Modeling tropospheric O$_3$ evolution during the 2016 Group of Twenty summit in Hangzhou, China

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Abstract: To elucidate the factors governing the urban O$_3$ pollution during the campaign period of 2016 Group of Twenty (G20) summit in China, the Weather Research Forecast with Chemistry (WRF-Chem) model was used to simulate the spatial and temporal O$_3$ evolution in the Yangtze River Delta (YRD) region from August 24 to September 06, 2016. A unique mechanism was found to modulate the high ozone episodic event. Before the tropical cyclone, a prevailing north wind component brought in emission sources which are favorable for ozone formation. With the invasion of tropical cycle, subsidence air and stagnant weather were induced. Together with local urban heat island effect, there factors intensify ozone pollution in the YRD region. Different atmospheric processes were further analyzed to investigate the control factors of ozone formation through the integrated process rate method. It was found that both the vertical diffusion and the enhancing process of local chemical generation accounted for the growth of surface O$_3$ concentration in Hangzhou. Besides, dynamical circulations of O$_3$ advection associated with urban heat island effect were observed during the high O$_3$ episode (August 24–25, 2016), and low O$_3$ episode on September 5–6, 2016 was mainly resulting from the local chemical consumption. This provides insight into urban O$_3$ formation and dispersion in East China during the tropical cyclone events.

Keywords: Ozone, Tropical cyclone, WRF-Chem, Process analysis, Air quality
1. Introduction

Tropospheric \( \text{O}_3 \) is generated by a series of photochemical reactions involving volatile organic compounds (VOCs), nitrogen oxides (\( \text{NO}_x \)), and CO. Severe \( \text{O}_3 \) pollution usually occurs with the presence of sunlight, unfavorable meteorological conditions, and abundant \( \text{O}_3 \) precursors (Wang et al., 2006). As a primary ingredient in photochemical smog, ground-level \( \text{O}_3 \) pollution not only has detrimental effects on human health (Ha et al., 2014; Kheirbek et al., 2013) and the ecosystem (Landry et al., 2013; Teixeira et al., 2011) but also has warming effects as a short-lived climate forcer (Monks et al., 2015). The contribution of outdoor air pollution sources to premature mortality could be increasing globally in the coming decades (Lelieveld et al., 2015). In Europe, 98% of the urban population is exposed to \( \text{O}_3 \) concentrations exceeding those reported in the World Health Organization Air Quality Guideline from 2010 to 2012 (Ortiz, 2015). \( \text{O}_3 \) levels in the United States of America (USA) and European cities are increasing more than at rural sites, while peak values are decreasing during 1990-2010 (Paoletti et al., 2014). Nagashima et al., (2017) states long-term (1980–2005) increasing trend in surface \( \text{O}_3 \) over Japan is mainly explained as the sum of trends in contributions of other regions (particularly from China) to photochemical \( \text{O}_3 \) production. In addition, urban \( \text{O}_3 \) pollution events can also be observed in developing countries, such as Thailand (Zhang and Kim Oanh, 2002) and India (Calfapietra et al., 2016).

Recent years in China, air quality is deteriorating with the evolving urbanization and motorization. Many field and modeling studies have been conducted to investigate the photochemical characteristics of near-surface \( \text{O}_3 \) (Tang et al., 2009, 2012; Wang et al., 2013, 2014), photochemistry of \( \text{O}_3 \) and its precursors (Xie et al., 2014), interactions of \( \text{O}_3 \) with \( \text{PM}_{2.5} \) (Shi et al., 2015), and urban \( \text{O}_3 \) formation (Tie et al., 2013). In addition to anthropogenic emissions of \( \text{O}_3 \) precursors, uncontrollable meteorology is an important factor modulating changes in \( \text{O}_3 \) concentration, through atmospheric physical and chemical processes (Xue et al., 2014). \( \text{O}_3 \) concentrations over the Yangtze River Delta (YRD) region, China were mainly contributed by the transport and diffusion from surrounding areas (Gao et al. 2016; Jiang et al. (2012). Synoptic
patterns related to tropical cyclones may be optimal weather conditions conducive to this high O\textsubscript{3} concentrations (Huang et al., 2005). Jiang et al., (2015) states the enhancement of stratosphere–troposphere exchange (STE) driven by a tropical cyclone, abruptly increased O\textsubscript{3} (21–42 ppb) in the southeast China during June 12–14, 2014. STE has recently been highlighted to be a significant contributor to near-surface O\textsubscript{3} concentrations (Lin et al. 2012; Lin et al., 2015). However, understanding the complex dynamics in atmospheric processes regarding O\textsubscript{3} formation, as well as identifying the main processes accounting for high O\textsubscript{3} concentrations, is nontrivial due to the limited measurements. O\textsubscript{3} pollution characteristics and underlying causes, in particular over megacities, are still unclear, thus understanding the mechanism modulating O\textsubscript{3} variations is vital for pollution prevention.

In this study, we used a regional air quality model to elucidate the chemical and physical factors governing O\textsubscript{3} abundance during the Group of Twenty (G20) summit. This summit was held in Hangzhou, China to discuss the sustainable and healthy development of the world economy. Emergency emission control measures (e.g., industrial stoppages, vehicle-limiting movement, and artificial rainfall) have been implemented over an area with a diameter of approximately 600 km to improve the air quality from August 24 to September 6, 2016. With severe concerns regarding O\textsubscript{3} concentrations in Hangzhou, this episode of megacity O\textsubscript{3} pollution has attracted wide policy-related interest. The rest of this paper is organized as follows. Section 2 outlines the methodology of the model system and its configuration. Section 3 presents the synoptic weather conditions, O\textsubscript{3} formation-related individual atmospheric processes. Section 4 discusses the background O\textsubscript{3}, transport patterns, and reasons for O\textsubscript{3} pollution in Hangzhou. Finally, Section 5 presents a summary of the findings.

2. Methodology

2.1. Regional chemistry modeling system

To understand the interactions among emissions, meteorology, and chemistry, the WRF-Chem model (Version 3.7) was used to simulate the temporal and spatial O\textsubscript{3} evolution. WRF-Chem is a
regional online-coupled air quality model that simultaneously simulates air quality components with meteorological components by using identical transport schemes, grid structures, and physical schemes (Grell et al., 2005). Two model domains were designed in this study (Fig. 1a), namely an outer domain (horizontal resolution: 30 km), covering East China (20.0–44.5°N, 99.0–126.5°E), and an inner domain (horizontal resolution: 6 km), covering the YRD region (27.6–32.7°N, 116.9–122.4°E), with a “Lambert conformal conic” projection centered on Central China (34°N, 111°E). The domains included a total of 31 vertical layers up to 100 hPa with finer vertical resolutions near the surface. The simulation period was from August 17 to September 6, 2016, with the first week simulations conducted to spin up the model; the hourly data during August 24–September 6, corresponding to the official air pollution control measures implemented during the G20 summit, were used in the following analysis. Other detailed information regarding the configuration of WRF-Chem model has been described by our previous study (Ni et al., 2018).

Fig. 1. Double-nested simulation domains. (a) Domain 1: 30 km in East China with 102 (W–E) × 111 (S–N) × 31 (vertical layers) grids; Domain 2: 6 km in the Yangtze River Delta (YRD) region with 100 (W–E) × 115 (S–N) × 31 (vertical layers) grids. (b) Color bar (right) represents the terrain elevations. Blue dots denote the air quality monitoring sites. The red circle represents the control scales of emission control measures. Geographical data, including terrain elevations (Fig. 1b), soil properties, and albedo, were primarily interpolated from the United States Geological Survey database (Brown et al., 1993). Land surface parameters, including land use categories, green vegetation fraction, and leaf area
index were specified by applying the Moderate-Resolution Imaging Spectroradiometer (MODIS) satellite observations (Friedl et al., 2002; Li et al., 2014). The meteorological boundary and initial conditions were determined from the global objective final analysis (FNL) data of the National Centers for Environmental Prediction. The FNL data were also assimilated to domain 1 (East China) by using the grid-nudging method (Stauffer et al., 1991) to reduce the meteorological integral errors. Furthermore, the chemical boundary and initial conditions were interpolated from the results of the global Model for Ozone and Related Chemical Tracers Version 4 (MOZART4) (Emmons et al., 2010).

2.2. Emissions

As crucial model inputs, primary anthropogenic emissions included species of SO$_2$, NO$_x$, CO, NH$_3$, PM$_{2.5}$, and VOCs, mainly from several sectors including the power, industrial, residential, transportation, and agricultural sectors. The monthly Multiresolution Emission Inventory for China (MEIC, 0.25°× 0.25°; http://www.meicmodel.org/) was used for domain 1 in East China (Li et al., 2017). Custom finer emission inventories in Hangzhou were used for domain 2 in the YRD region, in accordance with the policies of emission control strategies implemented. The emission inventories for the two domains were projected into horizontal and vertical gridded-hourly emissions with temporal and vertical profiles obtained from Wang et al. (2011). VOCs emissions were categorized into modeled species, according to von Schneidemesser et al. (2016). Biogenic emissions were generated using the Model of Emission of Gases and Aerosols from Nature (Guenther et al., 2006). Dust emissions were calculated online from surface features and meteorological fields by using the Air Force Weather Agency and Atmospheric and Environmental Research scheme (Jones et al., 2011). Other uncontrollable or small amounts of emissions (i.e., biomass burning, aviation, and sailing ship) were not considered in this particular period.

2.3. Integrated process rate analysis

To understand the mechanism underlying O$_3$ formation, individual physical and chemical processes of O$_3$ formation were investigated using integrated process rate (IPR) analysis.
incorporated into the WRF-Chem model. IPR analysis has been widely applied and proven to be an effective tool for demonstrating the relative importance of individual processes and providing a fundamental interpretation of O$_3$ concentrations (Goncalves et al., 2009; Tang et al., 2017; Shu et al., 2016). In this study, atmospheric processes of O$_3$ formation, including gas chemistry, vertical diffusion, and horizontal and vertical advection, were investigated. Other processes (i.e., cloud process and horizontal diffusion) that either play minor roles or act as a sink (i.e., dry and wet deposition) were not presented in this study.

2.4. Evaluation method

To gain confidence in model result interpretation, the first step is to evaluate model outputs based on observations. Accordingly, in this study, the model results derived from domain 2 were compared with hourly surface observational data obtained from 96 air quality monitoring sites in the YRD regions (blue dots, Fig. 1b). The air pollutants included O$_3$ and NO$_2$. Model performance was evaluated using statistical measures, namely mean fractional bias (MFB) and mean fractional error (MFE) and correlation coefficient (R), with formula shown in Table S1, following the recommendation of the US Environmental Protection Agency (US EPA; 2007). Additionally, the meteorological parameters included temperature at 2 m (T2), relative humidity at 2 m (RH2), and 10-m wind speed (WS10) and direction (WD10). Commonly used mean bias (MB), gross error (GE), and root mean square error (RMSE), with equations shown in Table S1, were calculated as the statistical indicators, according to the study of Zhang et al. (2014).

The vertical distribution of modeled O$_3$ in Hangzhou was evaluated by conducting comparisons with the observed differential absorption LiDAR (DIAL) data. In the DIAL technique, the mean gas concentration over a certain range interval is determined by analyzing the LiDAR backscatter signals for laser wavelengths tuned “on” ($\lambda_{on}$) and “off” ($\lambda_{off}$) a molecular absorption peak of the gas under investigation (Browell et al., 1998). The application of the DIAL technique measurement of O$_3$ concentrations above or around a specific location (Browell, 1989). In our
DIAL datasets, the available vertical height ranged only from 0.3 to 3 km, because of the limitation of the signal-to-noise ratio and detection range.

3. Results

3.1. Model performance evaluation

![Statistical performance of the modeled and observed concentrations of the air pollutants from 96 air quality monitoring sites over YRD from August 24 to September 6, 2016 (1,344 daily pairs). Mean fractional bias (MFB) and mean fractional error (MFE) for (a) O$_3$-8h and (b) daily mean NO$_2$. (Each point denotes a site). Performance goals (red box) for O$_3$ are the benchmarks. Correlation coefficient (r) for (c) O$_3$-8h and (d) daily mean NO$_2$. (Each point denotes a daily pair).](image)

We first evaluate the overall performance of WRF-Chem over the YRD region by incorporating the 96 air quality monitoring sites. The maximum daily 8-hr (O$_3$-8h) ozone and daily mean NO$_2$ at surface were used. The model-simulated air pollutants in general agree with the observations, shown in Fig. 2. The mean MFB and MFE O$_3$-8h was -6%, 17%, respectively (Figs.
2a and c), within the benchmarks (MFB: 15% and MFE: 35%) proposed by the US Environmental Protection Agency (US EPA; 2007). The daily mean NO$_2$ level also achieved a reasonable performance, with MFB of -12%, MFE of 34% (Figs. 2b and d). Both the simulated O$_3$ (Pearson r of 0.70) and NO$_2$ (Pearson r of 0.67) shows statistically significant correlation with the observed data at the 95% level. The performance in this study is comparable to the previous studies (Tuccella et al., 2012; Zhang et al., 2016).

Following the overall evaluation over YRD above, the site of Hangzhou was zoomed in to elucidate the ability of WRF-Chem in reproducing the air quality and meteorological conditions. Time series of hourly simulated and observed air pollutants (O$_3$, Fig. 3a; NO$_2$, Fig. 3b) and meteorology (2-meter air temperature: T2, Fig. 3c; 2-meter relative humidity: RH2, Fig. 3d; 10-meter wind speed: WS10, Fig. 3e and 10-meter wind direction: WD10, Fig. 3f) were shown in Fig. 3. The observed diurnal variations were in general well captured by WRF-Chem. For example, the
MFB and MFE for both $O_3$ and $NO_2$ was close to benchmark in particular of $O_3$ (MFB/MFE: 4%/21%), well below the standard (MFB/MFE: 15%/35%) (US EPA; 2007).

For meteorological parameter evaluation, Emery et al. (2001) proposed benchmarks, including 2-meter air temperature ($MB \leq \pm 0.5$ °C, $GE \leq 2.0$ °C), 10-meter wind speed ($MB \leq 0.5$ m/s, $RMSE \leq 2.0$ m/s) and 10-meter wind direction ($MB \leq \pm 10$ deg, $GE \leq 30$ deg). McNally (2009) indicated a relaxed benchmark for 2-meter temperature ($MB \leq \pm 1.0$ °C). The 10-meter wind speed and wind direction is well within the criteria. The $GE$ of 2-meter air temperature (1.9 °C) also satisfies the criteria, albeit the mean bias is slightly higher (-1.6 °C), and the slightly higher temperature bias occurs in the previously study as well (Zhang et al., 2014). Overall, the meteorological parameter yields good performance in comparison to observations.

![Fig. 4. Upper-level comparison of hourly (a) observed (from differential absorption lidar) and (b) simulated $O_3$ concentrations (ppb) in Hangzhou from August 24 to September 6, 2016. Purple regions in the top panel denote the invalid data with a low signal-to-noise ratio. For an easy direct comparison, the red dashed line indicates the ozone level at exactly the same time period (starting from 12:00, August 24) and vertical heights (0.3–3 km) between the observations and simulation results.](image)

To further delve into the ability of model in reproducing the vertical structure of ozone concentration, a qualitative comparison of the vertical distribution between the modeled $O_3$ against the DIAL datasets was shown in Fig. 4, depicting good consistency between model and observation. Diurnal $O_3$ variations were observed mainly within the planetary boundary layer (approximately < 2 km). Notably, the model successfully captured a nocturnal $O_3$-rich mass, which exhibited an n-shaped distribution in the upper air (approximately 1 km) on August 24, 2016, thus indicating that the promising applicability of the model to pollution monitoring. Occasionally, the model revealed a
high $O_3$-rich mass (>90 ppb) at a height of approximately 3 km (nearly 700-hPa) i.e., on August 29 and September 2, 2016; however, no valid observed data could be used considering the low signal-to-noise ratio.

### 3.2. Synoptic weather system

Fig. 5. Tropical cyclone evolution in East Asia during the 2016 G20 summit. Weather charts for four representative periods at 08:00 LST on (a) August 25, (b) August 27, (c) August 31, (d) September 6, 2016. LST: Local Sidereal Time; H: High-pressure system; L: Low-pressure system. The red triangle denotes the location of Hangzhou.

Because synoptic circulation is closely related to $O_3$ abundance, four representative surface weather charts obtained from the Korea Meteorological Administration were used to track the tropical cyclone (Fig. 5). In the early stage of the tropical cyclone during August 24–25, 2016 (Fig. 5a), strong uniform high-pressure fields covered vast regions of southeastern China. A tropical cyclone moved northeastward in the East China Sea. In the middle stage (Fig. 5b), the tropical...
cyclone approached the YRD region and brought strong north wind fields. Notably, the long narrow rain band arrived in Hangzhou (red triangle) on August 27, 2016. In the later stage (Fig. 5c), the cyclone continually moved toward Japan on the following days and hit the land. Furthermore, the tropical high in the YRD region recovered gradually. Finally, the cyclone faded, and a rainstorm appeared in most of the YRD region. This rainstorm was sustained from almost September 2 to 7, 2016 (Fig. 5d, only the data for September 6 are presented for clarity).

3.3. O$_3$ distribution at different heights

**Fig. 6.** Distribution of the simulated daytime mean concentrations of O$_3$ (08:00–17:00 LST on August 24–September 6, 2016) and its precursor gas NO$_x$ (shaded, µg m$^{-3}$) and wind fields (vector, m s$^{-1}$) in domain 2 at several layers, as labeled on top of the plots.

The O$_3$ concentrations increased in the daytime. As illustrated in Fig. 6, the daytime mean distributions of O$_3$ significantly varied at different vertical heights, with the dominant north wind fields being from the surface to 700-hPa (approximately 3 km). On the surface (Fig. 6a), a relatively high O$_3$ concentration (>150 µg m$^{-3}$) was found in Anhui province and the surrounding areas of Hangzhou. By contrast, the O$_3$ concentrations were relatively low in mountainous areas, and south
of Jiangsu province (upwind regions of Hangzhou), which are industrial areas with high concentration of NO$_2$ (Fig. 6e). At 900-hPa, the O$_3$ concentrations (>150 µg m$^{-3}$, shown in yellow, Fig. 6b) were high in most of the YRD region, which were substantially higher than those at the ground level and 850-hPa layer. However, mountainous areas still had low O$_3$ concentrations, whereas those above the south of Jiangsu province notably had high O$_3$ concentrations. At 850-hPa (Fig. 6c), nearly on top of the planetary boundary layer (approximately 1.5 km), the O$_3$ distribution pattern was similar to that at 900-hPa; however, the O$_3$ concentrations at this level were lower because of the low concentrations of precursor gases. At 700-hPa (Fig. 6d), the O$_3$ distribution was less influenced by surface anthropogenic emissions. However, a notable background O$_3$ concentration was still uniformly distributed (nearly 140 µg m$^{-3}$). The concentrations of a precursor gas, NO$_x$, significantly decreased as the altitude increased (Figs. 6e–h), and NO$_x$ was observed in trace amounts in the upper air. This result is in contrast to the O$_3$ variation found in the vertical layers.

3.4. O$_3$ pollution and transport patterns

Hourly vertical and horizontal O$_3$ distributions and wind fields in the YRD region are presented for three representative episodes (Fig. 7) according to the movement of the tropical cyclone. For stagnation days with weak wind fields (i.e., August 25 and September 2) before or after the tropical cyclone, meteorological conditions were unfavorable to pollutant dispersion. O$_3$ pollution was more regional and intense, with an hourly O$_3$ peak concentration of 250 µg m$^{-3}$ at 14:00 LST below the high layer (1.5 km) around Hangzhou (Figs. 7a and f). For nighttime transport (Figs. 7b and c), a large O$_3$-poor mass (<30 µg m$^{-3}$) intruded downward. This nocturnal O$_3$-poor mass can be explained by the NO$_x$-rich mass that consumed O$_3$ through titration reaction. Subsequently, at 14:00 LST (Fig. 7d), high O$_3$ concentrations appeared in the widespread region of south YRD (mountainous areas; Fig. 1b). By contrast, for daytime transport (Fig. 7e), a large belt of O$_3$-rich mass (>160 µg m$^{-3}$) appeared in the upwind direction and moved toward Hangzhou. Both of the described transport effects occurred under a prevailing north wind field. Fig. S1 shows the
corresponding patterns of NOx. Besides, relevant atmospheric trajectories also support this transport from North China (Fig. S2).

Fig. 7. Surface and upper-level O3 distributions (µg m⁻³) and wind fields (vectors, m s⁻¹) for representative episodes. (a) Stagnant weather before the tropical cyclone, (b–e) pollutant transport when the tropical cyclone approached, and (f) stagnant weather after the cyclone. The red line denotes the cross section line of upper-level O3 distributions. The red triangle denotes the location of Hangzhou.

3.5. Process analysis of O3 formation

Four hourly modeled processes indicated the diurnal fluctuations in loops. Gas chemistry generated O3 nearly above the upper-air height of 2 km in the daytime but depleted O3 at the near-surface height (< 0.3 km) in the nighttime (Fig. 8a). O3 from the upper layer diffused downward to the ground through vertical diffusion during the study period but was significantly high in the daytime (Fig. 8b). In addition, as presented in Figs. 8c and d, several O3 dynamical circulations were observed between the near-surface and upper-air heights, which were notable during August 24–25 and on September 2, 2016. An O3-rich mass in the lower layer (<1 km) traveled to
Hangzhou through horizontal advection, and it was transported from the upper layer to the high layer (approximately 1.5 km) through vertical advection. The mass subsequently traveled out again at the high layer through horizontal advection circularly. Urban heat island circulations caused the upward and downward flows.

**Fig. 8.** Hourly variations in the change rate of upper-level $O_3$ (ppb/hour) because of (a) gas chemistry, (b) vertical diffusion, (c) horizontal advection, and (d) vertical advection in Hangzhou.

Quantifying the daytime mean variations of $O_3$ at the ground level due to atmospheric processes (Fig. 9a) revealed major positive contributions of gas chemistry, vertical diffusion, and horizontal advection to surface $O_3$ formation, with mean production rates of 1.9, 3.3, and 6.7 ppb/hour, respectively, from August 24 to September 6, 2016. First, the trends between the daytime mean values associated with gas chemistry and observed $O_3$ concentration were consistent (Fig. 9b), indicating the trade-off effect among vertical diffusion and horizontal and vertical advection. High $O_3$ concentrations were accompanied by high gas chemical generation. Second, vertical diffusion may compensate for gas chemistry to some extent when the chemical reaction rate is relatively low or negative. For example, on August 26–27 and September 5–6, 2016, the vertical diffusion rates were mostly greater than the chemical production rates. Finally, advection processes were essential and integral components of air circulation, whereas horizontal advection exerted...
remarkably positive effects on surface O$_3$ concentrations in Hangzhou and vertical advection exerted dispersion effects.

Fig. 9. (a) Daytime mean (08:00–17:00 LST) variations in simulated surface O$_3$ change rate (ppb/hour; left y axis) because of gas chemistry, vertical diffusion, and horizontal and vertical advection in Hangzhou. (b) Comparison of daytime mean gas chemistry generation (ppb/hour; left y axis) and observed surface maximum daily 8-hour concentration of O$_3$(O$_3$-8h; ppb; right y axis) in Hangzhou. China’s national standard is approximately 75 ppb (160 µg m$^{-3}$).

4. Discussions

The results of this study reveal notable background O$_3$ concentrations in the upper-air layer in the YRD region. O$_3$ concentrations were significantly higher at 900-hPa (approximately 1 km) than at the surface, which is consistent with field study (Xing et al., 2017). This is probably because the surface NO concentrations were still adequately high to consume O$_3$ through a titration reaction. By contrast, at 900-hPa, the efficiency of O$_3$ photochemical production was highly nonlinear, with the production rates being higher at lower NO$_x$ levels (Zhang et al., 2008). This significant concentration gradient explains the major downward vertical diffusion process. At 700-hPa
(approximately 3 km), the uniformly distributed O$_3$ (>130 µg m$^{-3}$) can be explained by the 316 concentration redistribution engendered by the diffusion process. Peripheral downdrafts in the 317 large-scale cyclone circulation can transport an extremely high O$_3$-rich mass in the upper 318 troposphere and lower stratosphere downward to the surface (Tang et al., 2011; Hsu and Prather, 319 2014). This O$_3$ intrusion was also reported in southeast China (Jiang et al., 2015). According to our 320 results, we can infer that a considerably high background O$_3$ concentration in the upper air may 321 markedly contribute to surface O$_3$ pollution, which is in agreement (hemispheric background) with 322 the findings of studies conducted in Europe (Wilson et al., 2012) and the United States (Lin et al., 323 2012; 2015).

Our results demonstrate that Hangzhou experienced strong regional transport of pollutants 325 from North China on August 26–27, 2016. The transport was caused by a reinforced north wind 326 component because of the convergence of the tropical cyclone in East China Sea. This southward 327 transport of pollutants supplies raw materials for photochemical O$_3$ generation and explains the high 328 O$_3$ concentrations in the south of the YRD region, which comprises mountainous or scenic areas 329 with low anthropogenic emissions, despite the implementation of stringent emission control 330 measures. Our results suggest that more cooperation with upwind regions, such as North China, is 331 required to alleviate the potential transport of pollutants by tropical cyclones. Additional analysis 332 such as regional contributions to O$_3$ or its precursors in Hangzhou may yield quantitative evidence.

We demonstrate that the local chemical generation in Hangzhou was enhanced during episodes 335 of high O$_3$ concentrations before and after the tropical cyclone. Chemical generation of O$_3$ is the net 336 effect of photochemical generation and titration consumption. Oxidation reactions of VOCs, under 337 the present of CO, provide alternative oxidants (i.e., HO$_2$ and RO$_2$) that efficiently convert NO to 338 NO$_2$. This conversion enriches the reactants to O$_3$ photochemical generation while suppressing 339 titration consumption, resulting in the accumulation of O$_3$ (Jenkin et al., 1997; Sillman, 1999; Wang 340 et al., 2017). Downward shortwave flux at the ground level (Fig. S3) is more intense on days having 341 high O$_3$ concentrations than on those having low O$_3$ concentrations. This strong solar radiation
strengthens O$_3$ photochemical generation. In addition to the stagnant weather conditions, air subsidence in peripheral circulations of tropical cyclones helps to trap heat and pollutants at the surface (Jiang et al., 2015; Shu et al., 2016). Furthermore, a tropical system with calm hot–dry weather favors the development of an urban heat island, which causes the thermal circulations and converges the surrounding O$_3$ and its precursors (Lai and Cheng, 2009). Consequently, the increased temperature also accelerates the photochemical reactions (Narumi et al., 2009; Walcek et al., 1995). Therefore, enhanced photochemistry dominated the O$_3$ chemical generation, resulting in high O$_3$ concentrations. This is consistent with field study (Su et al., 2017). By contrast, low-level O$_3$ episodes (i.e., August 27 and September 6) in Hangzhou were determined to be accompanied by a rain band in the YRD region. Rain-band-related cumulus clouds block solar radiation, thus weakening O$_3$ photochemical generation. Therefore, titration consumption dominated the chemical generation process, resulting in low or negative O$_3$ chemical production.

5. Conclusions

O$_3$ evolution in Hangzhou during the G20 summit was well represented using the WRF-Chem model. Statistical evaluation in meteorological and chemical fields suggested that the model system results satisfactorily match the observed data both at ground and upper-air levels. The model results reveal that the O$_3$ concentrations in Hangzhou were highly relevant to the tropical cyclone in the East China Sea. Throughout the simulation period, large-scale air mass circulations and energy transport by the tropical cyclone probably resulted in a considerably high upper-air O$_3$-rich mass in the YRD region in both horizontal and vertical scales; this thus engendered a negative background O$_3$ concentration. As the tropical cyclone approached and hence a prevailing north wind component, Hangzhou experienced strong regional transport from North China, which supplied the precursors to Hangzhou. After or before the tropical cyclone, peripheral downdraft or air subsidence produced stable and calm weather, such as a high pressure and temperature and weak wind, in addition to aggravating the urban heat island effect. These combinations enhanced the chemical generation process and markedly increased the surface O$_3$ concentrations. Our study provides scientific insight
into urban O$_3$ formation and dispersion under short-term emission reductions for major events in summer in East China.

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