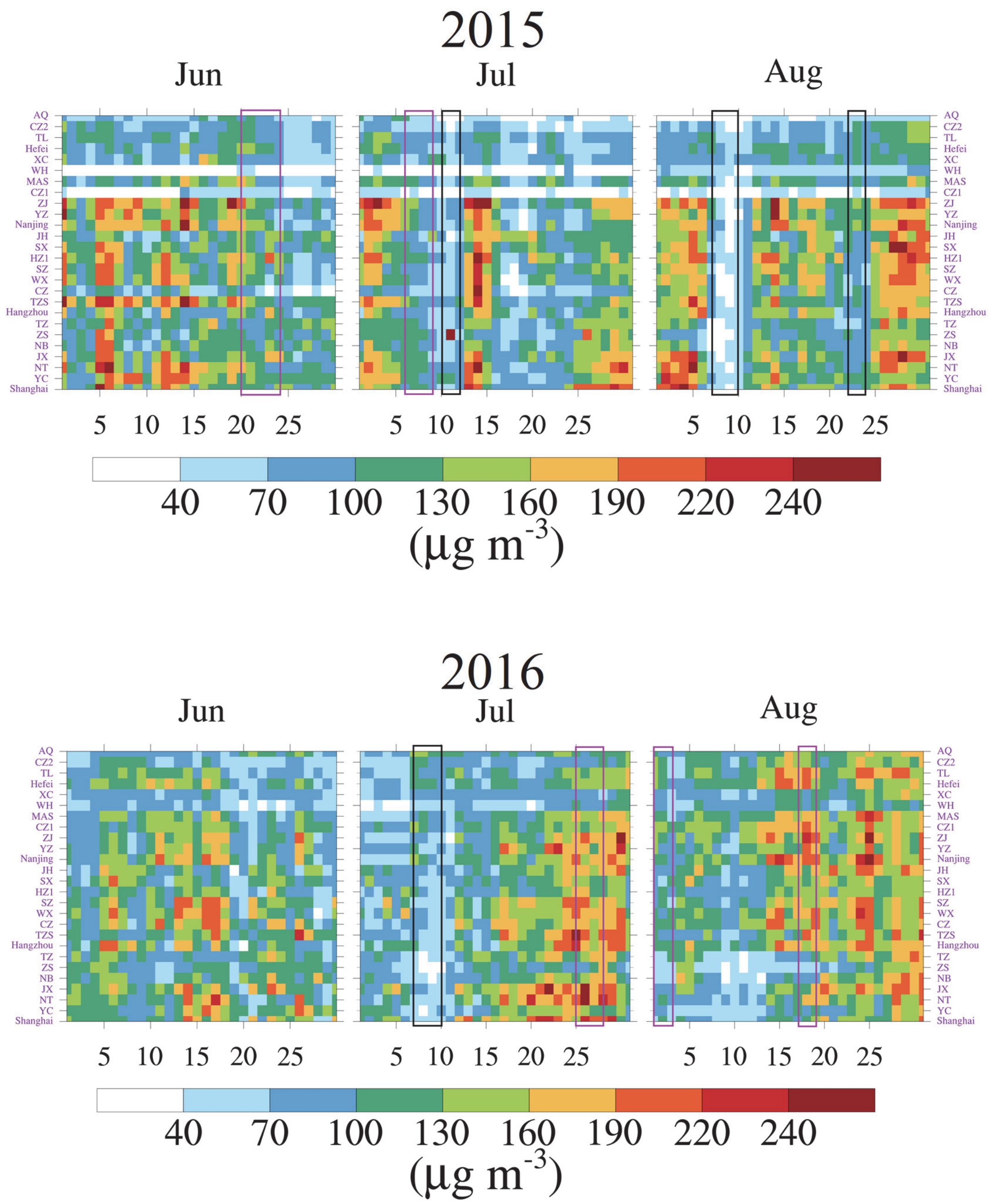
Response: Thanks for the constructive comment. We have accepted your suggestion, and carefully sorted out the O_3 concentrations as well as the typhoon information in summer from 2015 to 2019. We have included this information Supplement in this revised version. Also, we have revised our manuscript simultaneously. Please see lines 242-244 (Sect. 3.1) in the revised manuscript.

According to the conclusion of our paper, the moment that typhoon reaches the 24-h warning line is crucial. Thus, we list all the typhoons that can reach this warning line (Table R1), and mark the corresponding moment on the O_3 concentration map (Figure R1). Actually, similar phenomena can also occur in other years, not just in 2018. That is, O_3 pollution episodes tend to occur during the period from the end of a typhoon and the arrival of the next typhoon, and O_3 pollution occurs earlier in cities near the coastline (Figure R1: July in 2015, July in 2016, July in 2017, July and August in 2018, and August in 2019). O_3 concentrations are more sensitive to typhoons landed in Fujian (Zhejiang) compared to those landed in Guangdong (Hainan). We choose 2018 because there are lots of landfall typhoons, and the landfall positions is further north in this year. Four consecutive landfall typhoons and four respective cities with different longitudes can provide a wealth of information about the mechanism of landfall typhoon affecting O_3 in the YRD. The major processes (the schematic diagram) in our paper may be universal as the similar phenomena can also occur in other years.

Table R1: Information on typhoons that can approach the 24-h warning line in the summer from 2015 to 2019.

Note. The start date is defined as the date of typhoon reaching the 24-h warning line, while the end date is the date of typhoon leaving the 24-h warning line. Dates of typhoon reaching/leaving 24-h warning line also represent the generation/death dates of typhoon as long as the typhoon is active within the 24-h warning line.

Year	Serial number	Name	Start date	End date	Whether typhoon landed?	Landfall position
2015	1508	Kujira	20 June	24 June	Yes	Hainan
	1509	Chan-hom	10 July	12 July	No	
	1510	Linfa	6 July	9 July	Yes	Guangdong
	1513	Soudelor	7 August	10 August	Yes	Fujian
	1515	Goni	22 August	24 August	No	
2016	1601	Nepartak	7 July	10 July	Yes	Fujian
	1603	Mirinae	25 July	28 July	Yes	Hainan
	1604	Nida	1 August	3 August	Yes	Guangdong
	1608	Dianmu	17 August	19 August	Yes	Guangdong
2017	1702	Merbok	10 June	13 June	Yes	Hong Kong
	1707	Roke	22 July	23 July	Yes	Hong Kong
	1709	Nesat	28 July	31 July	Yes	Fujian
	1710	Haitang	27 July	2 August	Yes	Fujian
	1713	Hato	22 August	24 August	Yes	Guangdong
	1714	Pakhar	26 August	27 August	Yes	Guangdong
2018	1804	Ewiniar	2 June	9 June	Yes	Guangdong
	1806	Gaemi	14 June	16 June	No	
	1808	Maria	10 July	11 July	Yes	Fujian
	1809	Son-tinh	16 July	19 July	Yes	Hainan
	1810	Ampil	21 July	24 July	Yes	Shanghai
	1812	Jongdari	1 August	3 August	Yes	Shanghai
	1814	Yagi	11 August	14 August	Yes	Zhejiang
	1816	Bebinca	9 August	17 August	Yes	Hainan
	1818	Rumbia	15 August	20 August	Yes	Shanghai
	1819	Soulik	22 August	24 August	No	
2019	1904	Mun	1 July	4 July	Yes	Hainan
	1905	Danas	17 July	20 July	No	
	1907	Wipha	30 July	3 August	Yes	Hainan
	1909	Lekima	7 August	13 August	Yes	Zhejiang
	1911	Bailu	23 August	25 August	Yes	Fujian



2015
Jun
Jul
Aug
AQ
CZ2
TL
Hefei
XC
WH
MAS
CZ1
ZJ
YZ
Nanjing
JH
SX
HZ1
SZ
WX
CZ
TZS
Hangzhou
TZ
ZS
NB
JX
NT
YC
Shanghai
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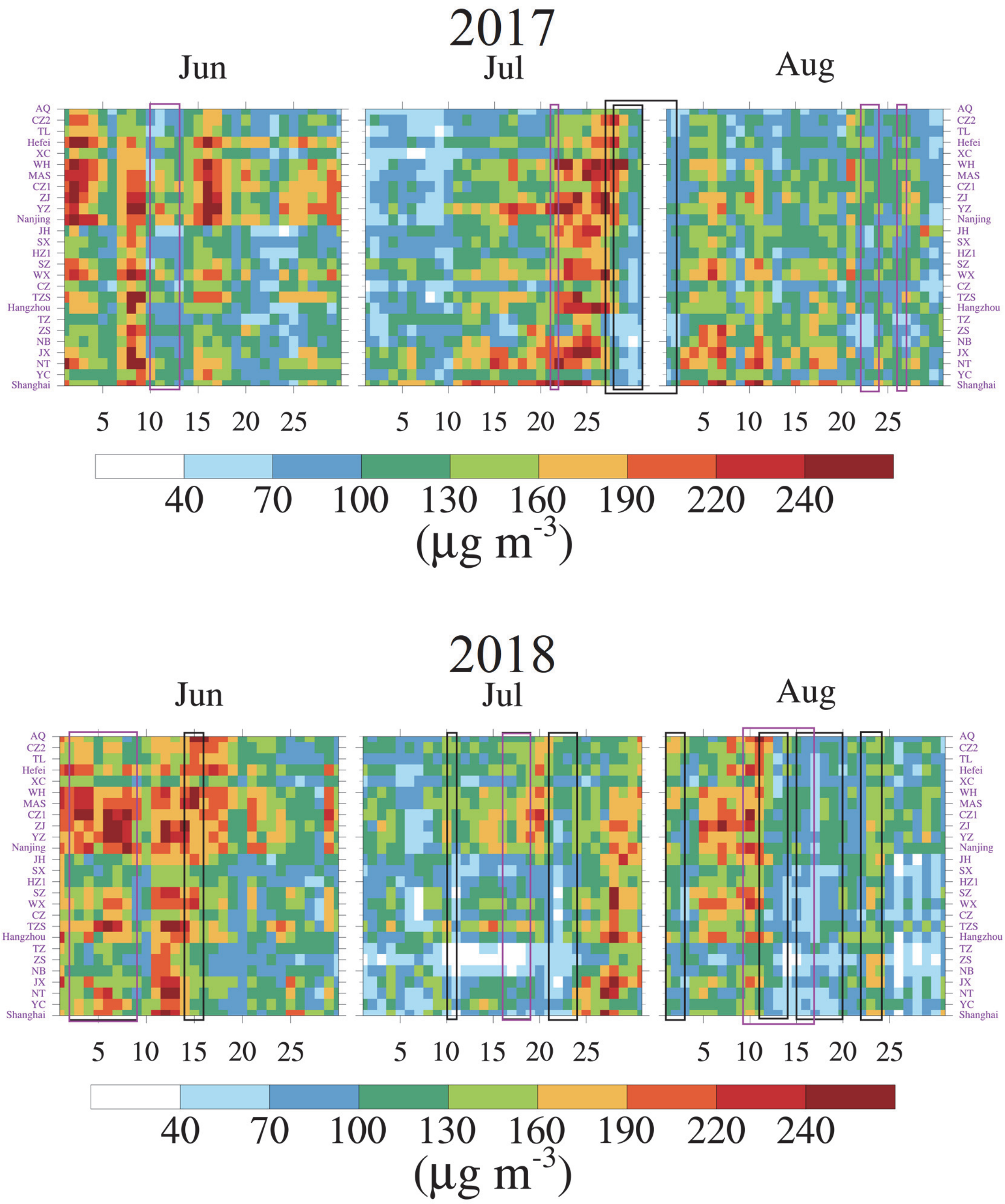
40 70 100 130 160 190 220 240
(μg m-3)
2016
Jun
Jul
Aug
5 10 15 20 25
40 70 100 130 160 190 220 240
(μg m-3)


2017
Jun
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AQ
CZ2
TL
Hefei
XC
WH
MAS
CZ1
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YZ
Nanjing
JH
SX
HZ1
SZ
WX
CZ
TZS
Hangzhou
TZ
ZS
NB
JX
NT
YC
Shanghai
5 10 15 20 25
40 70 100 130 160 190 220 240
(μg m-3)
2018
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40 70 100 130 160 190 220 240
(μg m-3)

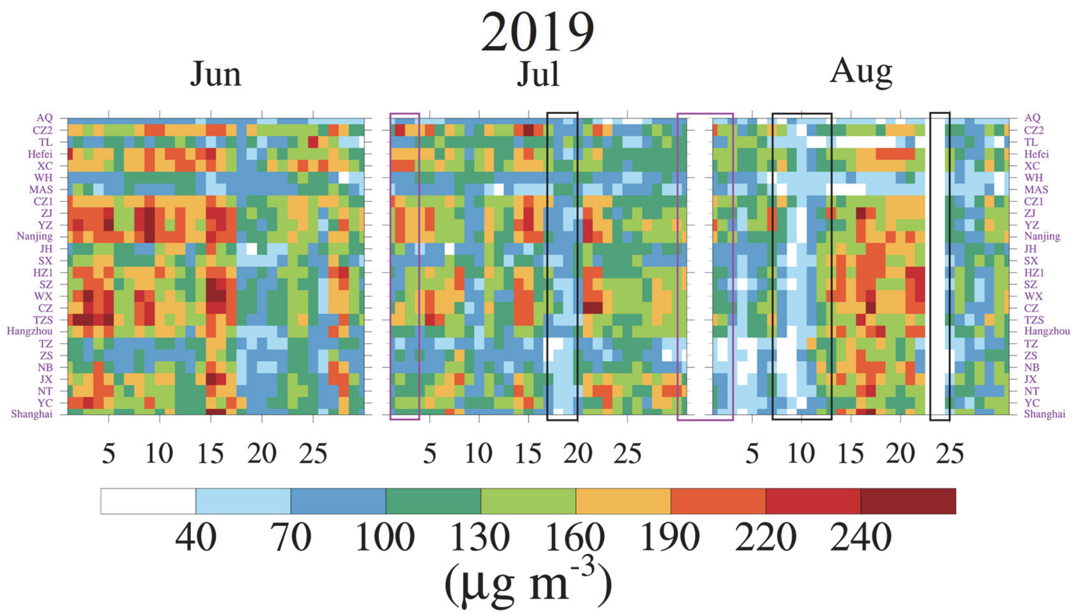


Figure R1. The MDA8 O_3 in 26 cities of the YRD in summer from 2015 to 2019. The open purple and blue boxes indicate that the affected region are mainly the Pearl River Delta and the Yangtze River Delta, respectively. The national ambient air quality standard for MDA8 O_3 is 160 μg m^{-3} in China. These cities are sorted by longitude.

2. Section 3.2, Line 309, Here the authors mentioned the "coastal" region and "inland" region, what is the distance definition for them? Could you describe them here?

Response: Thanks for the constructive comment. We are sorry that we did not give specific definitions of "coastal" and "inland" region in the last version. By consulting relevant information, we find that "inland" region usually refer to the area more than 500 km from the coastline in geography. Thus, the words "coastal" and "inland" are indeed inappropriate here. We have changed the "coastal region" to "cities along the coastline", and deleted the "inland regions" in our revised manuscript. Please see lines 327-328 (Sect. 3.2), 541 (Sect. 3.3.6) and 617-618 (Sect. 4) in the revised manuscript.

3. Section 3.3, Line 324, the representatives of the chosen cities should be addressed here, is it according to the distance off coastal lines?

Response: Thanks for the constructive comment. We are sorry that we did not explain why to select these cities, and we did not provide geographical information of these cities in our original manuscript. This important information is given in our new manuscript, please see lines 341-344 (Sect. 3.3) in the revised manuscript.

We selected Shanghai (121.77°E, 31.12°N), Hangzhou (120.17°E, 30.23°N), Nanjing (118.80°E, 32.00°N) and Hefei (117.23°E, 31.87°N) for the following reasons:

a. Shanghai is a megacity directly under the administration of China. Hangzhou, Nanjing and Hefei are the capital city of Zhejiang, Jiangsu and Anhui province, respectively. Pollution episodes in these cities can impact a large population.

b. These cities are distributed at different longitudes in various distances to the east coast. Therefore, O_3 variations in these geographic locations during a typhoon landing can reflect the impact of typhoons on O_3 as typhoons continue to approach the mainland.

c. During the typhoon, many observations were missing. We finally chose the data collected by the University of Wyoming (http://weather.uwyo.edu/surface/) due to its completeness and number of uses. However, the data only are available in these four cities in the Yangtze River Delta.

4. Section 3.3 Table 3, what is the situation for simulated precipitation compare with the observed one?

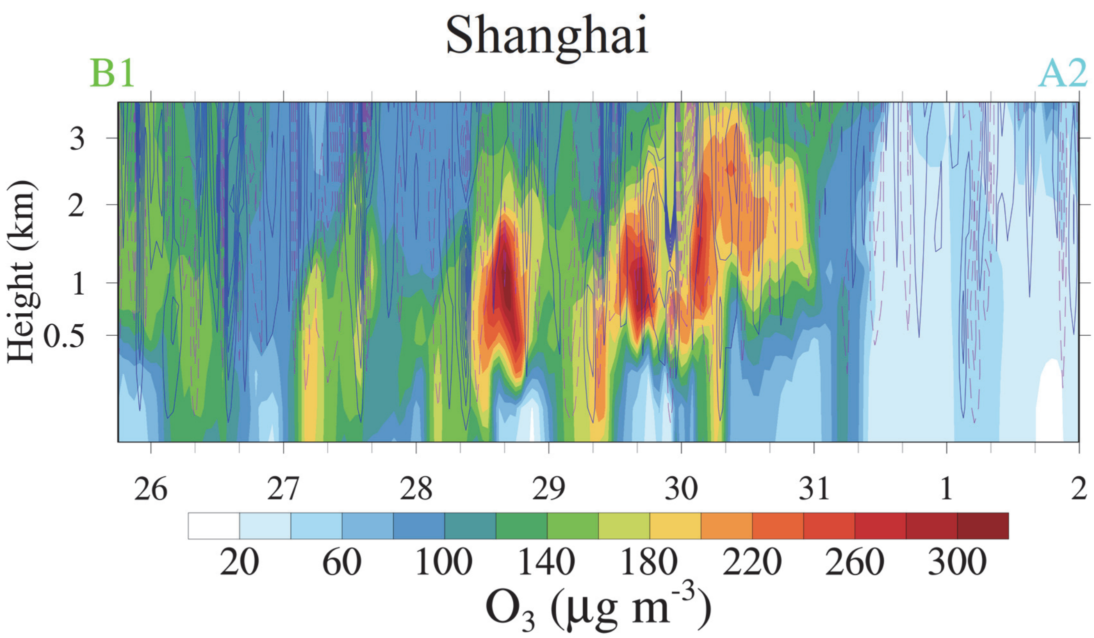
Response: Thanks for the constructive comment. We strongly agree that precipitation is important. However, precipitation data are not available in the data sets provided by the University of Wyoming. Their data only contain the variables of pressure, temperature, dew point, relative humidity, wind direction, wind speed and visibility. Therefore, we cannot make a comparison between the simulated and observed precipitation. We have discussed this limitation in line 143 in the revised manuscript. Future work can be done in comparing the simulated and observed precipitation.

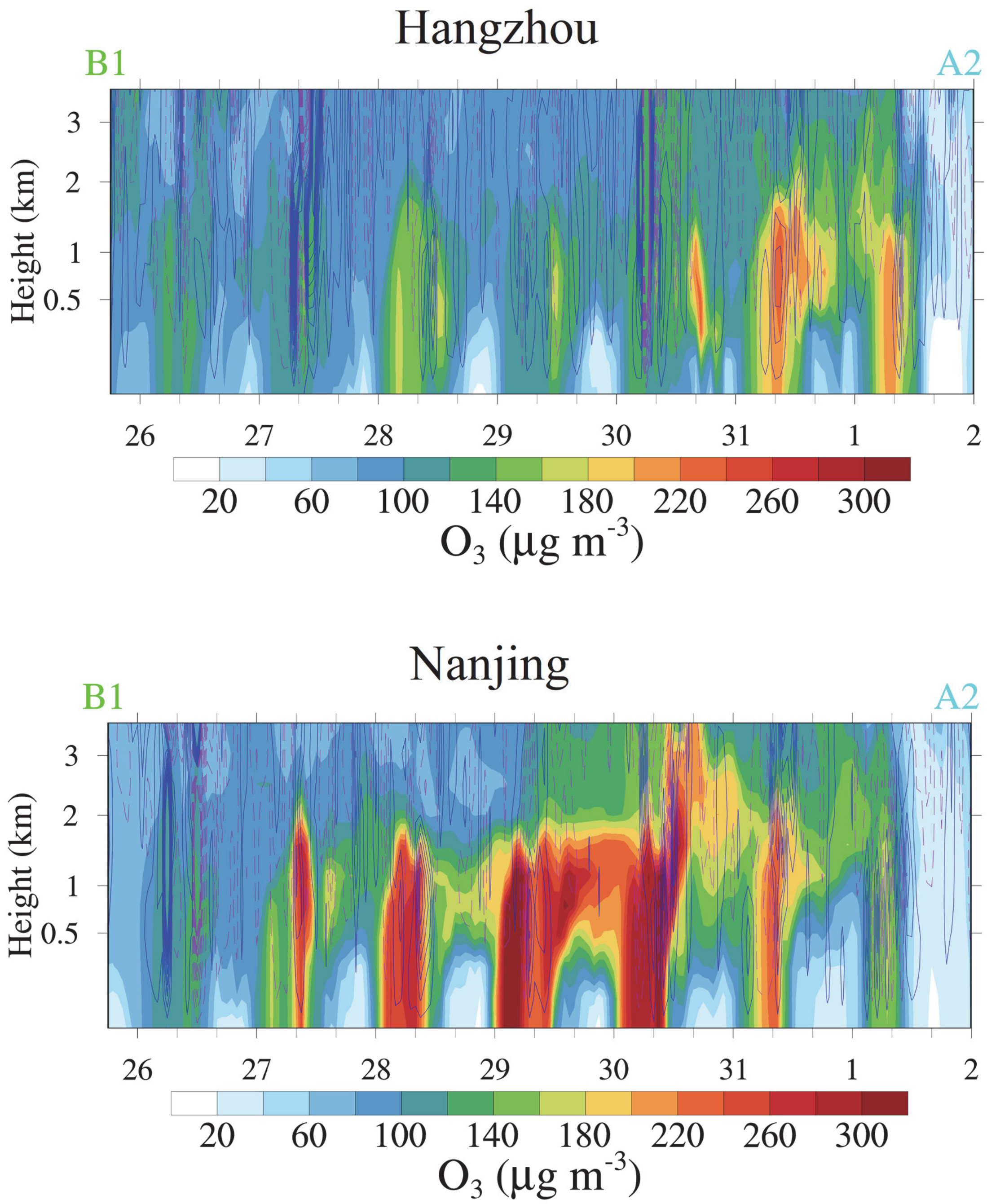
5. Also, Line 386-388, the authors mentioned the high value center of O_3 appeared near altitude of 1km instead of near surface caused by the high photochemical production efficiency of ozone. What is the physical transport role in the high O_3 here?

Response: Thanks for the constructive comment. According to your suggestion, we have added the physical role that causes high surface O_3, and largely reorganized the content in the revised manuscript. Please see lines 30-38 (Abstract), 410-422 (Sect. 3.3.2), 545-552 (Sect. 3.3.6) and 634-

641 (Sect. 4).

Figure R2 presents a fine map of temporal-vertical distribution of O_3 with vertical wind velocity over Shanghai, Hangzhou, Nanjing and Hefei during high O_3 pollution episodes, which may be helpful to study how high-level O_3 is transported to the surface. After typhoon, the downdraft airflows gradually became dominant, the atmosphere was stagnant, and the temperature rose. During the day, O_3 was produced by photochemical reactions, and high O_3 flooded the entire boundary layer due to a well-mixed boundary layer. Most of the O_3 remained in the residual layer (Surface O_3 was much lower due to NO_x titration) at night. By the second day, high O_3 in the residual layer can be transported to the surface by the downward airflows as the boundary layer gradually mixed. Combined with the newly generated O_3, high O_3 would be easy to appear on the surface.





Hangzhou
B1
A2
Height (km)
3
2
1
0.5
26
27
28
29
30
31
1
2
20
60
100
140
180
220
260
300
O3 (μg m-3)
Nanjing
B1
A2
Height (km)
3
2
1
0.5
26
27
28
29
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31
1
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20
60
100
140
180
220
260
300
O3 (μg m-3)

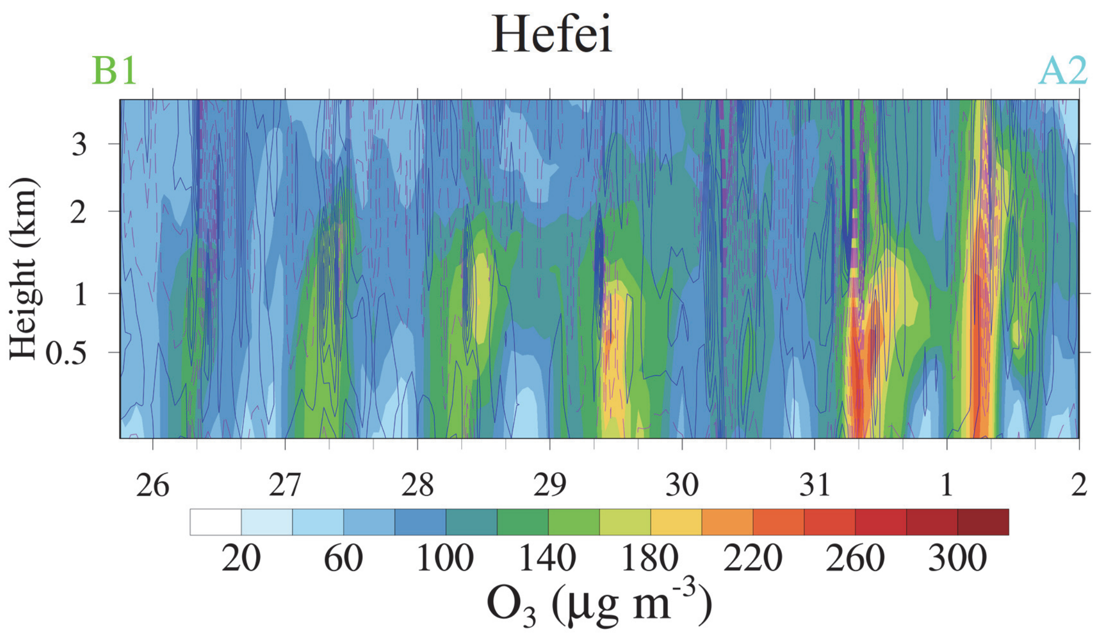

Figure R2: Temporal-vertical distribution of O_3 with vertical wind velocity over Shanghai, Hangzhou, Nanjing and Hefei. The dashed purple line and solid blue line indicate the downward airflows and upward airflows, respectively. The time refers to UTC.

6. Section 3.7, the evaluation on the premature mortalities induced by O_3 exposure are important, but here the authors did not give detailed methodologies or any reference about the estimation of premature mortalities. More details should be added here.

Response: We appreciate this constructive comment. In our revised manuscript, we have added a brief description of the methodology for the estimation of premature mortalities (The detailed calculation method can be found in Section 2.7 Estimate of health impacts), which makes the structure of the article more coherent. Please see lines 590-593 (Sect. 3.3) in the revised manuscript.

Technical corrections

1. Table 3: the authors need indicating o and s with “observation” and “simulation” as a note.

Response: Thanks for the constructive comment. We have added the note that $\overline{\mathrm{O}}$ and $\overline{\mathrm{S}}$ are the average value of observations and simulations in Table 3. Please see lines 370-371 (Table 3) in the revised manuscript.

Ozone affected by a succession of four landfall typhoons in the Yangtze River Delta, China: major processes and health impacts

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Abstract: Landfall typhoon can significantly affect O_3 in the Yangtze River Delta (YRD) region. In this study, we investigate a unique case characterized by two multiday regional O_3 pollution episodes related to four successive landfall typhoons in the summer of 2018 in the YRD. The results show that O_3 pollution episodes mainly occurred during the period from the end of a typhoon to~~and~~ the arrival of the next typhoon. The time when a~~moment that~~ typhoon reached the 24-h warning line and the time when the ~~last moment of~~ typhoon dies away~~activity~~ in the mainland China can be roughly regarded as time nodes. Meanwhile, the variations of O_3 was related to the track, duration and landing intensity of the typhoons. The impact of typhoons on O_3 was like a wave superimposed on the background of high O_3 concentration in the YRD in summer. When a typhoon was near the 24-h warning line before it landed the coast line of the YRD, the prevailing wind originally from the ocean changed to from the inland, and transported lots of precursors from the polluted areas to the YRD. Under influences of the~~With~~ typhoon, the low temperature, strong upward airflows, more

precipitation and wild wind hindered occurrences of ~~prevented~~ high O_3 episodes. After the passing of the typhoon, the air below the 700 hPa atmospheric layer was warm and dry, and the downward airflows resumed. The low troposphere was filed with high concentration of O_3 due to O_3-rich air transported from the low stratosphere and strong photochemical reactions. ~~which was conductive to the formation of O_3 from the abundance of precursors.~~ It is note-worthy that O_3 was~~is~~ mainly generated in the middle of boundary layer (~ 1000 m) instead of at the surface.~~,~~ High O_3 remained in the residual layer at night, and would~~ and~~ be~~then~~ transported to the surface by downward airflows or turbulences by the second day. Moreover, O_3 can be accumulated and trapped on the ground due to the poor diffusion conditions because the vertical diffusion and horizontal diffusion were suppressed by downward airflows and light wind, respectively. The premature mortalities attributed to O_3 exposure in the YRD during the study period was~~is~~ 194.0, more than the casualties caused directly by the typhoons. This work has enhanced~~s~~ our understanding of how landfall typhoons affect O_3 in the YRD and thus can be useful~~, which can be helpful~~ to forecast~~ the~~ O_3 pollution ~~synthetically impacted by the subtropical high and typhoon.~~in regions strongly influenced by typhoon activities.

Key Words: ozone; landfall typhoon; the Yangtze River Delta region;

1 Introduction

The tropospheric ozone (O_3), which is formed by a series of complex photochemical reactions between volatile organic compounds (VOCs) and nitrogen oxides (NO_x=NO+NO_2) in combination with sunlight (Chameides and Walker, 1973; Xie et al., 2014), has received continuous attention due to its negative impact on air quality (Chan and Yao, 2008; Monks et al., 2015), human health (Jerrett et al., 2009), climate (Allen et al., 2012; IPCC, 2014) and biosphere (Dingenen et al., 2009). Research on urban O_3 pollution can be dated back to the early 1950s, beginning with the Los Angeles smog. In China, the photochemical smog, which is characterized by high level of O_3, was first discovered in Xigu district of Lanzhou in 1970s (Tang et al., 1989). However, with the key atmospheric environmental problem was coal-smoke pollution (such as acid rain) at that time (Wang et al., 2019), little systematic research and coordinated O_3 monitoring were performed in China until the mid-2000s (Wang et al., 2017).

Since the beginning of the 21st century, the complex air pollution, which is dominated by fine particulate matter ($PM_{2.5}$, particles of 2.5 microns or less in aerodynamic diameter) and surface O_3, has been ingrained in the megacities of China (Chan and Yao, 2008; Jin et al., 2016; Kan et al., 2012). Air pollution has evolved into a political and economic concern in China. Due to the strict~~drastic~~ air pollution control since 2013, particle pollution has been greatly reduced, appearing a significantly decrease in sulfur dioxide (SO_2), NO_x and $PM_{2.5}$. However, the concentrations of O_3 and VOCs have~~d an~~ increased from 2013 to 2017 (Li et al., 2017), suggesting that more attention should be paid to controlling O_3 and VOCs in the future. Overall, the causes of air pollution ~~and the control policies~~in China are remaining~~still a major~~ challenges to confront~~ in China~~, especially in understanding the sources, transport and dispersion processes, and chemical formation mechanisms of O_3 and its precursors (Ding et al., 2016; Guo et al., 2014; Huang et al., 2014).

A t~~T~~yphoon (tropical cyclone, TC) is one of the most severe~~important factors of~~ natural disasters in East Asia. Out of the total provinces in China, 10 coastal and 6 island provinces are affected by typhoon induced disasters, with more than 250 million lives are affected (Liu et al., 2009). The average number of typhoons making landfall in China is 9 each year, and those typhoons usually inflict vast losses in human life and property due to the accompanied strong wind, torrential rains and huge storm surges (Zhang et al., 2009; Zhao et al., 2012). Because of the long lifetime and tremendous energy, typhoons can~~ has a~~ significantly impact~~influence on~~ local atmospheric conditions, and thereby can affect surface O_3 concentration through advection, diffusion, deposition and other processes. The impact of typhoons on O_3 has attracted extensive attention in recent years (Deng et al., 2019; Huang et al., 2005; Jiang et al., 2015; Shu et al., 2016; Wang and Kwok, 2002; Wei et al., 2016; Yang et al., 2012). For example, Deng et al. (2019) reported that high O_3 and high aerosol concentrations (double high episodes) are likely to occur when the PRD is under the control of the typhoon periphery and the subtropical high with strong downdrafts. Previous studies were mainly in the southern China (including Hong Kong and Taiwan), where ~~are frequently affected by~~ typhoons occur frequently. Still~~However~~, research on the impact of landfall typhoons on O_3 is rather~~still~~ limited.

The Yangtze River Delta (YRD) region, being one of the most developed and densely populated regions in China, is located on the western coast of the Pacific Ocean. With 3.7% of the area and 16.0% of the population of China, the YRD contributed over 20% of the national total Gross Domestic Product (GDP) in 2019. Due to the rapid economic development and high energy consumption, this region has been ~~is~~ suffering from intense air pollution (Ding et al., 2013; Li et al., 2019; Wang et al., 2015; Xie et al., 2016). In 2017, the 90th percentile of the maximum daily 8-hour average (MDA8) O_3 concentration was 170 μg m^{-3}, and 16 of the 26 cities (Figure 1b) in the YRD failed to meet national standard (http://www.cnemc.cn/jcbg/zghjzkgb/201905/t20190529_704755.html). Therefore, it is ~~an~~ urgent ~~task~~ to investigate the spatiotemporal characteristic of O_3 as well as its formation mechanisms in the YRD. Influenced by the monsoon weather, the warm and stagnation conditions play an important role in the occurrence of high-level O_3 in summer (Li et al., 2018; Liao et al., 2015; Lu et al., 2018; Zhao et al., 2010). Synoptic weather systems, such as typhoons and cold fronts, can~~also have~~ significantly impact~~effects on~~ O_3 in the YRD (Hu et al., 2013; Shu et al., 2016). This work aims to reveal the main processes of landfall typhoon affecting surface O_3 in the YRD, ~~hoping~~ to fill the knowledge gap and thus provide scientific insight ~~be helpful~~ for effective~~making reasonable~~ pollution control measures.

In this study, we report a typical~~n outstanding~~ case observed in the YRD during the period from 16 July to 25 August, 2018, during which multiday episode of high O_3 occurred and was found to be related to four successive landfall typhoons. Base on the monitoring data and numerical simulation, we ~~further~~ explore the impact of landfall typhoons on O_3 in the YRD, including the major processes and health impacts. The following part of this paper is structured as the follows: Section 2 gives a brief description of monitoring data, the analysis methods, and model configurations. The results as well as the discussions are detailed in section 3. Section 4 summarizes the main conclusions.

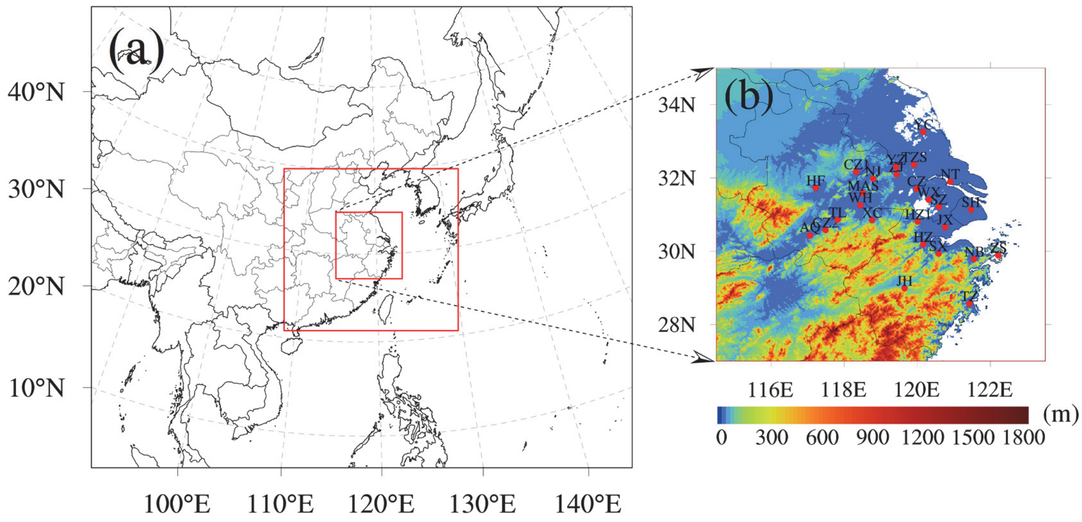


Figure 1. The three nested modeling domains (a) in WRF, and the locations of 26 ~~typical~~ cities in the YRD with terrain elevation data (b). The cities in (b) include: Nanjing (NJ), Wuxi (WX), Changzhou (CZ), Suzhou (SZ), Nantong (NT), Yancheng (YC), Yangzhou (YZ), Zhenjiang (ZJ) and Taizhoushi (TZS) located in Jiangsu province; Hangzhou (HZ), Ningbo (NB), Jiaxing (JX), Huzhou (HZ1), Shaoxing (SX), Jinhua (JH), Zhoushan (ZS) and Taizhou (TZ) located in Zhejiang province; Hefei (HF), Wuhu (WH), Maanshan (MAS), Tongling (TL), Anqing (AQ), Chuzhou (CZ1), Chizhou (CZ2) and Xuancheng (XC) located in Anhui province; and the megacity Shanghai (SH). The terrain elevation data are available at https://www.ngdc.noaa.gov/mgg/global/relief/ETOPO1/data/bedrock/cell_registered/netcdf/.

2 Data and methods

2.1 Air quality data

Surface air pollutants monitored by the China National Environmental Monitoring Center (CNMC) Network are used in this study. The nationwide observation network began operating in 74 major cities in 2013, and it included 1597 nonrural sites covering 454 cities by 2017 (Lu et al., 2018). The monitoring data are strictly in accordance with the national monitoring regulations (http://www.cnemc.cn/jcgf/dqhj/), and can be acquired from the national urban air quality real-time publishing platform (http://106.37.208.233:20035/). Each monitoring site automatically measures hourly air pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3 and CO), and the urban hourly pollutants are calculated by averaging the pollutants measured at all monitoring sites in that city. The MDA8 O_3

is calculated based on the hourly O_3 with more than 18-h measurements (Liao et al., 2017). Manual inspection, including the identification and handling of invalid and lacking data, is performed following previous studies (Xie et al., 2016; Shu et al., 2017; Zhan et al., 2019).

2.2 Surface and sounding meteorological data

With respect to surface observed meteorological data, stations at the three provincial capital cities (Hefei, Nanjing and~~,~~ Hangzhou~~u and Hefei~~) and the megacity Shanghai are selected, which are ZSOF (117.23°E, 31.87°N), ZSNJ (~~32.00°N,~~ 118.80°E, 32.00°N), ZSHC (~~30.23°N,~~ 120.17°E, 30.23°N), ~~ZSOF (31.87°N, 117.23°E)~~ and ZSPD (~~31.12°N,~~ 121.77°E, 31.12°N), respectively. These surface observations, including 2-m temperature, 10-m wind speed and direction and 2-m relative humidity, are recorded hourly and can be obtained from the website of the University of Wyoming (http://weather.uwyo.edu/surface/). The precipitation data is not included in the dataset.

To verify the upper-air fields, the sounding observations at Shanghai (~~31.40°N,~~ 121.46°E, 31.40°N) and Nanjing (~~32.00°N,~~ 118.80°E, 32.00°N) are used. These sounding observations (pressure, temperature, relative humidity, wind direction and wind speed etc.) are also acquired from the website of the University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html), with a time resolution of 12 h (00:00 and 12:00 UTC).

2.3 The best-track TC dataset

To capture the characteristics of landfall typhoons, the best-track TC dataset issued by the China Meteorological Center (CMA) is considered due to its good performance on the landfall typhoons in the mainland China (available at http://tcdata.typhoon.org.cn/zjljsjj_sm.html). The dataset covers seasons from 1949 to the present, the region north of the equator and west of 180°E, and is updated annually (Li and Hong, 2016; Ying et al., 2014). A wealth of information on typhoon is recorded every 6h in the dataset, including location, minimum sea level pressure, etc. For landfall typhoons, 24h before their landing ~~y land~~ and during their activities in the mainland China, the meteorological data are~~will be~~ recorded every 3h. Refer to the national standard for grade of tropical cyclones (GB/T 19201-2006), the intensity category (IC) of tropical cyclones is provided~~given~~ in the dataset, which is based on the near surface maximum 2-min mean wind speed near the tropical cyclone center, ranging~~es~~ from 1 to 6 (Table 1).

Table 1. The intensity category of tropical cyclones

Intensity category (IC)	The near surface maximum 2-min mean wind speed near the tropical cyclone center (m/s)	Beaufort scale
Tropical depression (IC=1)	10.8-17.1	6-7
Tropical storm (IC=2)	17.2-24.4	8-9
Severe tropical storm (IC=3)	24.5-32.6	10-11
Typhoon (IC=4)	32.7-41.4	12-13
Severe typhoon (IC=5)	41.5-50.9	14-15
Super typhoon (IC=6)	$\geq$ 51.0	$\geq$16

2.4 Model description and configurations

To simulate the high O_3 episodes over the YRD during the ~~period with~~ typhoon periods, the WRF-CMAQ one-way coupled model is applied, which consists of WRF v3.6.1 (https://www2.mmm.ucar.edu/wrf/users/) developed by the United States National Center for Atmospheric Research (NCAR) and CMAQ v5.0.2 (https://github.com/USEPA/CMAQ/tree/5.0.2) developed by the United States Environmental Protection Agency (EPA).

WRF generates offline meteorological inputs for CMAQ with initial and boundary conditions from the National Centers for Environmental Prediction (NCEP) global final analysis fields every 6 h at a spatial resolution of 1° × 1° (https://rda.ucar.edu/datasets/ds083.2/). Three nested domains are used, with horizontal resolutions of 81, 27 and 9 km, and grids of 88 × 75, 85 × 79 and 97 × 97, respectively (Figure 1a). There are 24 vertical sigma layers from surface to 100 hPa, with about 8 layers located below 1.5 km to resolve the boundary layer processes. Furthermore, the major physical options for the dynamic parameterization in WRF are summarized in Table 2.

Table 2. The domains and physical options for WRF in this study

Items	Contents
Dimensions (x, y)	(88, 75), (85, 79), (97, 97)
Grid spacing (km)	81, 27, 9
Microphysics	WRF Single-Moment 5-class scheme (Hong et al., 2004)
Longwave radiation	RRTM scheme (Mlawer et al., 1997)

Shortwave radiation	Goddard scheme (Kim and Wang, 2011)
Surface layer	Moni-Obukhov scheme (Monin and Obukhov, 1954)
Land-surface layer	Noah land-surface model (Chen and Dudhia, 2001)
Planetary boundary layer	YSU scheme (Hong et al., 2006)
Cumulus parameterization	Grell-Devenyi ensemble scheme (Grell and Devenyi, 2002)

Since the horizontal domains of CMAQ are one grid smaller than WRF, all three nested domains are adjusted automatically. The vertical layers of CMAQ are the same as WRF. The Meteorology Chemistry Interface Processor (MCIP) can convert WRF outputs to the necessary meteorological inputs for CMAQ. Moreover, the CB05 gas-phase mechanism with aqueous/cloud chemistry is selected in the CMAQ configurations.

The anthropogenic emissions are from the Multi-resolution Emission Inventory for China (MEIC) in 2016 with the resolution of 0.25° (http://meicmodel.org/), including anthropogenic emissions from power generation, industry, agriculture, residential and transportation sectors. All emission estimates are spatially allocated to the relevant grid cells based on the meteorological fields obtained from WRF, and are temporally distributed on an hourly basis. The simulation starts from 00:00 UTC on 13 July to 00:00 UTC 27 August, with the first 72 h as spin-up time.

2.5 Integrated process rate (IPR) analysis

To quantify the contributions of individual processes to~~in~~ O_3 formation, the IPR analysis provided in the CMAQ is utilized. The IPR analysis can illustrate the contributions to changes in pollutant concentrations from seven different types of processes, including horizontal advection (HADV), vertical advection (ZADV), horizontal diffusion (HDIF), vertical diffusion (VDIF), dry deposition (DDEP), cloud processes with the aqueous chemistry (CLDS) and chemical reaction process (CHEM), with a mass conservation adjustment at each model grid cell. The IPR analysis has been widely applied to investigate regional air pollution (Fan et al., 2015; Li et al., 2012; Wang et al., 2010). In this study, MADV is defined as the sum of HADV and ZADV, and TDIF is defined as the sum of HDIF and VDIF.

2.6 Model evaluation

To evaluate the model performance, the simulation results in the innermost domain, including O_3 concentration, air temperature at 2 m (T_2), relative humidity (RH), wind speed at 10 m (WS_{10})

and wind direction at 10 m (WD_{10}), are examined against the hourly observations at the representative cities (Table 3). The statistical metrics, including correlation coefficient (R), root-mean-square error (RMSE) and normalized mean bias (NMB), are used~~ in this study~~. They are defined as follows:

$$R = \frac{\sum_{i=1}^{N}(S_i - \bar{S})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^{N}(S_i - \bar{S})^2}\sqrt{\sum_{i=1}^{N}(O_i - \bar{O})^2}}, \tag{3}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(S_i - O_i)^2}{N}}, \tag{4}$$

$$NMB = \frac{\sum_{i=1}^{N}(S_i - O_i)}{\sum_{i=1}^{N}O_i} \times 100\%, \tag{5}$$

where S_i and O_i are the simulations and observations, respectively. N is the total number of valid data. $\bar{S}$ and $\bar{O}$ are the average value of simulations and observations, respectively. In general, the model results are acceptable if the values of R, RMSE and NMB are close to 1, 0 and 0, respectively (Li et al., 2017; Shu et al., 2016; Xie et al., 2016).

2.7 Estimate of health impacts

Previous studies showed that surface O_3 pollution can induce a series of adverse health problems ~~impacts by causing~~from the incidence and mortality of respiratory diseases (Ghude et al., 2016; Jerrett et al., 2009; Lelieveld et al., 2015). To arouse more attention on the issue that O_3 can be significantly affected by typhoons in the YRD, we further estimate the premature mortality attributed to O_3 during the study period.

A standard damage function (Anenverg et al., 2010; Liu et al., 2018; Voorhees et al., 2014; WS/T 666-2019, Technical specifications for health risk assessment of ambient air pollution of China) is employed to quantify premature mortality due to O_3 exposure:

$$\Delta M = y_0\left(\frac{RR - 1}{RR}\right)Pop, \tag{1}$$

where ΔM is the excess mortalities attribute to O_3 exposure, y_0 is the baseline mortality rate, RR is relative risk and (RR-1)/RR is the attributable fraction, and Pop is the exposed population. RR can be calculated using the following relationship:

$$RR = \exp(\beta(C - C_0)), \tag{2}$$

where β is the concentration-response factor, C is the exposure concentration and C_0 represents the theoretical minimum-risk concentration.

In this study, the mortality rate for respiratory disease is obtained from China Health and Family Planning Statistical Yearbook 2018 (https://www.yearbookchina.com/navibooklist-n3018112802-1.html), which is 68.02/100000. The β is generated from Dong et al. (2016), that is 0.461%. The population data are obtained from the B~~b~~ureau of S~~s~~tatistics of different cities in the YRD. The C_0 is 70 μg m^{-3} for MDA8 O_3 given by the World Health Organization (WHO).

3 Results and discussions

3.1 Characteristic of O_3 episodes

In the midsummer~~ season~~, the warm sea surface (high temperature) is conducive to the generation of typhoons (high O_3 concentration),~~ which~~ providing~~es~~ a good opportunity to investigate the mechanism of typhoons affecting O_3 in the YRD. Figure 2 shows the MDA8 O_3 in the typical 26 cities of the YRD in summer of 2018. Actually, it is common for typhoons to affect O_3 in the YRD during summer, and 2018 is special because there were 8 landfall typhoons and many of them landed further north than in the normal years (see Supplement for details). O_3 concentration was relatively ~~tended to be~~ high in June, and relatively low in July and August. The relatively low O_3 may be attributed to the maritime air masses transported by the Asian summer monsoon (Ding et al., 2008; Xu et al., 2008). Nevertheless, we notice that there are two regional multiday O_3 pollution episodes from 24 July to 11 August in the YRD, which means that about half of the cities in the YRD exceed the national air quality standard (The national ambient air quality standard for MDA8 O_3 is 160 μg m^{-3} in China). The first multiday O_3 episodes appeared in most of the cities from 24 July to 2 August. The highest MDA8 O_3 concentration reached up to 264 μg m^{-3} on 27 July in Ningbo (NB). O_3 pollution was even observed for 6 consecutive days from 27 July to 1 August in Maanshan (MAS). Only two days later, regional O_3 pollution occurred in the YRD again from 5 August to 11 August.

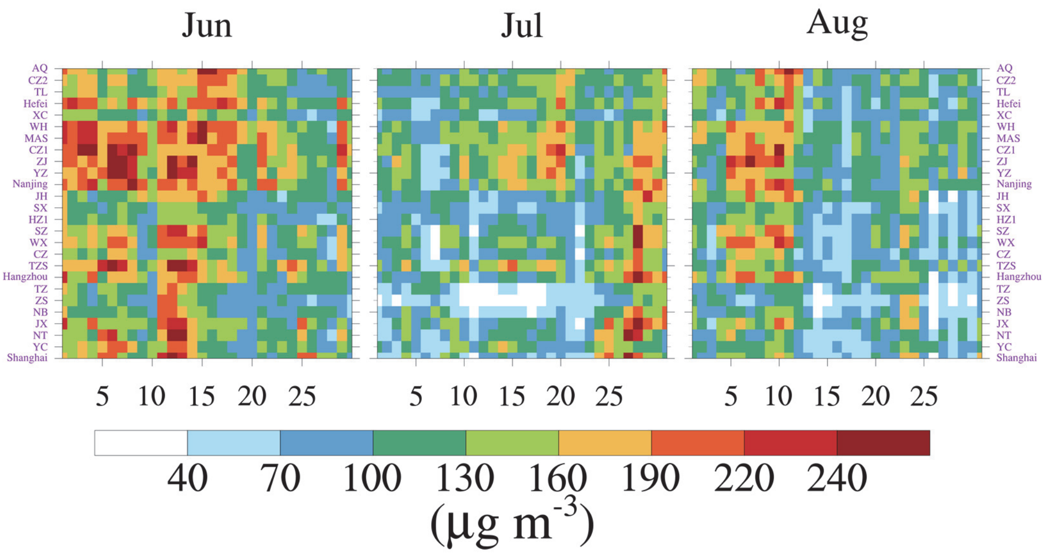
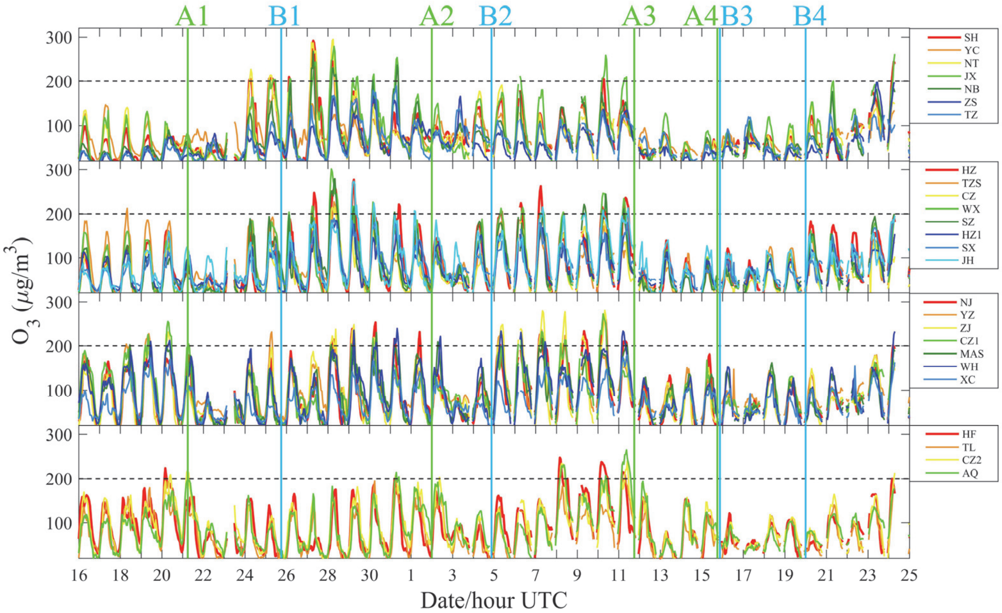


Figure 2. The MDA8 O_3 in 26 cities of the YRD in June (left panel), July (middle panel), and August (right panel) 2018~~summer of 2018~~. The national ambient air quality standard for MDA8 O_3 is 160 μg m^{-3} in China. These cities are sorted by longitude.

Figure 3 further shows diurnal variation of O_3 in all 26 cities of the YRD from 00:00 16 July to 00:00 25 August (throughout this paper the time refers to UTC, unless LST is specifically stated~~mentioned~~). Interestingly, O_3 pollution occurred earlier in cities near the coastline (e.g. large longitudes in °E, Figure 1b) rather than concurrently during the two multiday O_3 episodes. For example, from 24 July to 2 August, the first day that hourly O_3 concentration exceeded the national air quality standard (The national ambient air quality standard for hourly O_3 is 200 μg m^{-3} in China) in Shanghai, Hangzhou, Nanjing and Hefei was 24 July, 27 July, 28 July and 31 July, respectively. Thus, we classify the 26 cities in the YRD into four categories based on their longitudes, surrounding the four representative cities (Figure 4). The category I cities include SH, YC, NT, JX, NB, ZS and TZ. The category II cities include HZ, TZS, CZ, WX, SZ, HZ1, SX and JH, and the category III cities include NJ, YZ, ZJ, CZ1, MAS, WH and XC. Other cities are classified as the category IV cities, which are HF, TL, CZ2 and AQ. The first category cities are closest to the coastline, while the fourth category is the opposite.



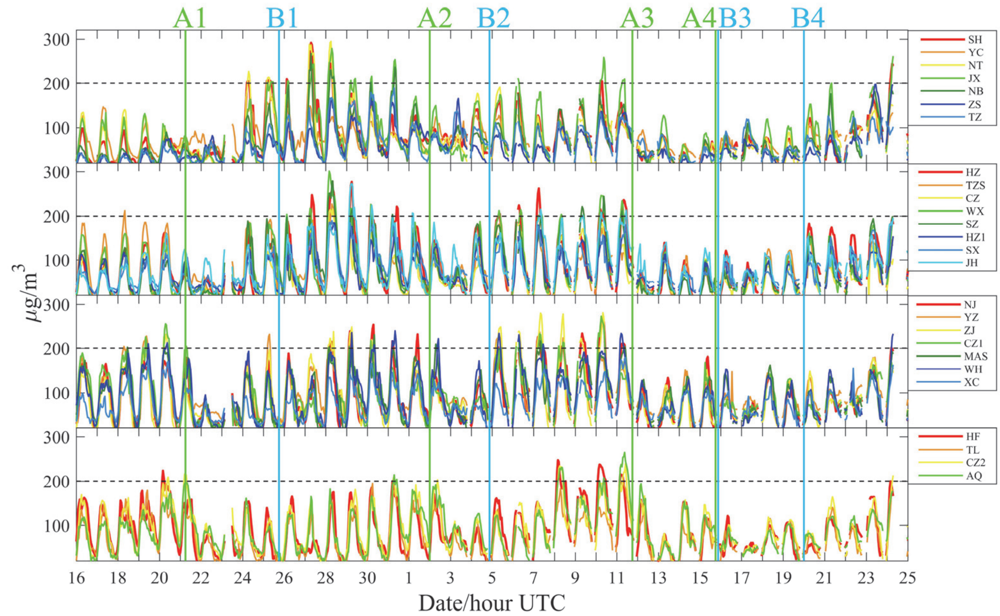


Figure 3. Diurnal variation of O_3 in~~ all~~ 26 cities of the YRD from 16 June to 25 August, 2018. The grey dotted lines are the national ambient air quality standard for hourly O_3 (200 μg m^{-3}) in China. The letter A indicates the moment that the typhoon has reached the 24-h warning line, and letter B indicates the last moment when the~~of~~ typhoon was active~~activity~~ in the mainland China. These time~~moment~~s are acquired from the best-track TC dataset, depending on the start and end times of the 3h~~densified~~ observations. Coordinates 1, 2, 3, and 4 represent Typhoon Ampil, Typhoon Jongdari, Typhoon Yagi, and Typhoon Rumbia, respectively. Note: these cities are sorted by longitude.

3.2 Landfall typhoons and their effects

~~For such~~ O_3 episodes with regional and~~,~~ long-lasting characteristics~~,~~ may often be associated with slow-moving synoptic weather systems. We find that the O_3 episodes coincided well with activities of landfall typhoons~~ activities~~, showing in their~~and the~~ tracks and intensities~~y of typhoons are given~~ in Figure 4. Typhoon Ampil was first observed at 00:00 on 18 July, and landed in Shanghai around 4:30 on 22 July with an intensity of severe tropical storm (IC=3). While ~~During the time of~~ Typhoon Ampil remained active, Typhoon Jongdari generated over the western North Pacific at 12:00 on 23 July, and made landfall at the junction of Zhejiang province and Shanghai at 21:00 1 August. After Typhoon Jongdari, Typhoon Yagi generated at 00:00 7 August. At around 15:35 12 August, it landed in Zhejiang province and remained active in the mainland China until 21:00 15 August. Before the end of Typhoon Yagi, Typhoon Rumbia was observed over the western North Pacific at 6:00 14 August. It finally landed in Shanghai at around 20:00 16 August, causing huge economic losses.

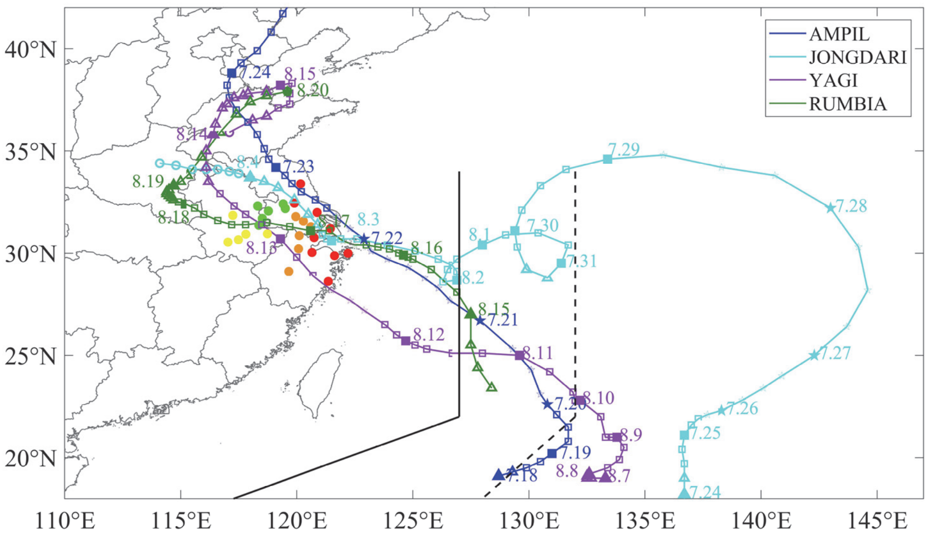


Figure 4. The track and intensity of Typhoon Ampil, Typhoon Jongdari, Typhoon Yagi, and Typhoon Rumbia. The track is labeled with the date of the month and day (in month.day). The circle, triangle, square and pentagram indicate the intensity category of tropical cyclones is less than 1 (IC < 1), equal to 1 (IC = 1), equal to 2 (IC = 2), and not less than 3 (IC >= 3), respectively. Black solid line and dotted line represent the 24-hour and 48-h warning line for

tropical cyclones, respectively. The colored solid points are the locations of cities in the YRD, and different color represents different cities categories. Wherein, red, carrot, green and yellow are category I, II, III and IV cities, respectively.

To further understand the relationship between O_3 episodes and landfall typhoons, we mark the critical moments of landfall typhoons in Figure 3. The letter A indicates the moment when a~~that~~ typhoon~~s~~ has~~ve~~ reached the 24-h warning line, and the letter B indicates the last moment of that typhoon remains active~~activity~~ in the mainland China. These moments are acquired from the best-track TC dataset, depending on the start and the end time of the ~~densified~~ 3h observations. Coordinates 1, 2, 3, and 4 represent Typhoon Ampil, Typhoon Jongdari, Typhoon Yagi, and Typhoon Rumbia, respectively. As shown in Figure 3, O_3 exhibited a significant cycle during the study period. That is, when the typhoon is close enough (near moments A1, A2, A3 and A4), the O_3 concentrations decreased, but O_3 concentrations would increase as long as the typhoon was not active in the mainland China (B1, B2 and B4) any more. This cycle would repeat if the next typhoon approached. O_3 pollution was likely to occur during the period from the end of a~~the~~ typhoon to the arrival of the next typhoon (B1A2 and B2A3) in the YRD.

Furthermore, we find that the variations of O_3 was related to the track, duration and landing intensity of the typhoons. For example, during the B1A2 period when the O_3 pollution occurred, the moments that hourly O_3 concentrations first exceed 200 μg m^{-3} in about half of cities of the categories I, II, III and IV were 6:00 UTC (14:00 LST) 27 July, 6:00 UTC (14:00 LST) 28 July, 3:00 UTC (11:00 LST) 29 July and 6:00 UTC (14:00 LST) 31 July, respectively. This phenomenon also suggests that O_3 pollution first occurs~~–~~ in cities along the coastline~~in coastal region will be ahead of that in inland regions~~, which may be related to the track of typhoons (Figure 4). Regarding~~As for~~ the impact of typhoon duration, the A4B3 period provided a good interpretation. While Typhoon Yagi was still active in the mainland China, Typhoon Rumbia had reached the 24-hour warning line. Hence, the O_3 remained a low level throughout the period (A3B4), which was quite different from B1A2 and B2A3 period. Noted that the landing point and active path of Typhoon Ampil and Typhoon Jongdari were very similar (Figure 4). However, the landing intensity of Typhoon Ampil was severe tropical storm (IC = 3), and that of Typhoon Jongdari was tropical storm (IC = 2), resulting in a difference in O_3 concentrations for Shanghai. Within 24 hours after Typhoon Ampil

(Jongdari) reached the 24-hour warning line, the average O_3 concentrations reached~~was~~ 40.9 (80.1) μg m^{-3} in Shanghai. This is because that the stronger the typhoon landed, the gale (The 10-m wind speed near moment A1 was larger than that near moment A2 in Shanghai, Figure 7a) and precipitation accompanying the typhoon will be more effective in removing O_3.

3.3 Processes of O_3 pollution affecting by typhoons

To reveal the major processes of O_3 pollution episodes affected by landfall typhoons, ~~four representative cities (Shanghai, Hangzhou, Nanjing and Hefei)~~one municipality and three provincial capital cities with different longitudes, including Shanghai (121.77°E, 31.12°N), Hangzhou (120.17°E, 30.23°N), Nanjing (118.80°E, 32.00°N) and Hefei (117.23°E, 31.87°N), are selected for further analysis – based on monitoring data and model results.

3.3.1 Evaluation of model performance

To evaluate the simulation performance, the hourly simulation results are compared with the measurements from~~during~~ 00:00 16 July to 00:00 25 August. Table 3 presents the statistical metrics for selected variables, including temperature at 2 m (T_2), relative humidity (RH), wind speed at 10 m (WS_{10})~~, and~~ wind direction at 10 m (WD_{10}), and surface O_3. T_2 is reasonably well simulated, with R values of 0.75, 0.77, 0.72 and 0.64 in Shanghai, Hangzhou, Nanjing and Hefei, respectively. Though our simulation underestimates T_2 to some~~ certain~~ extent, th~~is~~e slight~~ly~~ underestimation is acceptable because of~~due to~~ the small RMSE (3.2, 2.7, 2.9 and 3.3) and NMB (-7.5%, -5.1%, -5.5% and -5.5%) values. As for RH, the simulation results are overestimated in all four cities, leading to the NMB values of 9.1%, 4.6%, 6.7% and 0.5% in Shanghai, Hangzhou, Nanjing and Hefei, respectively. With high R values (0.69, 0.65, 0.71 and 0.71) and relatively low RMSE values (12.4, 12.8, 12.1 and 10.8), the WRF simulates RH over the YRD quite well. The wind fields are closely related to the transport processes of air pollutants. The overestimation of WS_{10} may partly be attributed to the unresolved terrain features by the default surface drag parameterization causing overestimation of wind speed in particular at low values (Jimenez and Dudhia, 2012; Li et al., 2017). With regards to WD_{10}, the simulation error is large based only on these statistical metrics. This is because that near-surface wind fields are deeply influenced by local underlying surface characteristics, and improving the urban canopy parameters might be useful (Liao et al., 2015; Xie et al., 2016). In term of O_3, the simulated~~ion results for~~ O_3 concentrations behave satisfactorily. R is~~ as high as~~ 0.55, 0.65, 0.66 and 0.54 for the simulations for~~in~~ Shanghai, Hangzhou, Nanjing and

Hefei, respectively, while the NMB values are 5.8%, 16.4%, -6.2% and -5.3%, respectively.

Table 3. Statistical metrics in~~for~~ meteorological variables and O_3 concentration between the observations and simulations~~chemical variables~~.

City	Variable	$\bar{O}$	$\bar{S}$	R	RMSE	NMB
Shanghai	T_2 (℃)	30.3	28.1	0.75	3.2	-7.5%
	RH (%)	75.0	81.8	0.69	12.4	9.1%
	WS_{10} (m s^{-1})	4.9	5.5	0.51	2.3	11.7%
	WD_{10} (°)	144.8	113.4	0.01	113.5	-22.9%
	O_3 (μg m^{-3})	74.3	76.5	0.55	45.3	5.8%
Hangzhou	T_2 (℃)	30.3	28.8	0.77	2.7	-5.1%
	RH (%)	75.1	78.5	0.65	12.8	4.6%
	WS_{10} (m s^{-1})	3.3	4.7	0.32	2.7	32.5%
	WD_{10} (°)	155.0	114.7	-0.10	132.5	-27.8%
	O_3 (μg m^{-3})	81.7	91.3	0.65	49.8	16.4%
Nanjing	T_2 (℃)	29.8	28.1	0.72	2.9	-5.5%
	RH (%)	77.4	82.6	0.71	12.1	6.7%
	WS_{10} (m s^{-1})	3.1	5.0	0.39	3.0	63.8%
	WD_{10} (°)	132.8	115.6	0.21	102.7	-15.0%
	O_3 (μg m^{-3})	87.6	79.8	0.66	46.7	-6.2%
Hefei	T_2 (℃)	29.3	27.7	0.64	3.3	-5.5%
	RH (%)	81.1	81.5	0.71	10.8	0.5%
	WS_{10} (m s^{-1})	3.2	3.2	0.37	2.2	2.9%
	WD_{10} (°)	147.0	128.6	0.04	136.7	-13.3%
	O_3 (μg m^{-3})	87.3	80.3	0.54	45.0	-5.3%

Note. R exceeds 0.1 to reach statistically significant at 99.9% confident level.~~-~~ $\bar{O}$ and $\bar{S}$ are the average values of the observations and simulations, respectively.

Figure 5 further shows hourly variations of O_3, T_2, WS_{10} and WD_{10} for measurements and simulations in four representative cities. The simulations effectively reproduce the diurnal variation of O_3, T_2 and WS_{10}, confirming the reliability of the simulation results. Moreover, the model well captures the shift in wind direction during the study period. Thus, the overall model performance in simulating~~for~~ wind fields is acceptable. In summary, the simulations~~ results~~ can capture and reproduce the major meteorological characteristics and O_3 evolution during~~of~~ the O_3 episodes, and thus~~including the meteorological conditions and evolution of O_3, which~~ can provide valuable insights into the formation of the O_3 episodes.

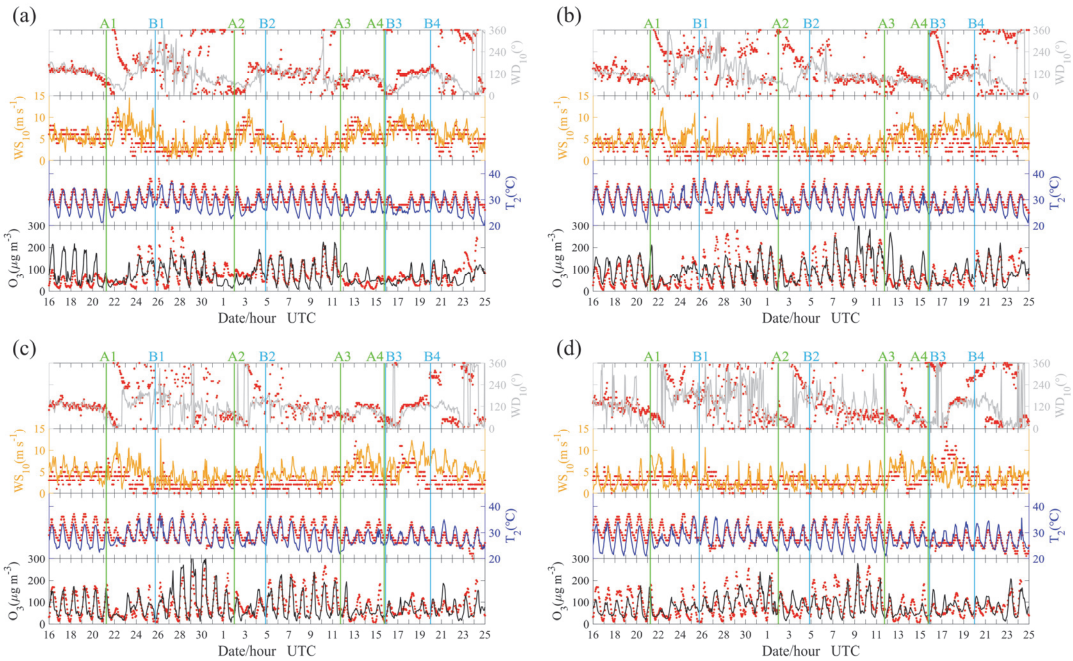
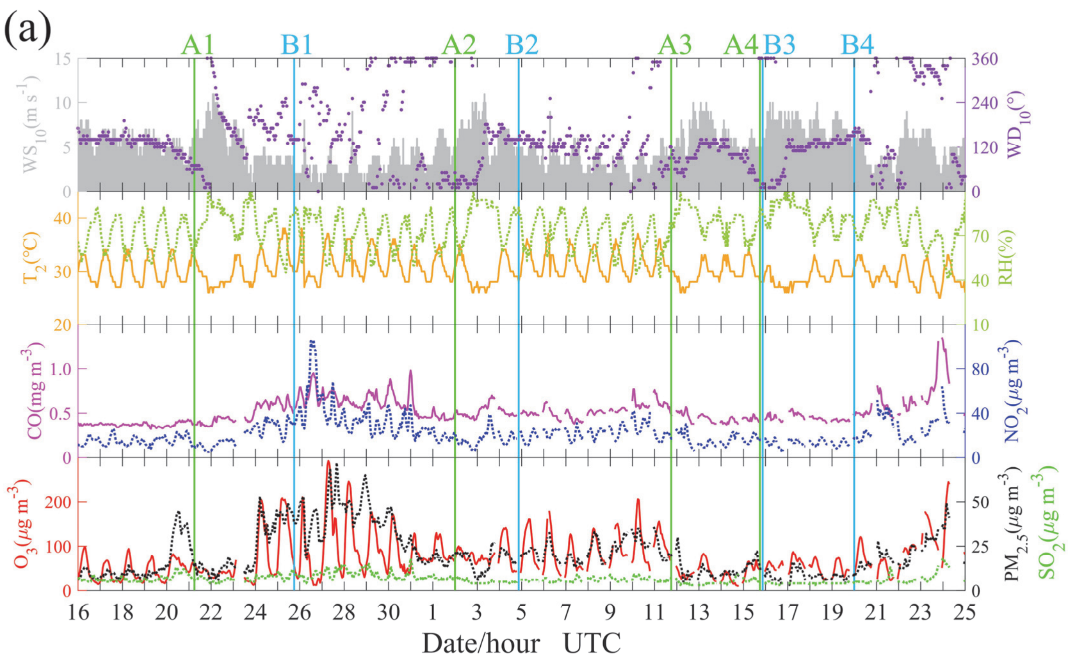


Figure 5. Hourly variations of O_3, T_2, WS_{10} and WD_{10} in~~for~~ measurements (red dots) and simulation (colored lines) in (a) Shanghai, (b) Hangzhou, (c) Nanjing and (d) Hefei.

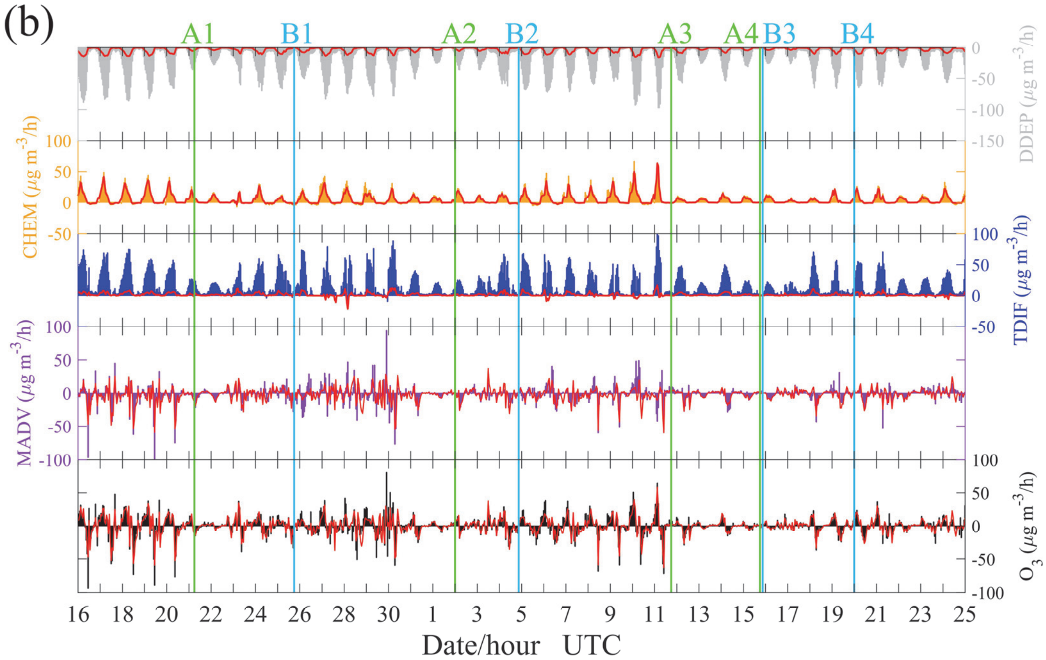
3.3.2 Shanghai in category I cities

In th~~is~~e study period, Shanghai was usually one of the first cities affected by landfall typhoons. We can see a multiday episode of O_3 during the period of 24-28 July, with a maximum of hourly O_3 up to 292 μg m^{-3} at 27 July (Figure 6a). The high O_3 concentrations together with high primary pollutants (CO and NO_2) suggest a strong photochemical O_3 production under the condition of high temperature (The daily maximum temperature can reach 35 °C) during this period, and the weak wind may play a significant role in the accumulation of surface O_3. The increase of the primary pollutants may be related to ~~the wind shift~~a change in wind direction from southeast to southwest causing by Typhoon Ampil (A1 in Figure 6a, -A1 and A1B1 in Figure 7), ~~resulting in air masses originally from the ocean had become inland~~which originally brought airmass from the ocean, shifted to from inland. Interestingly, $PM_{2.5}$ also showed good correlation with O_3 and primary pollutants, especially for NO_2 during this period. This indicates that a high level of oxidizability can promote the formation of secondary particles (Kamens et al., 1999; Khoder, 2002). From the results of process analysis (Figure 6b), the major contributions to surface O_3 were TDIF, CHEM and DDEP due to the small net contribution of MADV. TDIF had a considerable positive contribution while DDEP did the opposite, suggesting that high surface O_3 may be sourced from the upper layer via TDIF process, and be removed via DDEP process. However, for the whole boundary layer, which is defined as the layer less than 1500 m in this study, ~~it was~~ the balance was between CHEM and DDEP instead TDIF and DDEP. Thus, TDIF was likely to play the role of "transport" from the upper layer to surface. Figure 6c further shows the temporal-vertical distribution of O_3 with vertical wind velocity. The downward airflows ~~were~~ prevailed over Shanghai until 23 July, which are induced by the subtropical high. Then, strong upward airflows appeared as Typhoon Ampil arrived, and high level of O_3 disappeared. Around 27 July, the downward airflows gradually resumed and high level of O_3 occurred. The downward airflows are critical because they can not only inhibit the vertical transport of O_3 but also transport high-level O_3 to the surface. The high-level O_3 in the troposphere mainly comes from two sources. One is that O_3-rich air from the low stratosphere transported by the downdrafts in large-scale typhoon circulation (Jiang et al., 2015). The other is that O_3 produced by photochemical reactions during the day. It is note-worthy that ~~the high value center of O_3 appeared near the altitude of 1 km instead of near surface, indicting~~ high photochemical production efficiency of O_3 occurred in the middle boundary layer instead of at the surface. Moreover, most of the O_3 remained in the residual layer at night, while surface O_3 concentration was much lower due to NO_x titration. By the second day, high O_3 in the residual layer was transported to the surface by the downward airflows as air in the boundary layer is gradually mixed. Combined with the newly generated O_3, a high concentration of O_3 would eventually appear on the surface. ~~The downward airflows can not only inhibit the vertical transport of O_3 but also transport high-level O_3 to the surface, causing the episodes of surface O_3.~~

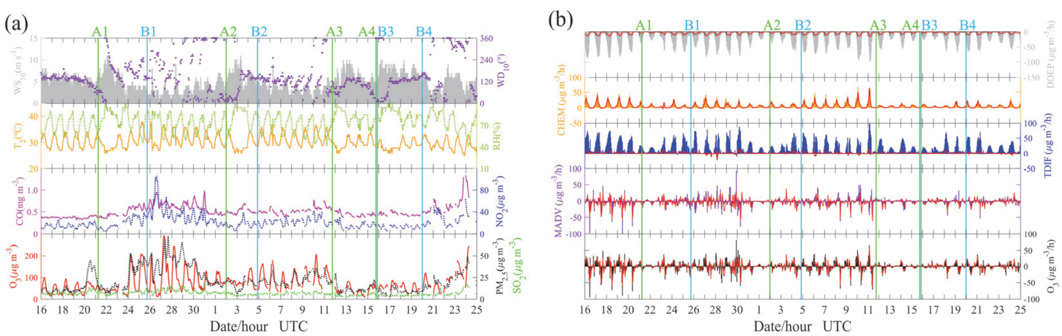
As shown in Figure 7, O_3 pollution tends to occur during the period from the end of a~~the~~ typhoon to the arrival of the next typhoon (B1A2 and B2A3) in the YRD. To reveal this phenomenon, we compare these two periods (B1A2 and B2A3) with their previous periods (A1B1 and A2B2) using the skew-T log-P diagram (Figure 6d and 6e). It is found that the atmospheric conditions of B1A2 (B2A3) were hotter and drier than A1B1 (A2B2) below 700 hPa in Shanghai, and wind speed is smaller in B1A2 (B2A3). Those changes in atmospheric conditions after typhoon will be conducive to the generation of high O_3 concentration in Shanghai.

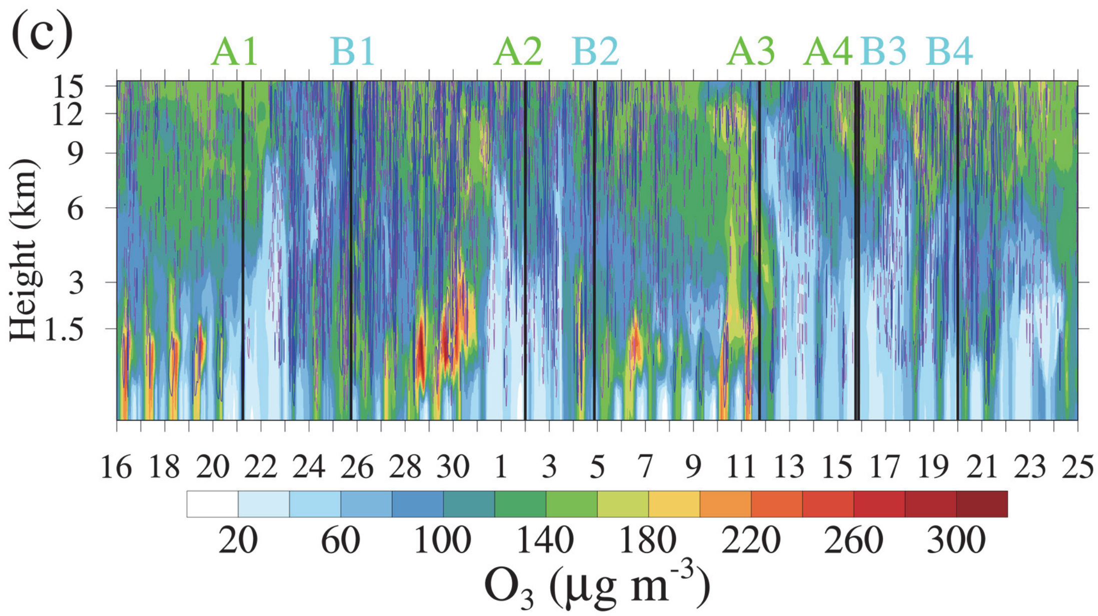


(a)
A1
B1
A2
B2
A3
A4
B3
B4
WS10(m s-1)
WD10(°)
T2(°C)
RH(%)
CO(mg m-3)
NO2(μg m-3)
O3(μg m-3)
PM2.5(μg m-3)
SO2(μg m-3)
Date/hour UTC



(b)
A1
B1
A2
B2
A3
A4
B3
B4
DDEP (μg m-3/h)
CHEM (μg m-3/h)
TDIF (μg m-3/h)
MADV (μg m-3/h)
O3 (μg m-3/h)
Date/hour UTC





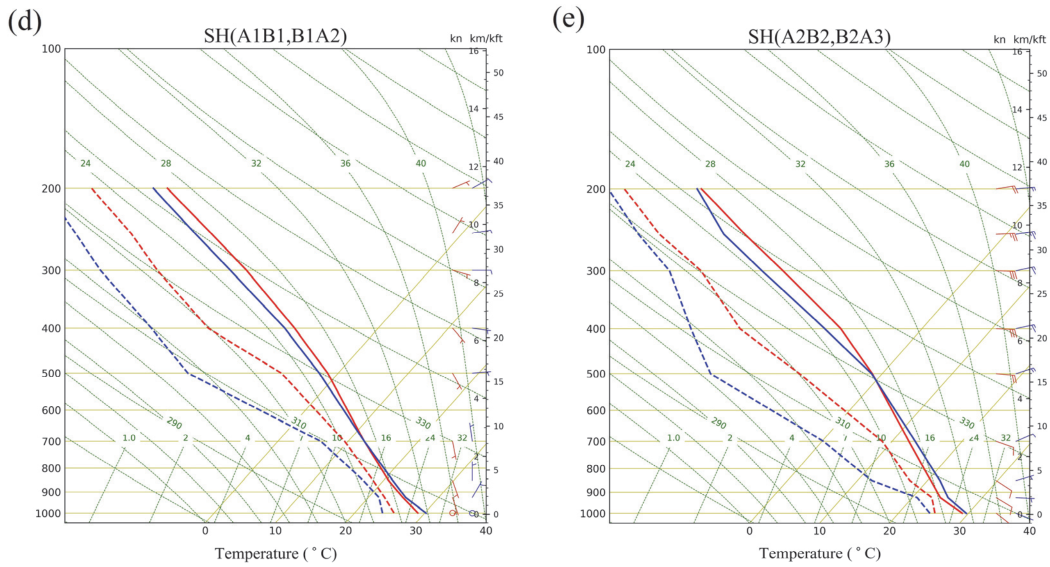


Figure 6. (a) Time series of air pollutants (O_3, $PM_{2.5}$, SO_2, CO and NO_2) and meteorological factors (T_2, RH, WS_{10} and WD_{10}) in Shanghai. (b) Individual processes contribution to net O_3 density at Shanghai. O_3 is the net increase, MADV is the sum of horizontal advection (HADV) and vertical advection (ZADV), TDIF is the sum of horizontal diffusion (HDIF) and vertical diffusion (VDIF), CHEM is the chemical reaction process, and DDEP is the dry deposition process. The color histograms indicate the results for the layer near the surface, while the solid red lines indicate the average results for all layers below 1500 m. (c) Temporal-vertical distribution of O_3 with vertical wind velocity over Shanghai. The dotted purple line and solid blue line indicate the negative wind speeds (downward airflows) and positive wind speeds

(upward airflows), respectively. (d) The skew-T log-P diagram at Shanghai. The average results of period A1B1 and B1A2 are shown in red and blue, respectively. (e) Same as (d), but for the average results of period A2B2 and B2A3.

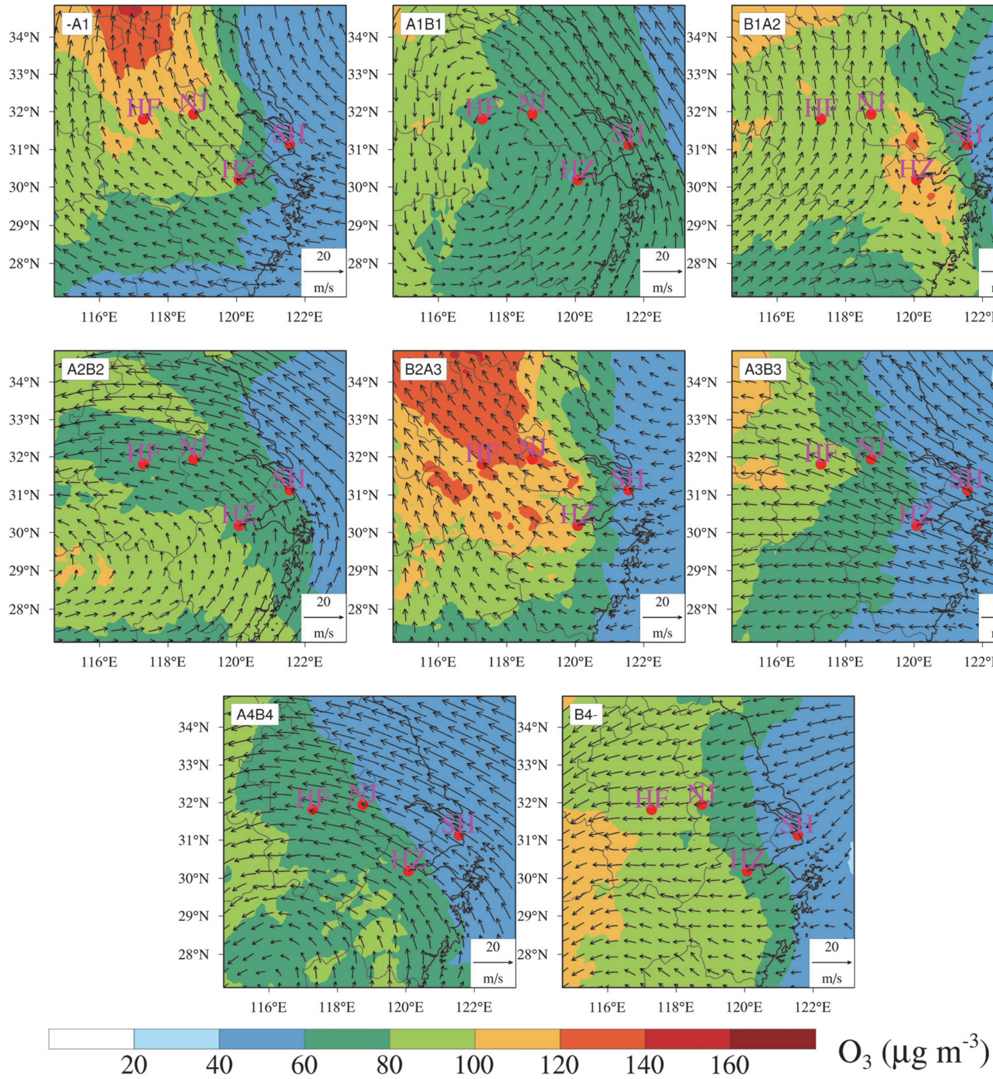
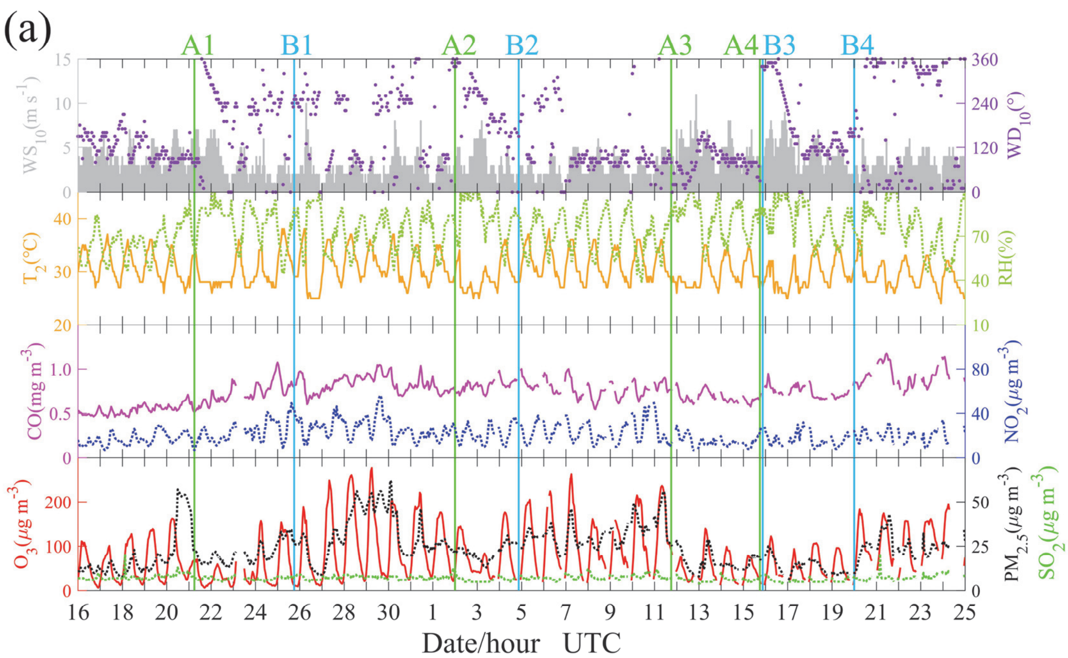
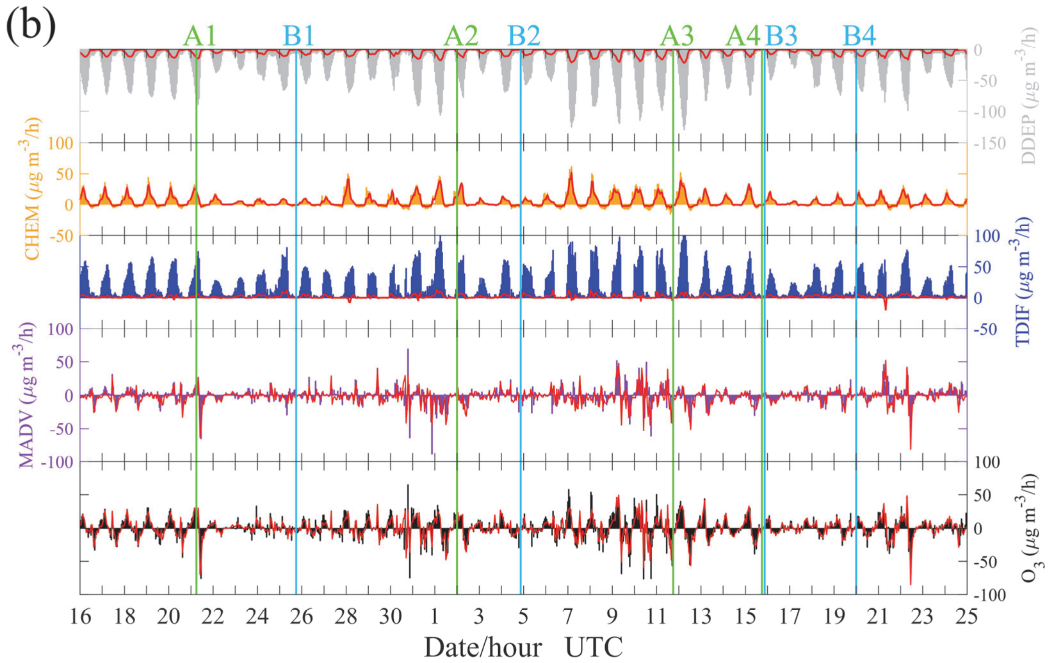


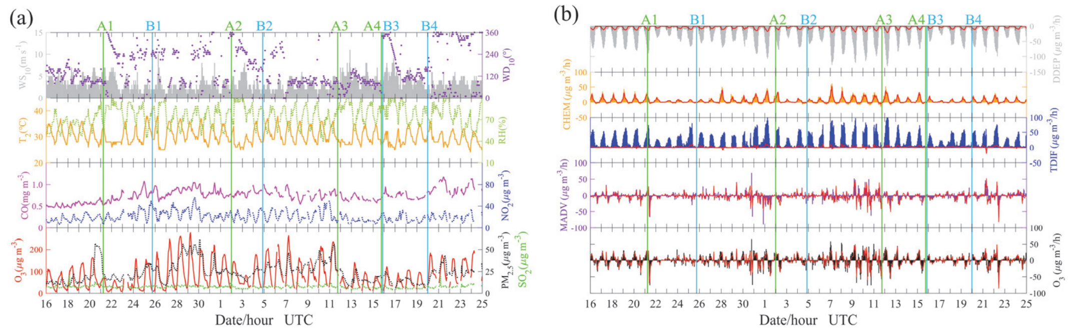
Figure 7. Spatial distribution of surface O_3 overlaid with wind fields at 850 hPa over the YRD. -A1, A1B1, B1A2, A2B2, B2A3, A3B3, A4B4, B4- are the average results from the beginning to A1, A1 to B1, B1 to A2, A2 to B2, B2 to A3, A3 to B3, A4 to B4, and B4 to the end, respectively. Details can be found in Figure 4.

3.3.3 Hangzhou in category II cities

Figure 8 presents the case in~~results for~~ Hangzhou. It shows that high O_3 concentrations occurred on 27-31 July and 5-7 August, which may also be related to the strong photochemical production of O_3 under the abundance of precursors (Figure 8a) and poor diffusion conditions due to the light wind (B1A2 and B2A3 in Figure 7). Figure 8a further shows that high O_3 was often associated with an increase in CO but the NO_2 concentrations usually remained at the same level. This phenomenon indicates a VOCs-limited regime in this city since CO usually have good correlation with VOCs and can play a similar role as VOCs in the photochemical production of O_3 (Atkinson, 2000; Ding et al., 2013). In fact, O_3 in other representative cities (Shanghai, Nanjing and Hefei) also showed a better correlation with CO than NO_2. Though Hangzhou is close to Shanghai, there is a significant difference of wind fields over these two cities. Starting from the arrival of Typhoon Ampil (A1). The wind direction in Hangzhou did not change back to southeast until a few days later after Typhoon Jongdari dissipated (B2). During this period (A1B2), the frequent southwest wind may be the reason for high CO concentrations in Hangzhou. In addition, the chaotic wind field during period B1A2 (B1A2 in Figure 7) may lead to the light wind in Hangzhou. With respect to the simulation results, the model simulated the variation of O_3 but failed to capture the O_3 peaks (e.g., the peak values on 27-31 July), which may be related to the strong upward airflows (Figure 8c) that inhibited the accumulation of O_3 (Figure 8b). This further illustrates that downward airflows may be an important factor for O_3 episodes in this case.







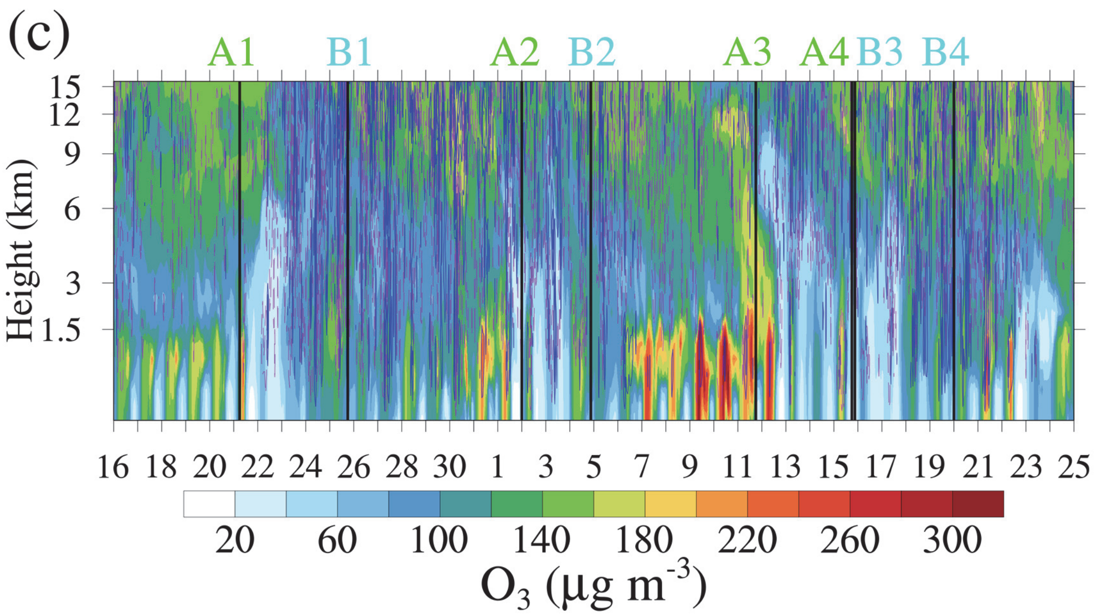
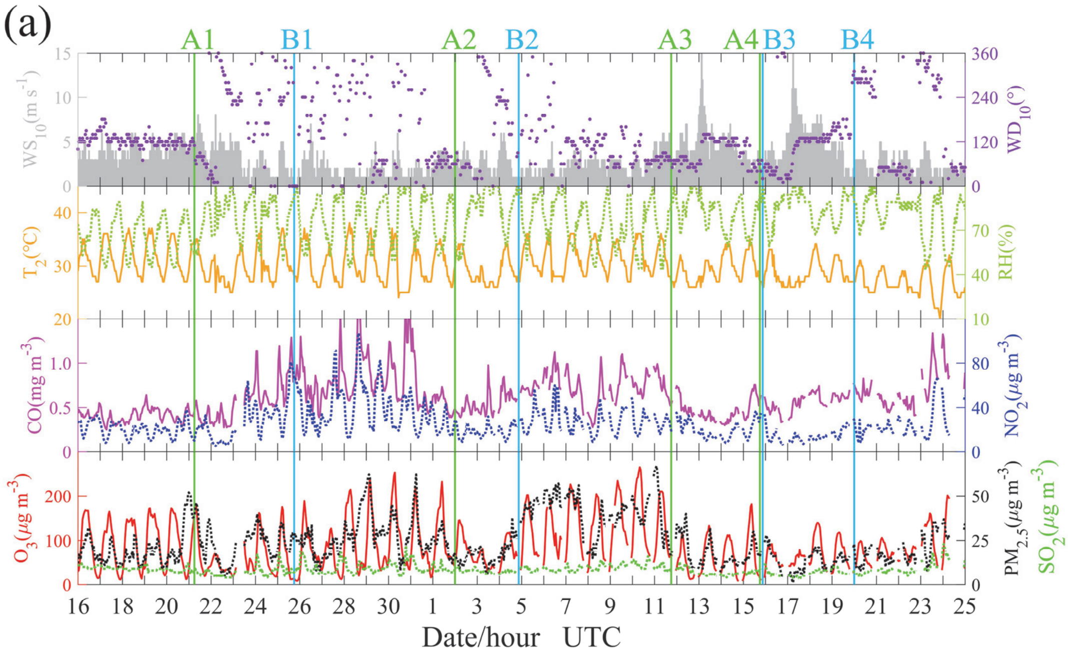
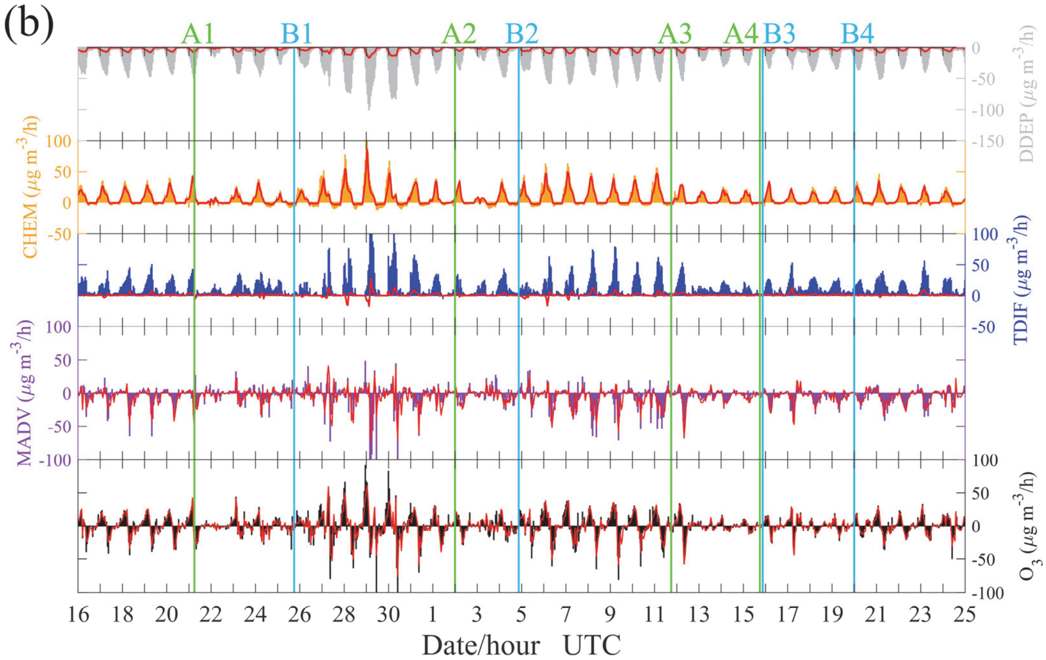


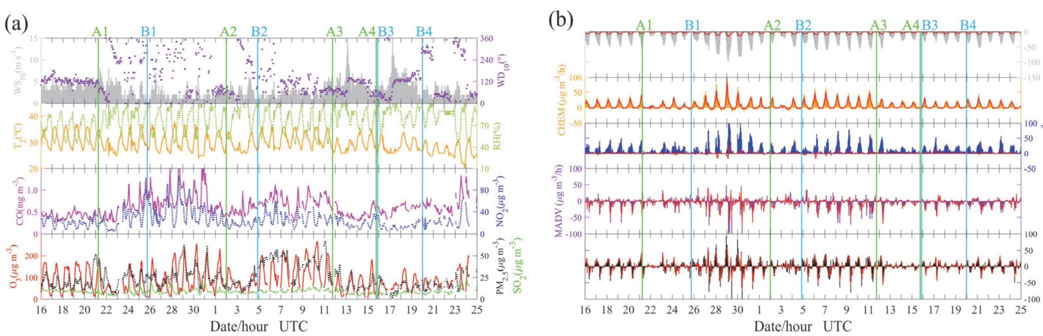
Figure 8. Same as Figure 6 (a)-(c), but for Hangzhou.

3.3.4 Nanjing in category III cities

In~~As for~~ Nanjing, the O_3 episode~~s with~~ exceeded the~~ance of~~ national air quality standards was~~ere~~ observed on 28 July to 1 August and 7-11 August. These O_3 episodes were characterized by abundant O_3 precursors under the condition of high temperature. Furthermore, light wind (B1A2 and B2A3 in Figure 7) and downward airflows (Figure 9c) also contributed greatly to the occurrence of O_3 pollution, resulting from a mechanism similar to~~with the similar mechanism as~~ that for~~of~~ Shanghai and Hangzhou. As early as on 22 July, the wind direction in Nanjing~~ had~~ changed from southeast to southwest because of the arrival of~~affected by~~ Typhoon Ampil, and thus the concentrations of the main primary pollutants (CO, NO_2 and SO_2) increased (Figure 9a). However, high-level O_3 episodes did not occur until 28 July even though the maximum temperature did not change significantly during 24-31 July. The "obstacle" for enhancing O_3 level~~of the O_3 episodes~~s may be the precipitation caused~~ing~~ by the strong upward airflows during 23-26 July (Figure 9c). As shown in Figure 9b, high surface O_3 concentration during the pollution episodes is the result of TDIF and CHEM processes, and is lost through DDEP and MADV processes. Regarding~~With respect to the~~ vertical structure of atmospheric, B1A2 (B2A3) was also hotter and drier than A1B1 (A2B2) below 700 hPa in Nanjing (Figure 9d and 9e). These consequences, similar to those in~~The similar results as~~ Shanghai, further confirm that high O_3 concentrations in a region are more likely to occur during the period from the end of an exciting~~the~~ typhoon to the arrival of the next typhoon (B1A2 and B2A3) than during the period when a~~the~~ typhoon approaches and is active in the region~~mainland China~~ (A1B1 and A2B2).


(a)
A1
B1
A2
B2
A3
A4
B3
B4
WS10(m s-1)
WD10(°)
T2(°C)
RH(%)
CO(mg m-3)
NO2(μg m-3)
O3(μg m-3)
PM2.5(μg m-3)
SO2(μg m-3)
Date/hour UTC


(b)
A1
B1
A2
B2
A3
A4
B3
B4
DDEP (μg m-3/h)
CHEM (μg m-3/h)
TDIF (μg m-3/h)
MADV (μg m-3/h)
O3 (μg m-3/h)
Date/hour UTC


(a)
(b)
Date/hour UTC
Date/hour UTC

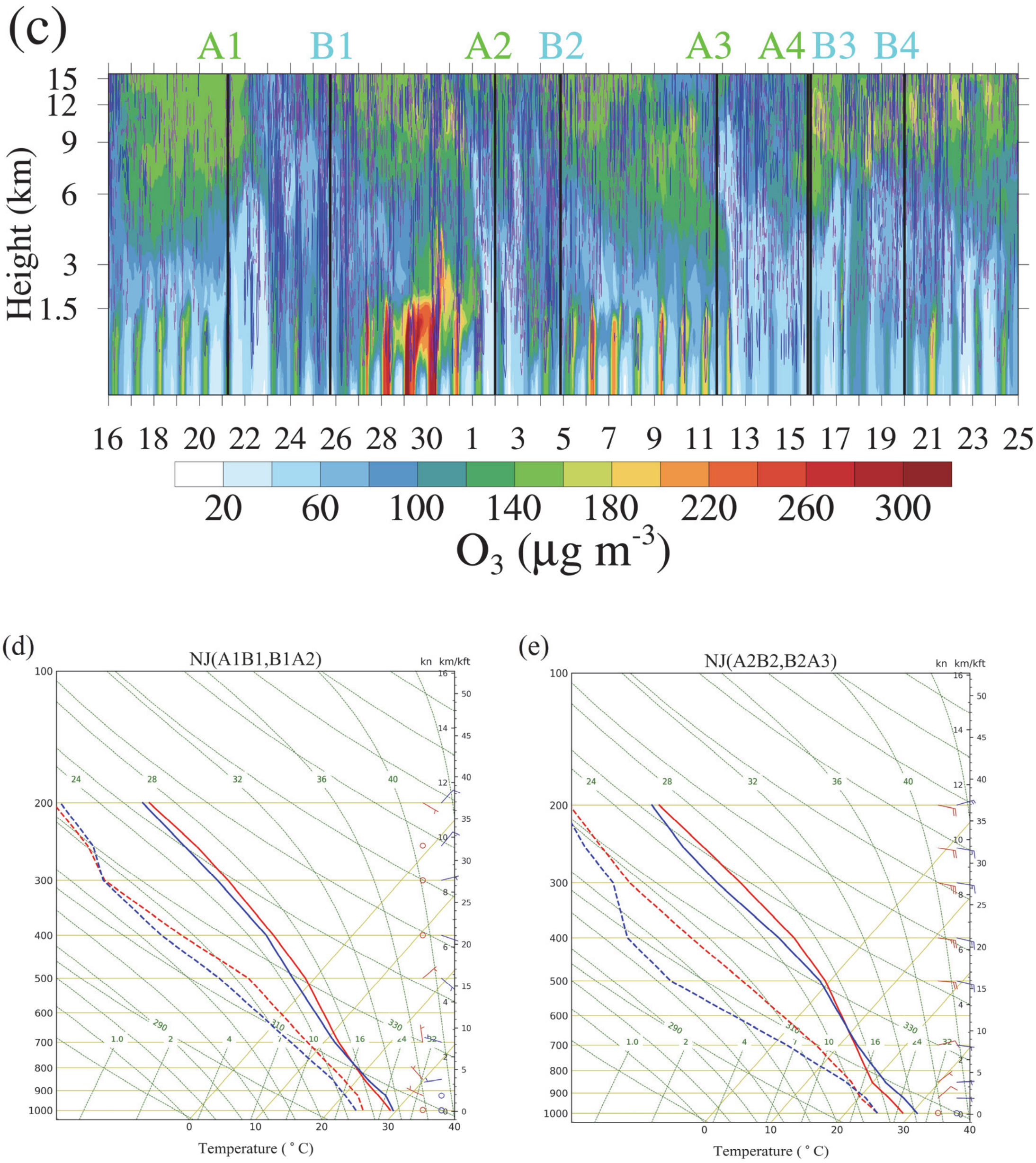
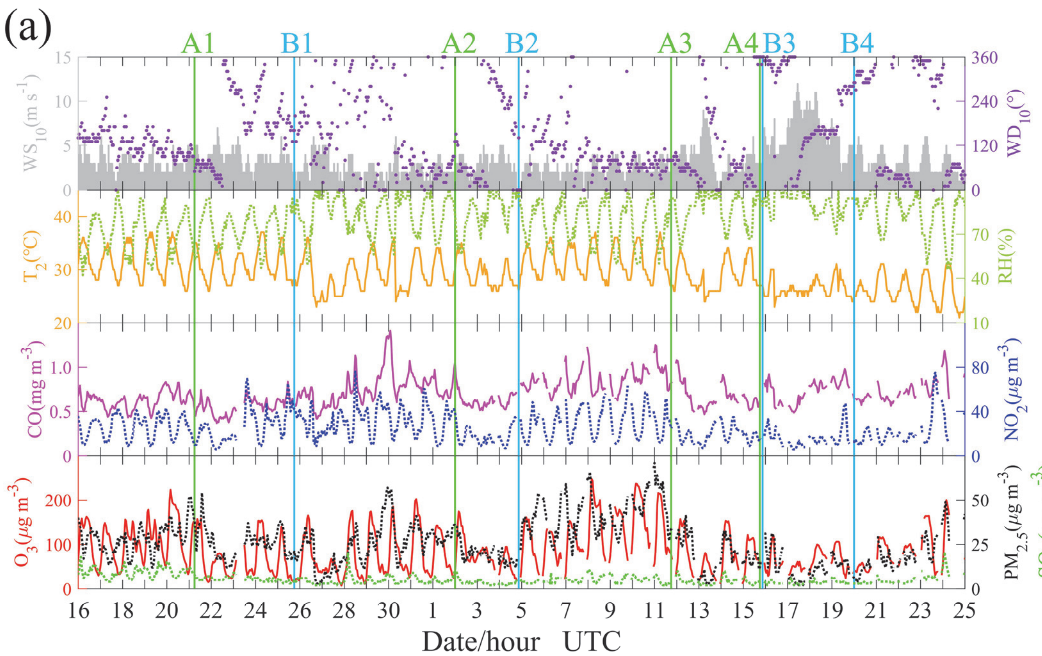
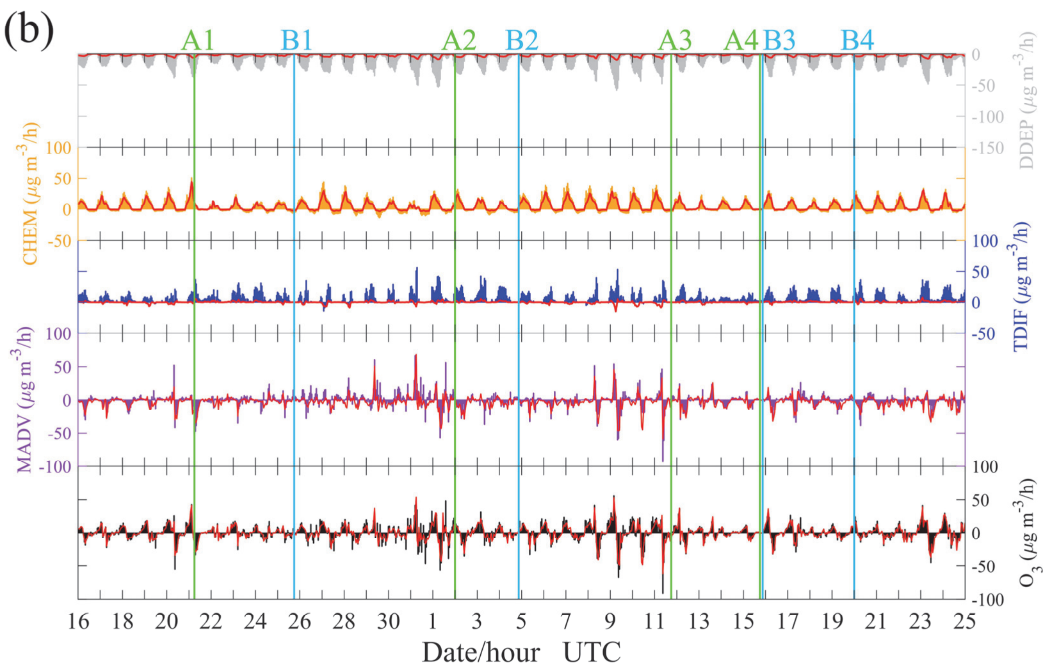


Figure 9. Same as Figure 6, but for Nanjing.

3.3.5 Hefei in category IV cities

Hefei is the city farthest from the coast among the four representative cities, and O_3 pollution occurred on 31 July and 8-11 August. We ~~can~~ also find the phenomenon that the precursors concentrations had an increase once the wind direction changed from southeast to southwest (Figure 10a). During B1A2 and B2A3, the concentrations of the main precursors of O_3 was~~had a~~ high ~~level~~. However, high O_3 concentration was mainly found in B2A3, and not in B1A2. This may be related to the relatively low temperature during B1A2 (Figure 10a), which is not conducive to photochemical production of O_3 (Figure 10b). As shown in Figure 10c, there were distinct upward airflows within the boundary layer, which may be related to urban effect (e.g., urban heat islands). These upward airflows within the boundary layer help mix the air, resulting in a uniform distribution of O_3 in the vertical direction. However, the downward airflows can still inhibit the vertical diffusion of O_3, and O_3 tends to be trapped within the boundary layer.





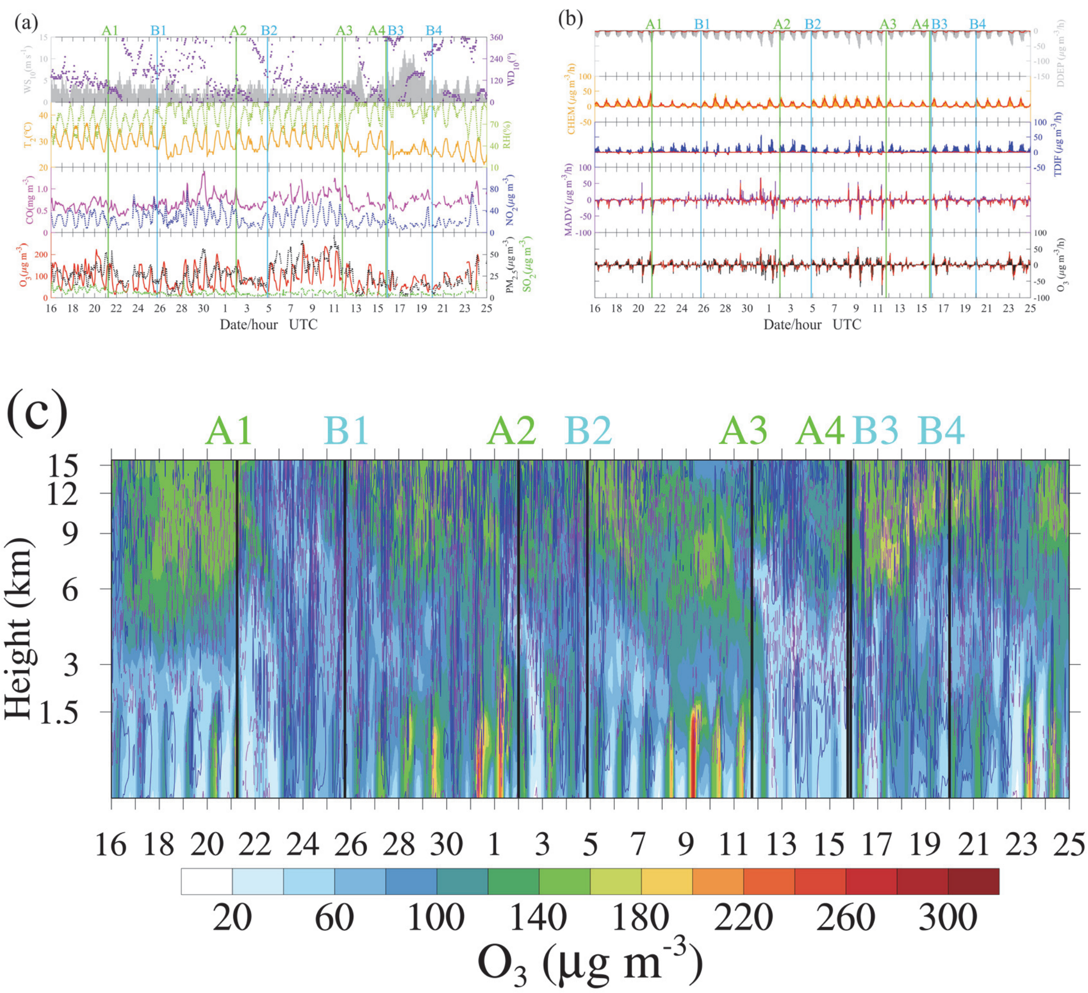
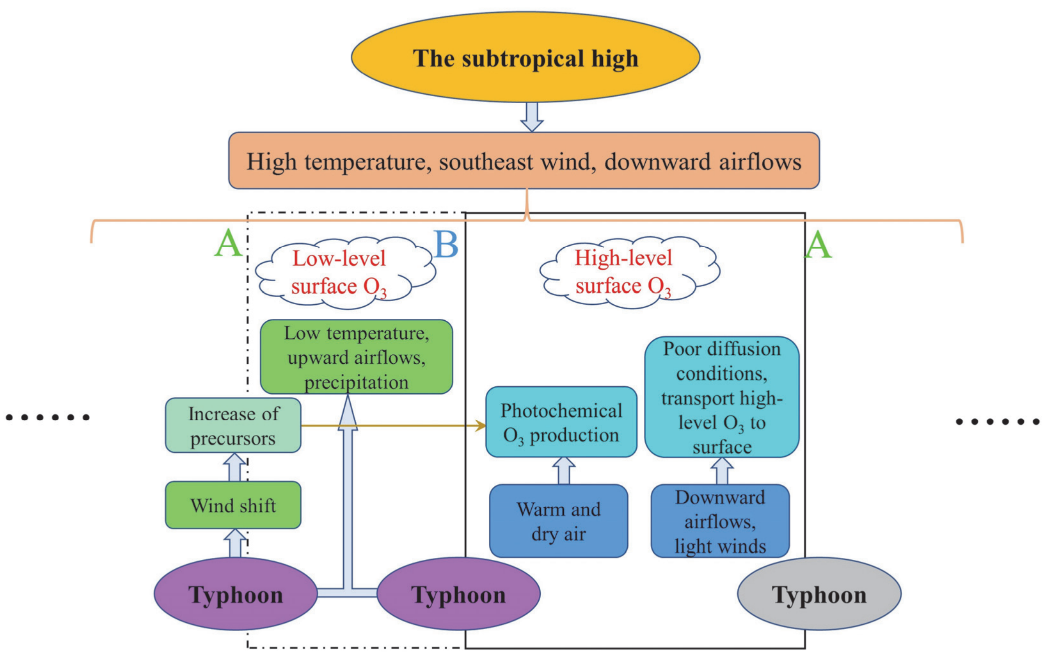


Figure 10. Same as Figure 6 (a)-(c), but for Hefei.

3.3.6 A schematic diagram of major processes

Although the processes of landfall typhoon affecting O_3 varied from city to city, the major processes have many similarities and can be summarized as a schematic diagram in Figure 11. The YRD region, as a typical region of East Asian monsoon climate, is strongly influenced by typhoon activities over the Western Pacific~~The YRD region, which features a typical subtropical monsoon climate, is strongly influenced by the western Pacific subtropical high in summer~~. ~~Dominated by the subtropical high~~In summer, the meteorological conditions of high temperature and downward airflows combined with high levels of precursors due to the huge energy consumption ~~tend to form high O_3 concentrations in this region~~are all favorable to O_3 accumulation in the region. However, powerful systems like typhoon can break this state. For typhoons that may land in the YRD, by the time they approach the 24-hour warning line, the prevailing southeast wind in the YRD will change to southwest wind, which can transport lots of precursors from inland to the YRD. The change in wind direction depends on the track of the typhoon and the geographical location of cities, and often appears first in cities along the coastline~~coastal region~~. With influence of a typhoon, the low temperature, precipitation (upward airflows) and wild wind ~~will~~ prevent high O_3 and $PM_{2.5}$ episodes from forming. Moreover, the effect of removing pollutants is related to the intensity of typhoon landing, but some of the main precursors of O_3 are still at a high level due to foreign sources superposed with local emissions. After the passing of typhoons, the atmosphere returns to a warm and dry state (even more so than before), and the downward airflows resumed. The troposphere is then flooded with high O_3 due to two main sources. One is that O_3-rich air transported from the low stratosphere by the downward airflows, and the other is that O_3 produced by strong photochemical reactions ~~begin to produce O_3~~ under the abundance of precursors. O_3 is mainly generated inside the boundary layer (~1000 m) instead of at the surface. ~~,~~The high-level O_3 can remain in the residual layer at night, and be ~~then~~ transported to the surface by downward airflows or turbulent mixing by the second day. At the same time, the wind readjusts to southeast and wind speed is light, resulting in poor diffusion conditions. The downward airflows and light wind obstruct the vertical and horizontal diffusion of O_3, leaving O_3 trapped on the ground. The thermal-dynamic effects result in high-level surface O_3 in the YRD.



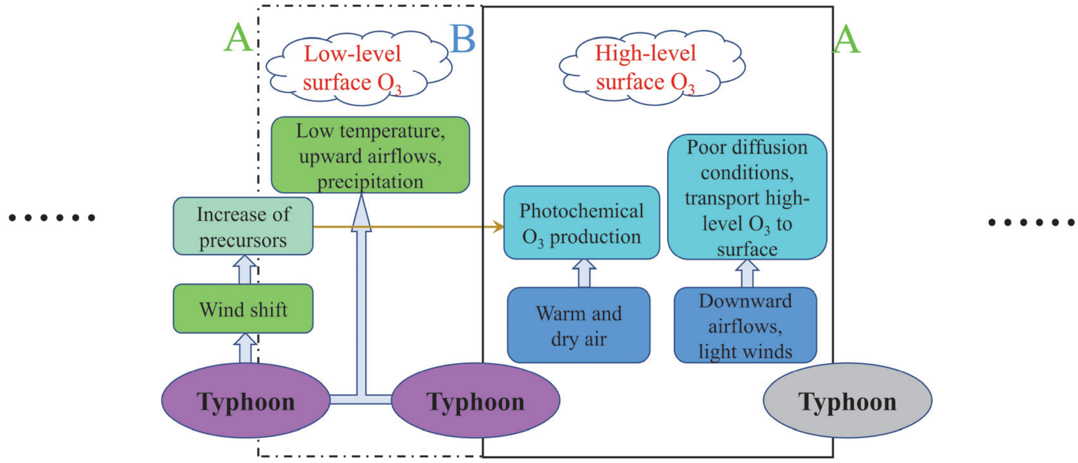


Figure 11. A schematic diagram of major processes that summertime O_3 is affected by landfall typhoons in the YRD. The letter A indicates the moment that the typhoon has reached the 24-h warning line, and letter B indicates the last moment when~~of~~ typhoon remains active~~activity~~ in the mainland China.

Typhoon can exert an enormous impact on energy transports and air mass in the troposphere as well as redistribution of pollutants. Though~~In fact,~~ most typhoons generated over the western North Pacific will not land in China, or they are more likely to land in the South China rather than the YRD. In our previous study (Shu et al., 2016), the typhoon did not land in the YRD, but the processes related to~~of~~ high-level O_3 formation may be the same~~common~~. That is, the processes shown in the open box enclosed by dashed lines~~dashed box~~ in Figure 11, which are unique to landfall typhoons, while the processes inside the box enclosed by solid lines ~~in the solid box~~ can be found between typhoons~~as long as the typhoons that can affect the YRD~~. Transport of precursors, downward airflows, high temperature and light wind are crucial factors, and how big~~the~~ roles of those factors play in O_3 episodes depends on behaviors of the typhoons and geographical locations of the cities~~typhoon and city~~. Q~~It is hard to q~~uantify these processes with just a few cases is a large challenge. For example, it is hard to find out~~we cannot estimate~~ whether the downward airflows are modulated~~dominated~~ by the subtropical high or the periphery circulation of typhoons since they usually occur simultaneously. Furthermore, the behave of particulate matter is intriguing since high-level $PM_{2.5}$ often occurs with high-level O_3 after typhoon, which is opposite to the suggestion ~~different from previous studies~~ that high particulate matter concentrations inhibit the formation of

O$_3$ in previous studies (Li et al., 2005; Xing et al., 2017). This may be related to the heterogeneous reactions (Lou et al., 2014) but research on this issue is quite limited to date.

3.3 Premature mortalities induced by O$_3$ exposure

When it comes to typhoons, especially landfall typhoons, the first concern is the huge damage caused by extreme weathers. After the passing of typhoons, people are relieved and go back~~busy~~ with their life~~work~~ as usual. However, our research indicates that high O$_3$ episodes are likely to occur in the short period after a typhoon landing in the YRD, and high O$_3$ concentrations can do harm to people's health. To arouse attention on this issue, we estimate the premature mortality attributed to O$_3$ for respiratory disease, we choose two complete cycles, which is the period A1A3 (21 July to 11 August), to do the calculation. In this study, we employ the standard damage function defined by epidemiology studies (Anenverg et al., 2010; Voorhees et al., 2014) to calculate the premature mortalities due to O$_3$ exposure, the specific formulas and parameters are described in Section 2.7. Table 4 summarized the premature mortalities in cities in the YRD. The premature mortalities are a function of both the population and O$_3$ levels, resulting in high premature mortalities in populated and heavily polluted areas. Out of the 26 cities in the YRD, Shanghai showed~~s~~ highest premature mortalities (29.2) due to its high surface O$_3$ concentrations and huge population. The city with the lowest premature mortalities (0.6) was~~is~~ Zhoushan, which may be related to removing effect of the maritime air masses as Zhoushan is located by the sea (Figure 1b). During this period, the total premature mortalities in the YRD was~~is~~ 194.0, which was~~is~~ larger than the number of casualties caused directly by the typhoons (80 people were killed by landfall typhoons in mainland China in 2018).

Table 4. Premature mortalities induced by O$_3$ exposure for respiratory disease

	City	Population (thousand)	Premature mortalities
Category I cities	Shanghai	24,240	29.2
	Yancheng	7,200	6.1
	Nantong	7,310	7.9
	Jiaxing	4,726	7.3
	Ningbo	8,202	8.1
	Zhoushan	1,173	0.6

	Taizhou	6,139	4.1
Category II cities	Hangzhou	9,806	16.5
	Taizhoushi	4,636	5.2
	Changzhou	4,729	4.4
	Wuxi	6,575	10.7
	Suzhou	10,722	15.3
	Huzhou	3,027	2.8
	Shaoxing	5,035	4.7
	Jinhua	5,604	8.2
Category III cities	Nanjing	8,436	13.4
	Yangzhou	4,531	5.5
	Zhenjiang	3,196	5.3
	Chuzhou	4,114	5.8
	Maanshan	2,337	3.6
	Wuhu	3,748	6.2
	Xuancheng	2,648	2.0
Category IV cities	Hefei	8,087	10.9
	Tongling	1,629	1.7
	Chizhou	1,475	2.1
	Anqing	4,691	6.4
Total		154,016	194.0

4 Conclusions

In this study, we investigate the detail processes of landfall typhoons affecting O_3 in the YRD based on a unique case from~~during~~ 16 July to 25 August, 2018, using both~~with the help of~~ monitoring observations and numerical simulations. This case was characterized by two multiday regional O_3 pollution episodes involving~~concerned with~~ four successive landfall typhoons. The two O_3 episodes appeared from 24 July to 2 August and 5 to 11 August, respectively, with the highest MDA8 O_3 reached up 264 μg m^{-3}.

The time when a~~moment that~~ typhoon reaches~~s~~ the 24-h warning line and the time when the ~~last moment of~~ typhoon dies away~~activity~~ in the mainland China are~~are~~ crucial, because O_3 pollution episodes mainly occur~~red~~ during the period from the end of a typhoon to~~and~~ the arrival of the next typhoon in the YRD. These two moments can be roughly regarded as time nodes. Furthermore, it is found that the variations of O_3 was related to the track, duration and landing intensity of the typhoons during the study period. O_3 pollution first appeared in cities along the coastline ~~coastal region was~~

~~ahead of that in inland regions due to~~along the track of the typhoons. The interval between two typhoons can affect the duration of high O_3 concentration in the YRD. Generally, sustained high O_3 concentration~~–~~ likely appeared in the region on days when the existing typhoon had dissipated before the arrival of the next one~~tends to appear on days when the typhoon has dissipated but not influenced by the new one~~. Regarding the impact of~~As for~~ the landing intensity of typhoon, the stronger the typhoon landed, the gale and precipitation accompanying the typhoon woul~~il~~d~~l~~ be more effective in suppressing O_3 generation~~removing O_3~~, resulting in lower O_3 concentration in the typhoon landing location.

The detail processes of landfall typhoons affecting O_3 depend on typhoons and cities. High temperature and downward airflows ~~dominated by the subtropical high~~ combined with abundant precursors are the main reasons for high O_3 concentration in the YRD in summer. And landfall typhoons can change this state through the following mechanism: When the landfall typhoon is close enough (~ 24-hour warning line), the prevailing southeast wind will change to southwest wind, which transports large amount of precursors from inland to the YRD. The southwest wind usually appears first in coastal regions, and the wind direction will turn~~ back~~ to southeast~~ wind~~ as long as the YRD is dominated by the subtropical high. Then the typhoon makes landfall, the low temperature, precipitation (upward airflows) and wild wind suppress the generation of O_3. After the typhoon passing, the atmosphere in~~at~~ low layers (below 700 hPa) will be warm and dry, and downward airflows resume. The troposphere is likely to fill with high concentration of O_3 due to O_3-rich air transported from the low stratosphere and strong photochemical reactions~~ begin to produce O_3 under the abundance of precursors due to foreign sources superposed with local emissions~~. O_3 is mainly generated in the middle of boundary layer (~ 1000 m) instead of at the surface.~~,~~ The high-level O_3 can remain in the residual layer at night, and can be ~~then~~ transported to the surface by downward airflows or turbulent mixing by the second day. The downward airflows also obstruct the vertical diffusion of O_3. Meanwhile, wind speed is light when the wind readjusts to southeast, which further reduces~~worsens~~ horizontal diffusion of O_3. Thus,~~The~~ O_3 can be accumulated and trapped on the ground. The thermal-dynamic effects results in high surface O_3 concentration in the YRD. Those processes will repeat if the next typhoon approaches.

The estimated premature mortalities attributed to O_3 exposure for respiratory disease in the YRD during 21 July to 11 August (two complete cycles of typhoons) was~~is~~ 194.0, which is larger than the number of casualties caused directly by the typhoons. This work has~~can~~ enhanced our understanding of how landfall typhoons affect O_3 in the YRD, which may help synthetically~~to~~ forecast~~ the~~ O_3 pollution modulated~~synthetically impacted~~ by the subtropical high and typhoons. Meanwhile, our results further confirm that large-scale synoptic weather systems play an important role in regional air pollution, suggesting a need in establishing potential links between air pollution and predominant synoptic weather patterns.

Author contributions. C. C. Zhan and M. Xie had the original ideas, designed the research, collected the data, and prepared the original draft. C. C. Zhan carried out the data analysis. M. Xie acquired financial support for the project leading to this publication. C. W. Huang taught and helped C. C. Zhan to do the numerical simulation. J. Liu and T. J. Wang~~ and J. Liu~~ revised the manuscript and helped to collect the data. C. Q. Ma helped to deal with the emission inventory. M. Xu and J. W. Yu helped to collect the data. M. M. Li, S. Li, B. L. Zhuang, and M. Zhao reviewed the initial draft and checked the English of the original manuscript. Y. M. Jiao and D. Y. Nie reviewed the initial draft and helped to improve the work of health impact.

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