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ORIGINAL PAPER

High reduction of ozone and particulate matter during the 2016 G-20 summit in Hangzhou by forced emission controls of industry and traffic

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Abstract Many regions in China experience air pollution episodes because of the rapid urbanization and industrialization over the past decades. Here we analyzed the effect of emission controls implemented during the G-20 2016 Hangzhou summit on air quality. Emission controls included a forced closure of highly polluting industries, and limiting traffic and construction emissions in the cities and surroundings. Particles with aerodynamic diameter lower than 2.5 µm ($PM_{2.5}$) and ozone (O_3) were measured. We also simulated air quality using a forecast system consisting of the two-way coupled Weather Research and Forecast and Community Multi-scale Air Quality (WRF-CMAQ) model. Results show $PM_{2.5}$ and ozone levels in Hangzhou during the G-20 Summit were considerably lower than previous to the G-20 Summit. The predicted concentrations of ozone were reduced by 25.4%, whereas the predicted concentrations of $PM_{2.5}$ were reduced by 56%.

Keywords Air quality forecast · Effects of emission reductions · WRF-CMAQ · 2016 G-20 Summit

Introduction

Many areas in China, such as the Beijing–Tianjin–Hebei region, the Pearl River Delta, and the Yangtze River Delta, experience air pollution episodes because of the rapid urbanization and industrialization over the past few decades (Zhao et al. 2013; Rohde and Muller 2015; Yan et al. 2015; Lu et al. 2016; Wang and Fang 2016; Huang et al. 2016; Hong et al. 2016). A number of major international events such as the 2008 Olympic Games, the 2014 Asia-Pacific Economic Cooperation summit (APEC), and the 2015 Grand Military Parade have been held in China, during which efforts were implemented to achieve good air quality (Xing et al. 2011; Li et al. 2014; Wen et al. 2016; Liu et al. 2016). To reduce air pollution during these events, a series of stringent emission control strategies, involving industries and power plants, motor vehicles, and even residential activities were enacted (Liu et al. 2016). Previous studies found that, during the Olympic Games, the APEC summit, and the Grand Military Parade, air quality improvements occurred after implementing a series of restrictive measures to reduce air pollution, which were termed "Olympic Blue," "APEC Blue," and "Parade Blue", respectively (Wang et al. 2011; Huang et al. 2015; Sun et al. 2016). As one of the six largest city clusters in the world, the Yangtze River Delta encompasses the Shanghai municipality, Jiangsu, Anhui, and Zhejiang provinces and accounts for 20% of China's Gross Domestic Product (http://en.people.cn/200407/08/eng20040708_148830.html). On the basis of long-term monitoring from 1980 to 2011 and 1-year field measurements in 2011–2012,

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Cheng et al. (2013) reported that visual range in the Yangtze River Delta experienced a sharp decrease from 13.2 to 10.5 km during 1980–2000. To improve the haze pollution in the Yangtze River Delta, it is necessary to decrease $PM_{2.5}$ (particles with aerodynamic diameter lower than 2.5 μm) concentrations. Here, we evaluate the effectiveness of emission controls on $PM_{2.5}$ and O_3 concentrations in the Yangtze River Delta region.

Hangzhou, located in northwestern Zhejiang province in the south-central portion of the Yangtze River Delta and the capital and most populous city of Zhejiang Province, is one of the most renowned and prosperous cities in China due in part to its natural scenery. By the end of 2015, Hangzhou's population had reached 9 million with an urbanization of ~75.3% (http://www.zj.stats.gov.cn/tjgb/rkcydcgb/201601/t20160128_168706.html). Due to the rapid urbanization and vigorous economic development over the past three decades, Hangzhou and its surroundings routinely experience air pollution and heavy haze (Sun et al. 2013; Yu et al. 2014a). For example, the mean concentrations of $PM_{2.5}$ in Hangzhou ranged from 106 to 131 $\mu g/m^3$ over September 2010 to July 2011 (Sun et al. 2013). The mean concentration of $PM_{2.5}$ during a week-long heavy haze episode from December 3–9, 2013 was 293.4 ± 103.2 $\mu g/m^3$ (Yu et al. 2014a). Li et al. (2015) showed that the surface O_3 concentrations in the summer of 2013 in Hangzhou were significantly affected by the air pollution transport from the north Zhejiang province (29.6%). As well, the occurrence of heavy haze episodes in Hangzhou was found to be closely associated with the contribution of regional transport of air pollutants (Yu et al. 2014a).

The G-20 2016 Hangzhou summit, the 11th annual meeting of the heads of government, was held during September 3–5, 2016, in Hangzhou, China. During this period, the governments of Hangzhou and its surrounding provinces enforced a series of emission reductions, including a forced closure of highly polluting industries, and limiting traffic and construction emissions in the cities and surroundings. The air quality forecasting system applied here consists of the two-way coupled Weather Research and Forecast and Community Multi-scale Air Quality (WRF–CMAQ) model, which has been used to forecast air quality in Hangzhou regularly (Yu et al. 2015). The objectives of the present study are to combine the WRF–CMAQ model simulations with ground-based observations to evaluate the effectiveness of emission reduction measures during the G-20 2016 Hangzhou summit period and their impacts on air quality on both local and regional scales.

Experimental details

Description of the WRF–CMAQ modeling system

The two-way coupled WRF–CMAQ modeling system (Wong et al. 2012; Yu et al. 2014b) is used to forecast air quality in Hangzhou regularly (Yu et al. 2015). The system was developed by linking the WRF (Skamarock et al. 2008) and the CMAQ models (Wong et al. 2012; Yu et al. 2014b; Eder and Yu 2006). A brief summary relevant to the present study is presented here. The model configurations are the same as those described in Yu et al. (2014b). The modeling domain, as shown in Fig. 1, covers most of China and parts of East Asia with 12 km × 12 km grid resolution. Both WRF and CMAQ use 27 vertical layers. The physics package of the WRF3.4 (ARW) includes the Kain–Fritsch (KF2) cumulus cloud parameterization, the Asymmetric Convective Model (ACM2) for a planetary boundary layer (PBL) scheme, RRTMG shortwave and longwave radiation schemes, two-moment cloud microphysics, and the Pleim–Xiu (PX) land-surface scheme. The meteorological initial and lateral boundary conditions were derived from the Global Forecast System (GFS) model data. The carbon bond chemical mechanism (CB05) (Yarwood et al. 2005) is used to represent photochemical reaction pathways, and the AERO6 aerosol module of the CMAQ version 5.0 is used to represent aerosol microphysics. Predicted aerosol chemical composition includes sulfate, nitrate, ammonium, water, primary organic aerosol, secondary organic aerosol from both anthropogenic and biogenic origin, and elemental carbon (Yu et al. 2014b). The default chemical boundary conditions (BCONs) in the CMAQ model were used in the simulations. Anthropogenic emissions of SO_2, NO_x, CO, NMVOC, NH_3, PM_{10} and $PM_{2.5}$ over China and the rest of domain were estimated on the basis of the regional inventories MEIC for 2012 (www.meicmodel.org) and Emissions Database for Global Atmospheric Research (EDGAR): HTAP V2 (0.10 × 0.10), respectively. Biogenic VOC emissions were estimated on the basis of the MEGAN model (Guenther et al. 2012). Model forecast results of the second day are used to compare with the observations.

Observations and model evaluation

Observations of hourly air pollutant ($PM_{2.5}$ and O_3) concentrations at 8 national monitoring stations in Hangzhou have been obtained, for which detailed information is available at the Web site of Ministry of Environmental Protection in China (http://datacenter.mep.gov.cn/). These hourly air pollutant data will be used to evaluate the model

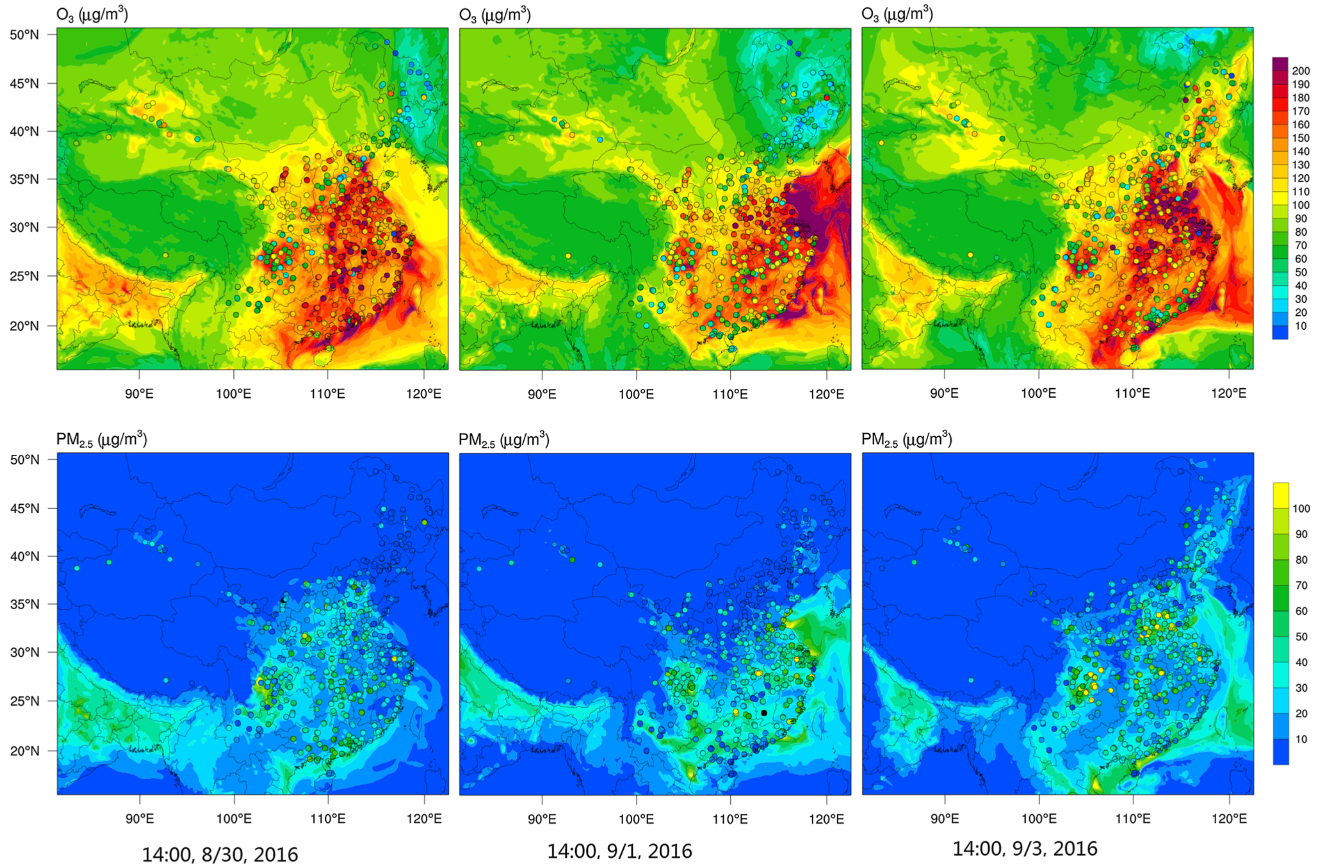

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Fig. 1 Concentrations of ozone (O_3) and $PM_{2.5}$ (particles with aerodynamic diameter lower than 2.5 µm) simulated by the WRF–CMAQ (based on the emission controls) with observed data overlaid (*circles*) at 14:00 (local time) on August 30, September 1 and September 3, 2016. The essential consistency between the model predictions and observations indicates that the spatial patterns of observed $PM_{2.5}$ and O_3 are captured reasonably well

Table 1 Emission sources targeted during the 2016 G-20 Hangzhou summit and their corresponding reduction percentages at four different provinces

Time period in 2016	Province	Sources	Emission reductions (%)	Reduction (%)	
				O_3	$PM_{2.5}$
August 24–28	Shanghai, Jiangsu, Anhui	Industry, power plant	−40	11.07	5.75
	Zhejiang	Industry, power plant, residential	−50		
August 28–September 1	Shanghai, Jiangsu, Anhui	Industry, power plant	−40	25.41	56.15
	Zhejiang	Industry, power plant, residential, transport	−50		
September 1–6	Shanghai, Jiangsu, Anhui	Industry, power plant	−40	43.55	47.12
	Zhejiang	Industry, power plant, residential, transport	−65		

Percentages of $PM_{2.5}$ and O_3 reductions for Hangzhou city between the two simulations with and without emission control are also summarized. Industrial and power plant emissions in Shanghai, Jiangsu, and Anhui were reduced by 40% from August 24 to September 6. For the G-20 Summit period from September 1 to 6, the reduction percentage required in Zhejiang province for industry, power plants, residential, and motor vehicle emissions increased from 50 to 65%

performance and analyze the effects of emission reductions on air quality in Hangzhou.

Prior to assessing the effects of emission control schemes on air quality, WRF-CMAQ was evaluated against the ground-based observations. In parallel with the observed hourly $PM_{2.5}$ and O_3 observations, concurrent hourly model concentrations at 8 monitoring sites in Hangzhou were averaged. The normalized mean bias (NMB) and correlation coefficient (R) were used to assess model performance based on paired observational and

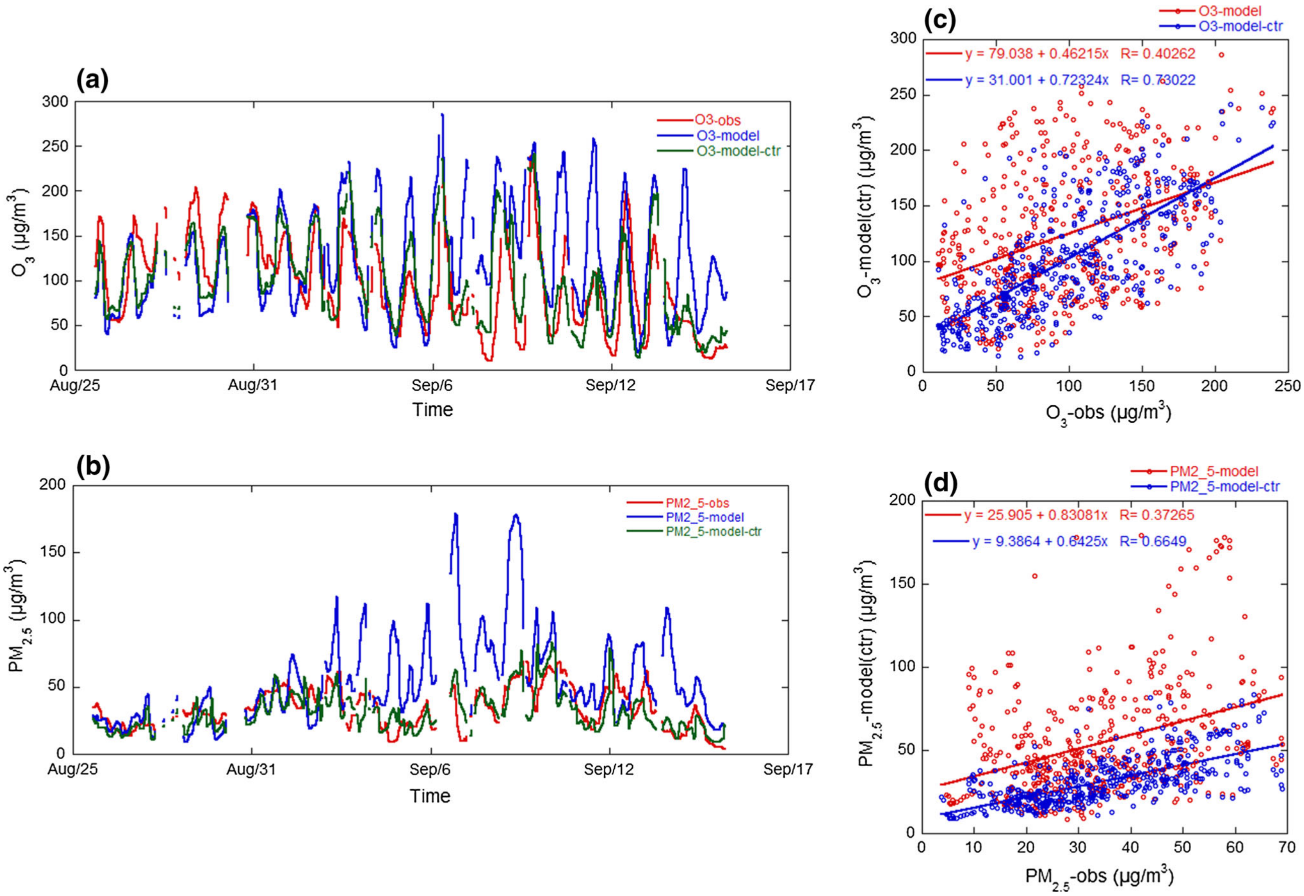

Fig. 2 Time series of observations and simulations with (O3-model-ctr, PM2_5-model-ctr) and without (O3-model, PM2_5-model) emission controls and the corresponding scatter plots between observations and predictions during August 26–September 15, 2016: **a** time series comparison for O_3, **b** time series comparison for $PM_{2.5}$, **c** scatter plots for O_3 and **d** scatter plots for $PM_{2.5}$. The correlation equations are also shown in the *scatter plots*. The "*model*" and "*model-ctr*" represent the results in the absence and presence of emission reductions, respectively. The "*obs*" represents observations. The average simulated concentrations of O_3 and $PM_{2.5}$ without emission reductions were significantly higher than the observed values during the G-20 Summit (**a**, **b**), indicating significant improvement of air quality

simulated data (Yu et al. 2006; Zhang et al. 2006). NMB reflects the degree of agreement between the simulated and measured values, and R indicates the extent of the relationship between simulated and observational values. Two simulation scenarios were set: one to simulate pollutant concentrations in the absence of emission reductions (denoted as "model") and another to simulate pollutant concentrations with emission control (denoted as "model-ctr").

Emission control schemes

For the emission control schemes, the Yangtze River Delta region (including Zhejiang province, Shanghai municipality, Jiangsu province, and Anhui province) was subject to emission controls for the G-20 2016 Hangzhou summit. Table 1 lists the emission sources involved in the reduction measures and their estimated reduction percentages for four different provinces before and during the summit obtained on the basis of internal document (i.e., Collaborative Environmental Air Quality Guarantee Scheme for the Yangtze River Delta Region and Its Surrounding areas during the G-20 2016 Hangzhou Summit, http://futures.hexun.com/2016-06-21/184510358.html). The amount of required emission reductions was dependent upon the distance to the G-20 Summit venue. As shown, industrial and power plant emissions in Shanghai, Jiangsu, and Anhui were reduced by 40% from August 24 to September 6. In the Zhejiang province from August 24 to September 1, in addition to required 50% reduction of the industrial emissions, power plants and residential, motor vehicle emissions were also required to be reduced by 50% for the period of August 28 to September 1, as shown in Table 1. For the G-20 Summit period from September 1 to 6, the

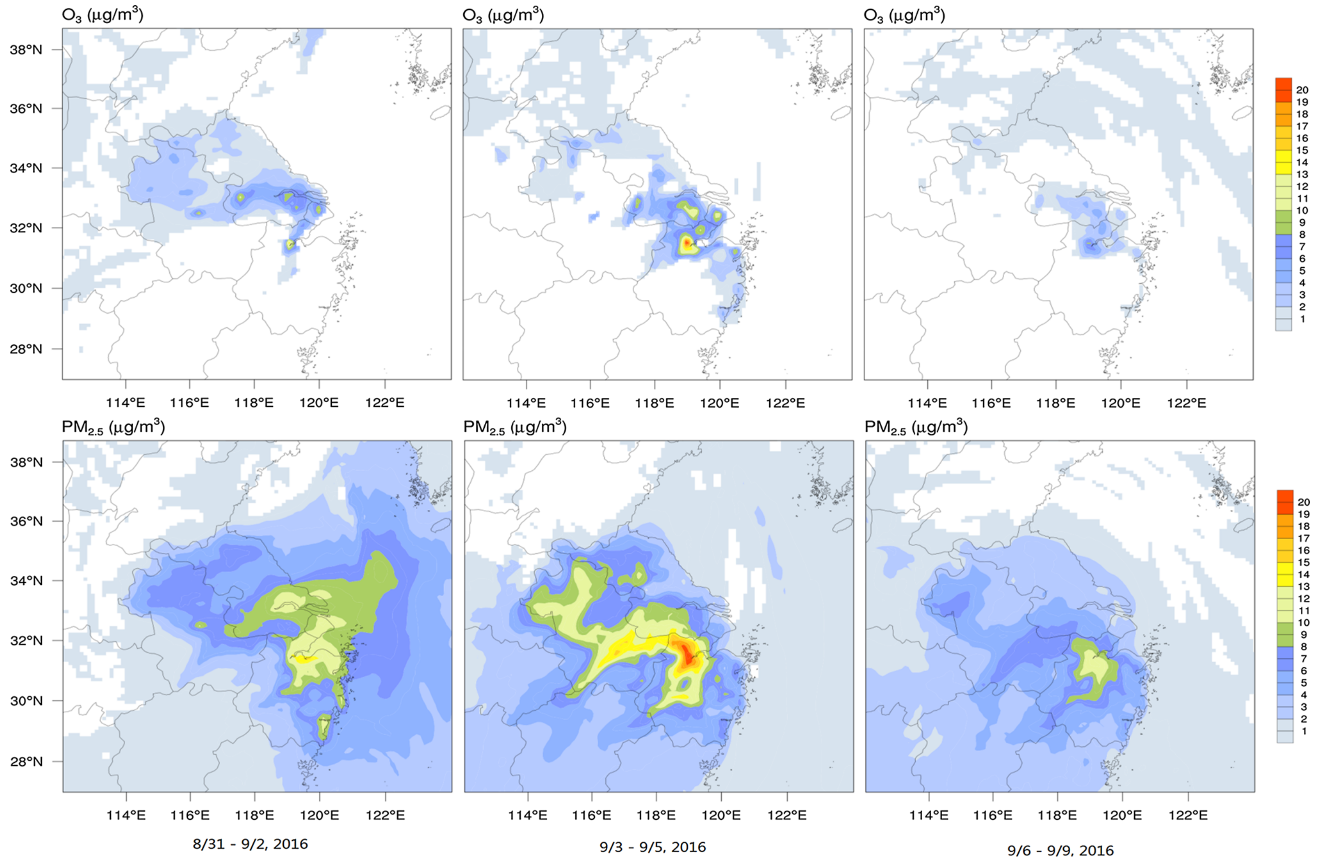

Fig. 3 Predicted reductions of hourly O_3 (*top*) and $PM_{2.5}$ (*bottom*) concentrations in the Yangtze River Delta region with and without the emission controls for the three periods (i.e., August 31–September 2, September 3–5, and September 6–9, 2016). During the G-20 Summit period, $\mathbf{O_3}$ concentrations were reduced by more than 20 μg/m^3 (or 25.4%) in Hangzhou and to a lesser extent in surrounding areas such as Shanghai. $\mathbf{PM_{2.5}}$ reductions exceeded 20 μg/m^3 (or 56.1%) in Hangzhou and to a lesser extent in surrounding Yangtze River Delta region

reduction percentage required in Zhejiang province for industry, power plants, residential, and motor vehicle emissions increased from 50 to 65%.

Results and discussion

Evaluation of the model performance before, during, and after the G-20 Summit

Figure 1 shows spatial distributions of simulated O_3 and $PM_{2.5}$ overlaid with observed data before and during the G-20 Summit at 14:00 LT on August 30, September 1 and 5, 2016. As shown, there is essential consistency between the model predictions and observations, indicating that the spatial patterns of observed $PM_{2.5}$ and O_3 are captured reasonably well. Figure 2 shows time series of observations and simulations for O_3 and $PM_{2.5}$ in the absence and presence of emission reductions during the period from August 26 to September 15. Model predictions with emission reductions ("model-ctr") give a much closer agreement with the observations for both $PM_{2.5}$ and O_3 than those without emission reductions. For the entire study period, the correlations (NMB) between predictions and observations are 0.73 (−17.7%) and 0.67 (24.4%) for O_3 and $PM_{2.5}$, respectively, for the simulations with the emission reductions, as compared to values of 0.40 (−28.5%) and 0.37 (59.5%) in the absence of emission reductions. In addition, predictions under the targeted emission controls are much closer to the observations of $PM_{2.5}$ and O_3 than those without the emission controls, as indicated by both time series and scatter plots in Fig. 2.

To assess the effects of emission reductions during the G-20 Summit 2016 in Hangzhou, the entire study period was separated into three subperiods: before the G-20 Summit (from August 26 to September 3), namely the start of the implementation of emission reduction; during the G-20 Summit (from September 4 to September 5), during which the more stringent emission reduction strategy was carried out, and after the G-20 Summit (from September 6 to September 15), during which the emission reduction was stopped (Fig. 2). During the G-20 Summit, the average observed O_3 concentration was 82.4 μg/m^3, as compared to 126.8 μg/m^3 before the G-20 Summit but still higher than after the G-20 Summit (75.2 μg/m^3) (Fig. 2a). The very low O_3 concentrations for the periods of September 9–12 and September 14–15 caused the average low O_3 concentration after the G-20 Summit as indicated in Fig. 2a. Figure 2b shows that the average observed $PM_{2.5}$ concentration during the G-20 Summit (25.9 μg/m^3) was somewhat lower than that before the G-20 Summit (33.5 μg/m^3) because of more stringent emission reduction strategies during the G-20 Summit, with the highest $PM_{2.5}$ concentration of 35.8 μg/m^3 after the G-20 Summit. The average simulated concentrations of O_3 and $PM_{2.5}$ without emission reductions were significantly higher than the observed values during the G-20 Summit (Figs. 2a, 3b), indicating significant improvement of air quality.

Impacts of emission control schemes on local air quality in Hangzhou

Figure 3 shows the geographical distributions of predicted reduction of hourly O_3 and $PM_{2.5}$ concentrations in the Yangtze River Delta region during three periods (i.e., August 31–September 2, September 3–5, and September 6–9, 2016) obtained by the difference between the model simulations in the presence and absence of emission controls. During the G-20 Summit period, $\mathbf{O_3}$ concentrations were reduced by more than 20 μg/m^3 (or 25.4%) in Hangzhou and to a lesser extent in surrounding areas such as Shanghai (Fig. 3). $\mathbf{PM_{2.5}}$ reductions exceeded 20 μg/m^3 (or 56.1%) in Hangzhou and to a lesser extent in surrounding Yangtze River Delta region, as shown in Table 1 and Fig. 3. Reductions of hourly $PM_{2.5}$ and O_3 in Fig. 2 showed noticeable trends; reduction of hourly levels increased gradually during August 31–September 3, and reaching a maximum during the G-20 Summit.

Conclusion

To prepare for the G-20 Hangzhou summit, held from September 3 to 5, 2016, in Hangzhou, China, governments of Hangzhou and its surrounding provinces (Shanghai, Jiangsu, and Anhui) enforced a series of air pollutant emission reductions. Ground-based observations show that the air quality in Hangzhou during the G-20 2016 Hangzhou summit was considerably improved, most likely due to efficient emission controls across the Yangtze River Delta region. Observations of $PM_{2.5}$ and O_3 at 8 monitoring sites in Hangzhou were used to evaluate simulations from the WRF-CMAQ model and assess the impact of emission controls on air quality in Hangzhou. Simulated results under the targeted emission controls are much closer to the observations of $PM_{2.5}$ ($R = 0.67$, NMB $= -8.7\%$) and O_3 ($R = 0.73$, NMB $= 4.6\%$) than those without emission controls. During the G-20 Summit period, $\mathbf{O_3}$ and $PM_{2.5}$ concentrations were reduced by 20.1 μg/m^3 (or 25.4%) and 20.5 μg/m^3 (or 56.1%), respectively, in Hangzhou, on the basis of the comparison of the model simulations without and with the emission controls.

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