Evolution and Assessment of the Atmospheric Composition in Hangzhou and its Surrounding Areas during the G20 Summit

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ABSTRACT

To evaluate the effectiveness of control strategies during the G20 Summit (August 24–September 6, 2016), five sites were selected for investigating the variation in air pollution in the city of Hangzhou and its surrounding areas. The results showed that the air quality in Hangzhou greatly improved after the implementation of strict emission controls. Compared to the same dates from the five preceding years, the G20 period exhibited low relative humidity during the early stage (August 27–31) and no significant differences in other meteorological conditions. The SO₂, NO₂, PM₁₀, and PM_{2.5} concentrations averaged across the five sites in Hangzhou decreased by 42.6%, 57.1%, 36%, and 38.5%, respectively, although the average O₃ concentration increased by 19%. These changes indicate that the emission reduction measures decreased the concentrations of several pollutants. Compared to the same dates from the previous year (August 24–September 6, 2015), the G20 period exhibited significantly decreased concentrations for most of the chemical components of PM_{2.5}, particularly SO₄²⁻, NO₃⁻, and NH₄⁺. Additionally, the aerosol optical depth (AOD) and the NO₂ column densities were found to exhibit similar trends with that of the pollutants in this city.

Keywords: Air quality; Emission reduction; G20 Summit; Ozone sensitivity.

INTRODUCTION

Characterized by fine particles (PM_{2.5}), nitrogen oxides (NO_x), and ozone (O₃), regional air pollution has been increasingly prominent in China in recent years due to the rapid development of urbanization and industrialization (Chan and Yao, 2008). Air pollutants such as PM_{2.5} and ozone have significant impacts on public health and have been estimated to cause millions of premature deaths per year worldwide (Cohen *et al.*, 2017). Extensive studies have been conducted through observational, modeling, and long-term data analyses to investigate the sources, evolution, and formation mechanisms of air pollution in China; however,

there are still many uncertainties remaining (Jin *et al.*, 2015; Hu *et al.*, 2016). Therefore, greater insights are required to generate evidence-based emission control policies. Air pollution in the Beijing-Tianjin-Hebei (BTH), Yangtze River Delta (YRD), Pearl River Delta (PRD), and Sichuan Basin (SCB) regions have been reported to be the most severe in China (Hu *et al.*, 2017). Strict short-term emission controls have effectively improved the air quality during several special events such as the Beijing Olympics in 2008, the Asia-Pacific Economic Cooperation (APEC) meeting in November 2014, the Nanjing Youth Olympic Games in 2014, and the China Victory Day Parade in 2015. These short-term emission controls provide an ideal opportunity for evaluating our current understanding of the formation mechanisms of air pollution and exploring the impact of alternative control options to aid in the formulation of more effective policies for emission reduction.

Hangzhou, which is located in the southern YRD region, is the capital of Zhejiang Province and a typical megacity

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that covers an area of about 16,596 km² and has a population of more than 9.18 million residents. The air pollution in Hangzhou has become more serious in recent years due to substantial local emissions and regional transport of air pollutants (Dong *et al.*, 2013; Liu *et al.*, 2015). Jansen *et al.* (2014) reported that the contribution of secondary inorganic aerosol to PM_{2.5} concentration has reached approximately 50% during haze episodes. Li *et al.* (2018) found that the secondary transformation of organic aerosols are the main sources of particle matter. In addition to local emissions, trans-boundary aerosol and trace gases transport also contributes to the severe air pollution in Hangzhou (Zhang *et al.*, 2018). The G20 Summit, which was held in Hangzhou from September 4 to 5 in 2016, provides an ideal opportunity for evaluating the effectiveness of emission reduction measures in the YRD region. To improve the air quality during the G20 Summit, the Zhejiang Summit Environmental Protection Plan (ZSEPP) was implemented by the Zhejiang provincial government from August 24 to September 6, 2016. In this plan, strict air pollution alleviation measures were adopted to reduce the emissions of air pollutants in Hangzhou and its surrounding cities. Considering the contribution of regional transport, the emission control strategy was extended to the surrounding areas of Hangzhou (e.g., Huzhou, Jiaxing, Jinhua, and Shaoxing).

A number of previous studies investigated the effect of emission controls during the G20 Summit by using surface observations and numerical models (Feng *et al.*, 2019; Ni *et al.*, 2019). Ji *et al.* (2018) analyzed the effects of regional transport and emission control on the formation of fine particles during the G20 Summit and found that the suppression of daytime peak secondary organic carbon (SOC) formation was the major reason for the decreased particle matter concentration. Su *et al.* (2017) utilized ozone lidar and vertical column densities (VCDs) of ozone for exploring ozone variation during the G20 Summit and reported that meteorological conditions dominated the variations of ozone concentration. However, these studies mainly focused on single pollutants such as PM_{2.5} or ozone while the overall variation of air pollutants during the G20 Summit remains unclear and should be explored further.

In this study, the meteorological conditions, concentrations of six criteria air pollutants (PM_{2.5}, PM₁₀, O₃, NO₂, SO₂, and CO), chemical composition of PM_{2.5}, aerosol optical depth (AOD), and NO₂ column data retrieved by satellite in Hangzhou before, during, and after the 2016 G20 Summit were analyzed for accurately assessing the contributions of the safeguard measures implemented during the G20 Summit to improve air quality. This paper is organized as follows. We first analyzed the daily average pollutant concentrations during the G20 period. Then we investigated the effect of meteorological conditions, diurnal variations, and the components on reducing air pollution by comparing the pollutant concentrations during days with stable meteorological conditions. Finally, we compared the emission reduction measures implemented for the G20 Summit with that of previous events to comprehensively evaluate the pollution control strategies implemented for the G20 Summit.

METHODS

Study Domain

Through the collaboration with surrounding cities, regional control levels were divided into three types (i.e., the core area, strictly controlled area, and controlled area), which were classified by their respective distances to the central main court (50 km, 100 km, and 300 km, as shown in Fig. 1). Of these three areas, the core area included Hangzhou (HangZ), Huzhou (HuZ), Jiaxing (JX), and Shaoxing (SX); the strictly controlled area included Ningbo (NB), Jinhua (JH), and Quzhou (QZ); and the control area included Wenzhou (WZ), Zhoushan (ZS), Taizhou (TZ), and Lishui (LS).

Measurements of Air Pollutants

In this study, the concentrations and variation characteristics of six air pollutants as well as the corresponding meteorological conditions during the G20 period were compared with those observed during the same period from 2011 to 2015 to explore the change in air quality in different situations (i.e., with vs. without the air quality improvement contributions of the safeguard measures). In addition, monitoring data of six air pollutants were collected from five sites in Hangzhou (Table 1 and Fig. 1), including Xiasha (XS; a regional site), Linping (LP; a suburban site), Xixi (XX; a background site), Zhaohui (ZH; a traffic pollution site), and Hemu (HM; an urban site). The method of observing air pollutants from 2011 to 2015 is the same as that monitored in the G20 Summit.

At these five sites, a TEOM 1405-D double-channel air particulate monitor by Rupprecht & Patashnick Co. was used to monitor PM_{2.5}. The aerosol passed through a PM_{2.5} cyclone; then, the PM_{2.5} particles in the ambient air were constantly inhaled to the internal region by the sampling cutter. Finally, a filter dynamic measurement system (FDMS) and a tapered element oscillating microbalance (TEOM) were utilized to measure the PM_{2.5} concentration. A Thermo Fisher 1400 monitor was used to monitor PM₁₀ using the TEOM method. A 49i ultraviolet spectrophotometry O₃ analyzer produced by Thermo Electron Corp. in the United States was used for O₃ observations, and it has a minimum detection limit of 2.0 µg m⁻³, a zero drift of less than 2.0 µg m⁻³ day⁻¹, and a span drift of less than ±1% day⁻¹. A Model 300E gas filter correlation analyzer was used as the CO analyzer, with a minimum detection limit of 1.0 µg m⁻³, a zero drift of less than 2.0 µg m⁻³ day⁻¹, and a cross drift of ±1% day⁻¹. The sampling and observations of NO_x were performed using a Model 400E NO-NO₂-NO_x analyzer. This instrument measures the fluorescence of the excited-state NO₂ produced from the chemical reaction of NO and O₃ to obtain the ambient NO concentration. There is a linear positive correlation between the intensity of the emitted light and the volume fraction of NO. While detecting NO₂, the NO₂ is converted to NO through a molybdenum converter, and then the quantitative analysis is conducted using chemiluminescence reactions. This converter has a minimum detection limit of 5 × 10⁻³ µg m⁻³, a zero drift of less than 2.5 × 10⁻³ µg m⁻³ day⁻¹, and a full drift of ±1% day⁻¹. All of the instruments collected data 24 h per day, and the data were read every 5 minutes. The accuracy of the observation data was ensured by the

Fig. 1. Location of the study area and air quality monitoring sites in Hangzhou. (a) Location of Zhejiang Province. (b) Locations of cities in Zhejiang Province. (c) Central urban area of Hangzhou.

Table 1. Information about air pollutant monitoring sites and meteorological station.

Monitoring site	Abbreviation	Location	Type
Xiasha site	XS	30.31°N, 120.32°E	Regional
Liping site	LP	30.41°N, 120.30°E	Suburban
Xixi site	XX	30.27°N, 120.10°E	Background
Zhaohui site	ZH	30.29°N, 120.16°E	Traffic pollution
Hemu site	HM	30.31°N, 120.12°E	Urban
PM _{2.5} chemical composition collector	\	30.26°N, 120.10°E	Background
Meteorological station	\	30.26°N, 120.10°E	Background

regular inspection of the zero point, full range, and precision of the instruments.

Meteorological Data

The meteorological data were obtained from the China Meteorological Station Data Sharing Service System (<http://cdc.cma.gov.cn/home.do>). The meteorological parameters were monitored at the Hangzhou meteorological

station, which is located near the Xixi monitoring site, and these parameters consisted of temperature (T), relative humidity (RH), sunshine duration (SD), solar radiation (SR), wind direction (WD), wind speed (WS), sea-level pressure (P), and precipitation (PREC).

Analysis of the PM_{2.5} Chemical Composition

The chemical composition of PM_{2.5} was measured at the

Hangzhou meteorological station (as shown in Fig. 1), which is located on the roof of a four-story building, approximately 20 m above the ground and approximately 800 m south of the Xixi monitoring site. We used an electronic balance to weigh the Teflon filters before and after sampling to obtain the daily average PM_{2.5} mass concentrations. The detection limit is 10 µg (AX105DR) in a superclean lab (T: 20 ± 1°C; RH: 40 ± 3%). Then, an online analyzer for the monitoring of aerosols (ADI 2080 MARGA; Applikon-ECN, Netherlands) was used to measure the water-soluble ions and trace elements in PM_{2.5}. A wet rotating denuder was used in the MARGA samples to allow gases to absorb on the wall of a liquid-coated annulus through which particles pass. A supersaturation treatment method was used in the steam-jet aerosol collector where the particles ultimately arrive. Droplets form due to the condensation of steam and can then be collected. The detection limits of major ions, Cl⁻, NO₃⁻, SO₄²⁻, NH₄⁺, Na⁺, K⁺, Mg²⁺, and Ca²⁺, were 0.008, 0.005, 0.007, 0.040, 0.070, 0.050, 0.013, and 0.030 µg m⁻³, respectively. We used a syringe system to collect both gases and aerosols and analyzed them via ion chromatography, which provided hourly results. The *R*² values of the calibration curves for the concentrations of ions and elements exceeded 0.999.

MODIS Aerosol and OMI NO₂ Column Data Set

The Moderate Resolution Imaging Spectroradiometer (MODIS) is carried on the Terra and Aqua satellites (Jin and Holloway, 2015). MODIS scans Hangzhou twice per day (10:30 and 13:30 BJT), and the recently released MODIS AOD product (Level 3 version 5) was applied to this study (<http://modis-atmos.gsfc.nasa.gov/>). The AOD is obtained by the 0.47 µm and 0.66 µm spectral channels and interpolated to the 0.55 µm channel. These MODIS AOD results include multiple AOD pixels covering the spatial scale of 0.5° × 0.5° and centered on Hangzhou (i.e., 30°N, 120°E). The total density of the NO₂ column in Hangzhou was derived from the Ozone Monitoring Instrument (OMI; which passes Hangzhou once per day, i.e., near 13:30 BJT) at a 0.25° × 0.25° resolution. The uncertainty in the NO₂ column density per pixel was estimated to be ± 0.5–1.5 × 10¹⁵ molecules cm⁻² with a relative error between 10% and 40%.

RESULTS AND DISCUSSION

Analysis of Daily Average Pollutant Concentrations during the G20 Period

Fig. 2 shows a comparison of the daily average concentrations of six air pollutants during the G20 period (2016) and those during the same period in the past three years (2013–2015). It can be seen that the concentrations of SO₂, NO₂, CO, PM₁₀, and PM_{2.5} decreased significantly during the G20 period. The NO₂ concentrations of the five sites decreased by 43.9–70.5%, with an average of 57.1%, which was the largest of the five air pollutants. And the SO₂ concentrations of the five sites declined by 17.5–56.6% (with an average of 42.6%). The PM_{2.5} and PM₁₀ concentration decreased by 34.5–42% (with an average of 38.5%) and 30.1–46.4% (with an average of 36.0%), respectively.

Notably, the O₃ concentration in Hangzhou increased

significantly during the G20 period. The average increase of O₃ at the five sites was 19%, especially the XX site reached 48.7%. This phenomenon may correspond to the O₃-NO_x-VOCs sensitivity. Yan *et al.* (2016) utilized the WRF-CMAQ model to analyze the O₃ formation in the YRD region and found that the sensitivity pattern of O₃ formation in Hangzhou was VOCs-limited. In these areas, if NO_x emissions are reduced, the O₃ concentration will first increase and then decrease. Therefore, the possible reason for the increase in O₃ concentration during the G20 period in 2016 is that the NO_x emission control measures were stronger than the VOCs emission control measures, which resulted in the weak inhibition of NO_x on O₃ production and significant increase of O₃ concentrations (Xing *et al.*, 2011; Yarwood *et al.*, 2013). In addition, biogenic VOC (BVOC) emissions also play an essential role in O₃ formation because they are highly reactive hydrocarbons that cause the rapid increase of O₃ when oxidized by hydroxyl radicals (Geng *et al.*, 2011; Situ *et al.*, 2014). Using the MEGAN model, Liu *et al.* (2018) estimated biogenic emissions at 18.86 × 10⁵ ton yr⁻¹ over the YRD region with higher emissions observed in Hangzhou and surrounding areas. Wu *et al.* (2019) employed the WRF-CMAQ model to investigate the effects of BVOC emissions on ozone formation over China and pointed out that the high BVOC emissions across eastern China increased the surface ozone levels, particularly in the YRD regions. During the G20 Summit, the T reached 31°C, and such a high T is beneficial to the emission of large amounts of BVOC. Therefore, BVOC emissions may also have significant contributions to the increased O₃ concentrations observed during the G20 period.

Meteorological Conditions

Fig. S1 presents the daily averages of the meteorological parameters (e.g., T, RH, P, and WS) during the G20 period and the same time period in the previous five years. In general, the RH during the G20 period was low in the early stage compared with the previous five years, and the T, P and WS did not show significant differences. In addition, we compared the meteorological parameters during the G20 period with those before and after the period (as shown in Table 2). The average T was highest before the G20 period, reaching up to 33.2 ± 1.8°C. The average RH and P during the G20 period were similar to those before the G20 period. The WS, SD, and SR were slightly higher during the G20 period than those before and after the G20 period.

To further investigate the impacts of meteorological conditions on changes in pollutant concentrations during the G20 period, the variations in surface meteorological parameters and their relationships with air pollutants were analyzed. According to the intensity of the emission reductions and joint control strategies over Hangzhou and surrounding areas, we divided the whole period into three stages. S1 (August 24–27) was the starting stage with industrial and construction emission control. During S2 (August 28–31), there was traffic restrictions added to the emission control strategy. And S3 (September 1–6) was the G20 Summit period, which was the strictest emission control stage. In the S1 stage, the concentrations of all pollutants (except O₃)

Fig. 2. Daily average concentrations of six air pollutants at different sites during the G20 period of 2016 and during the same period in the previous three years (2013–2015).

Table 2. Comparison of average values of meteorological parameters before, during, and after the G20 period from Aug. to Sep. 2016.

Period	T	P	RH	WS	SD	SR
Before G20 (Aug. 10–23)	33.2 ± 0.8	999.3 ± 1.8	71.8 ± 0.3	2.1 ± 0.4	7.8 ± 3.1	15.7 ± 3.3
During G20 (Aug. 24–Sep. 6)	31.0 ± 1.9	1002.2 ± 2.8	69.9 ± 1.4	2.7 ± 0.6	7.9 ± 3.6	16.2 ± 5.4
After G20 (Sep. 7–20)	23.7 ± 1.5	1007.3 ± 3.3	79.8 ± 1.0	2.5 ± 0.9	6.4 ± 3.1	14.6 ± 5.5

decreased. Compared with the NO₂ and PM_{2.5} concentrations on August 24, the average concentration of NO₂ and PM_{2.5} during S1 decreased by 19.9% and 6.8%, respectively. This occurred because construction sites temporarily stopped production and the meteorological conditions (i.e., easterly wind) were conducive to the dilution and removal of various pollutants. As shown in Fig. 3, with the effect of high pressure (see Fig. S2 in Supporting Information), the weather in Hangzhou was fair, with an average maximum T of 33.8°C over the four days. The maximum T on August 25 was 35.5°C, and the SD reached up to 11.6 h, which was the

maximum for the entire study period. Under the influence of strong radiation, the maximum 8-h daily average of O₃ on August 25 was 208 µg m⁻³ (i.e., the peak value during the study period). The average WS at 10 m was 2.9 m s⁻¹, and the dominant wind direction was easterly (the frequency of east-northeasterly, easterly, and east-southeasterly winds was 39.6%). With the effect of cold air on the night of August 26 (see Fig. S3), there were significant wind (the average WS at 10 m increased to 3.7 m s⁻¹), cooling (T decreased by approximately 3°C), and PREC (14.6 mm) processes in Hangzhou.

Fig. 3. Solar radiation (SR), sunshine duration (SD), wind speed (WS), temperature (T), relative humidity (RH), pressure (P), and hourly concentrations of six air pollutants at the XX site from August 24 to September 6, 2016. Blue arrows indicate precipitation.

In S2, under the influence of static weather and regional transport of air pollutants, the concentrations of various pollutants in Hangzhou reached peak values before and after August 29 (Ji *et al.*, 2018). During this stage, the WD in Hangzhou transformed from northwesterly to westerly winds and then to southwesterly winds. On August 28, Hangzhou experienced strong northwesterly winds, with the daily average WS reaching 3.9 m s^{-1} (the peak value during the study period). Influenced by the cold northwesterly winds, the pollutant concentrations increased compared with those observed on August 27 because of upstream pollutant transport, while the RH decreased to 45.6% (the minimum value during the study period). From August 29 to 31, the weather condition was constant, with a low planet boundary layer at night accompanied by low WS (with an average value of 2.3 m s^{-1}), which were unfavorable to the diffusion of pollutants. In addition, PREC was not observed in Hangzhou during this period, which had an average maximum T of

32°C and daily average SD of 10.75 h. These findings revealed that the radiation condition was good and the diffusion capacity was weak, which was beneficial for the formation and accumulation of O_3 from photochemical reactions. Compared with the S1 stage, the SO_2 concentration had the largest increase of 30.5% and reached $12.0 \mu\text{g m}^{-3}$ on August 28 and 29. Because the coal combustion control measures in this stage were maintained or more strictly controlled, the 30.5% increase should be considered a reflection of the contribution of regional transported pollutants to the air pollution level in Hangzhou (see Table S2).

During S3, a dramatic weather change occurred with many cloud systems. The daily average SD was 5.6 h, a decrease of 47.9% compared with that in the S2 which meant that photochemical consumption of O_3 precursors might be weakened on these days. And the average WS was 3.3 m s^{-1} on September 1 which was beneficial to the transmission of pollutants. The warm southwest flow that entered Hangzhou

had higher aerosol loading, which could have originated an aged air mass with secondary particle growth (Ji *et al.*, 2018). Then the $PM_{2.5}$ and PM_{10} concentrations reached their peak values due to the unexpected increases of secondary aerosol components during this period. On September 2–3, northwesterly flow following the passage of a trough dominated, with a low pressure field (see Fig. S4) with an average WS of 2.1 m s^{-1} . There was no PREC over 3 continuous days, which was not conducive to the diffusion and removal of pollutants. On September 4–6, persistent easterly winds with weak PREC occurred in Hangzhou, and these conditions had a wet scavenging effect on pollutants. The concentrations of $PM_{2.5}$, PM_{10} , NO_2 , and CO were lowest on September 5. In this stage, the total PREC, average RH, and average T were 2.3 mm, 65%, and 31°C , respectively. With high cloud coverage and low radiation at this time, the formation and accumulation of O_3 from photochemical

reactions were suppressed. The stable weather was beneficial for the accumulation of particles, and the humidity (65%) was greatly increased compared with that during S2 (50%). High-humidity conditions may have promoted the formation of sulfate and further increased the concentration of $PM_{2.5}$ (by 33.2%) and PM_{10} (by 21.5%). However, the pollutant concentrations on September 5, when the G20 Summit was held in Hangzhou, were significantly lower than those during the entire period due to the strict control measures.

Characteristics of Diurnal Variations in Pollutants during G20

The diurnal variations of SO_2 , CO, NO_2 , O_3 , PM_{10} , and $PM_{2.5}$ during the G20 period were compared with the same time period in 2015 (following the named non-G20 period, August 24–September 6, 2015), as shown in Fig. 4. The diurnal variations of $PM_{2.5}$, PM_{10} , SO_2 , NO_2 , and CO during

Fig. 4. Characteristics of diurnal variations in six air pollutants at the XX site during the G20 period (August 24–September 6, 2016) and the non-G20 period (August 24–September 6, 2015). The bars at the bottom of each panel represent the concentrations of pollutants in the G20 period minus the concentrations of pollutants in the non-G20 period. (Note: The arrows denote the max value)

the G20 period were significantly lower than the non-G20 period. The O_3 showed a single peak maximum at 16:00 local time which related to atmospheric photochemical reactions near the surface. Diurnal variation of $PM_{2.5}$ and PM_{10} were similar in these two periods with high concentrations in the morning due to the traffic source emissions. And the concentration of SO_2 exhibited a single-peak curve, and the peak appeared at 11:00. The strong vertical diffusion may have essential contribution on high SO_2 during daytime while the low concentration at night may correspond to the wet deposition of SO_2 from PREC events and dry deposition (Quan and Zhang, 2008). Diurnal variations of NO_2 and CO showed a less obvious bimodal diurnal change. During the rush hours in the late afternoon, the concentration of NO_2 began to increase until the following second peak appeared at 01:00 the next day. The second peak may be related to the decreased boundary layer height at night then impact the diffusion of pollutants.

In addition, it can be found that there were some similar patterns of air pollutants. The diurnal variation of $PM_{2.5}$ was highly correlated with PM_{10} , which is possibly because the ratios of $PM_{2.5}$ to PM_{10} were high (0.64–0.92) (as shown in Fig. 4). And this phenomenon may also suggest that they may have the same potential sources (Xu et al., 2018). As NO_2 and SO_2 are both precursors for particle matter through secondary inorganic aerosol (SIA) formation, NO_2 and SO_2 had positive correlations with $PM_{2.5}$ and PM_{10} . In addition, the SO_2 correlation with $PM_{2.5}$ and PM_{10} was better than that with NO_2 . This difference can be explained by the relative contribution of sulfate exceeding the nitrate in SIA which will be discussed later.

Analysis of Chemical Components of $PM_{2.5}$ during the G20 Period

Previous studies have shown that within $PM_{2.5}$, NH_4^+ is mainly formed through NH_3 gas-particle conversion; SO_4^{2-} is mainly related to H_2SO_4 , which is the result by the gas-phase oxidation of SO_2 ; and NO_3^- is related not only to the heterogeneous reaction of HNO_3 but also to the heterogeneous

hydrolysis of highly humid N_2O_5 (Riemer et al., 2003; Baek and Aneja, 2004; Chang et al., 2016). Fig. 5 compares the average concentrations of several $PM_{2.5}$ components during the G20 period and the non-G20 period. The concentrations of all components (except for Mg^{2+}) exhibited obvious decreases. Among them, SO_4^{2-} showed the largest decline of 62.7%, reflecting the effect of the “coal-reducing” measures during the G20 period. The decrease in NO_3^- was nearly 50%, which reflected the combined effects of motor vehicle restrictions and the reduction of biofuel combustion from human sources and point sources. Cl^- also exhibited a significant reduction, indicating the effect of the reduction of combustion emissions (Tao et al., 2017). The decreased concentrations of Na^+ and Ca^{2+} reflected the effect of dust control (Louie et al., 2005). K^+ is considered a tracer ion for biomass combustion (Wang et al., 2015). Notably, the decrease in the NH_4^+ concentration was 61.89% during the G20 period, which exceeded the decreases in NO_3^- . It is reported that NH_4^+ , NO_3^- , and SO_4^{2-} form a buffer system, existing as $(NH_4)_2SO_4$ and NH_4NO_3 (Tao et al., 2012). And the NH_4^+ concentration will not exceed those of nitrate and sulfate because the chemical activity of NH_4^+ needs an acidic environment. Therefore, the possible reason for this may be that decreases in SO_4^{2-} and NO_3^- lead to decreased NH_4^+ concentrations.

Fig. 6 shows the proportions of sulfate, nitrate, and ammonia in $PM_{2.5}$ ($\rho(SNA/PM_{2.5})$), the sulfur oxidation ratio ($SOR = [SO_4^{2-}]/[SO_2 + SO_4^{2-}]$), the nitrogen oxidation ratio ($NOR = [NO_3^-]/[NO_x + NO_3^-]$), and the $PM_{2.5}$ concentrations during the G20 period (Fig. 6(a)) and the non-G20 period (Fig. 6(b)). Higher SOR and NOR indicate increased formation of secondary aerosols in the atmosphere. During the G20 period, the average $\rho(SNA/PM_{2.5})$ was 15%, which was significantly lower than that during the non-G20 period (34%). However, the SOR and NOR exhibited similar patterns in which they reached their minimum values in S2 and their maximum values in S3 during the G20 period. Sun et al. (2013) reported that RH has the most significant effect on NO_3^- and SO_4^{2-} because higher RH can promote the formation of secondary inorganic ions in particles. The

Fig. 5. Average concentration of $PM_{2.5}$ chemical components during the G20 period (August 24–September 6, 2016) and the non-G20 period (August 24–September 6, 2015).

Fig. 6. Variations in sulfate, nitrate, and ammonia (SNA) in $\text{PM}_{2.5}$; sulfur oxidation ratio (SOR); and nitrogen oxidation ratio (NOR) during (a) the G20 period (August 24–September 6, 2016) and (b) the non-G20 period (August 24–September 6, 2015).

average RH during S3 was 65%, which was higher than that during S2 (only 48%). Therefore, although the concentration of SO_2 during S2 was similar to that during S3, the SOR and NOR were lowest in S2 and highest in S3.

Aw and Kleeman (2003) found that high T favors the volatilization of nitric acid and ammonia from the particulate phase of nitrate. As shown in Fig. 3, the T was similar during the G20 and non-G20 periods; thus, the NOR did not obviously change during the G20 and non-G20 periods. As for the variation of SOR, Liang *et al.* (2017) reported that the active photochemical oxidation could result in high SO_2 -to-sulfate conversion rates. And the higher RH in summer can also favor the heterogeneous reaction of sulfate formation (as shown in Fig. 3). It is recognized that the SOR was significantly positively correlated with the RH but only slightly correlated with the T in Hangzhou (Wu *et al.*, 2017). Hence, the variation of RH is the main reason for the change of SOR during different stages.

Changes in Satellite AOD and NO_2 Column during the G20 Period

In Fig. 7, the variation of AOD and NO_2 column over Hangzhou shows similar patterns to the air pollutants. In S3, the average AOD was 1.01, which decreased by 41% relative to S1 and decreased by 38% relative to S2. In S3, the average columnar NO_2 was $10.1 \text{ molecules cm}^{-2}$, which decreased by 30.3% relative to S1 and S2. This trend was consistent with the results of surface observations, which were discussed above.

Analysis of the Spatial Evolution of Air Pollutants between Hangzhou and the Surrounding Cities

Fig. 8 shows the pollutant concentrations of Hangzhou

and the surrounding cities during the G20 period and non-G20 period. The decreases in $\text{PM}_{2.5}$, PM_{10} , and CO in the core area were the most prominent, followed by the strictly controlled area, with the controlled area being the least affected. The percentages by which the $\text{PM}_{2.5}$ concentrations decreased in the three controlled areas from the non-G20 period to the G20 period were 42.64%, 30.25%, and 6.92%. However, the concentrations of PM_{10} and CO in the controlled area increased. The SO_2 concentrations decreased by 38.07% and 40.79% in the core area and the strictly controlled area, respectively, while SO_2 only decreased by 4.33% in the controlled area. The NO_2 concentrations decreased by 43.30% in the core area and only decreased by 16.53% and 18.80% in the strictly controlled area and controlled area, respectively. Despite the increase in the O_3 concentration in Hangzhou, the O_3 concentration in the core area was essentially the same as that observed during the same period in 2015. In addition, the O_3 concentration in the controlled area increased by 5.34% compared to that observed during the same period in 2015.

Comparison with Previous Studies

By comparing the pollutant concentration during the G20 Summit with that during the Beijing APEC conference in 2014, the Beijing military parade in 2015, and the Nanjing Youth Olympic Games in 2014, we found that the concentrations of NO_2 , SO_2 , CO, $\text{PM}_{2.5}$, and PM_{10} were reduced under the influence of emission reduction measures during these special events (as shown in Table S3). The O_3 concentration decreased significantly during the military parade and the Nanjing Youth Olympic Games while the O_3 concentration increased by 19% and 102% during the G20 Summit and APEC conference, respectively. This difference

Fig. 7. Aerosol optical depth (AOD) derived from MODIS satellite data and columnar NO₂ derived from OMI satellite data in the region of 29.5–30.5°N, 119.4–120.4°E in the G20 period. Green lines represent the average values of AOD and columnar NO₂ during S1, S2, and S3.

Fig. 8. Comparison of pollutant concentrations in Hangzhou and the surrounding cities during the G20 period (August 24–September 6, 2016) and the non-G20 period (August 24–September 6, 2015).

may be due to the large differences in meteorological conditions during the four important events and their different effects on O₃ generation. Huang *et al.* (2017) analyzed the meteorological conditions during the 2014 Nanjing Youth Olympic Games. The results showed that the T during the Youth Olympic Games was lower than that in the same period in 2013, and there were more cloudy and rainy days. The low T and cloudy weather were not conducive to the formation of O₃, and the O₃ concentration clearly decreased. Wang *et al.* (2017b) analyzed the Beijing military parade in 2015 and maintained that the continuous low T during the parade had an important contribution to the reduction in the O₃ concentration. We found that the average T during the G20 Summit reached 31°C, which is conducive to the large BVOC emissions and enhanced photochemical reactions.

The aforementioned differences during the four events may be due to a lack of sufficient consideration of the O₃ sensitivity pattern during the implementation of emission reduction measures. Previous studies have shown that the O₃ sensitivity patterns in Beijing, Nanjing, and Hangzhou are VOCs-limited (Tang *et al.*, 2012; An *et al.*, 2015; Li *et al.*, 2017). For these areas, if NO_x emission control measures are stronger than the VOC emission control measures, the inhibitory effect of NO_x on O₃ production will be weak, and the O₃ concentration will increase significantly. Wang *et al.* (2015) found that the regional VOC reduction during the APEC conference was significantly less than that of NO_x, while the regional VOC reduction during the parade was significantly higher than that of NO_x, which increased the O₃ concentration during the APEC conference and decreased the O₃ concentration during the parade. Ding *et al.* (2015) further verified this conclusion by estimating the NO_x emission reduction during the 2014 Nanjing Youth Olympic Games. Because this research did not synchronize VOCs and the Zhejiang provincial government did not publish the specific emission reduction plan and implementation strength during the G20 period, the reason for the increase in O₃ concentration during the G20 Summit requires further investigation.

CONCLUSIONS

In this study, the variations in the air pollutant characteristics and their corresponding meteorological conditions in Hangzhou and its surrounding areas during the G20 period (August 24–September 6, 2016) were analyzed and compared to those observed during the same dates for the five previous years. The RH was lower during the G20 period than the preceding years, whereas the other meteorological conditions were similar to their average levels. Furthermore, compared to the three previous years, the majority of the studied air pollutants were significantly reduced, with the average daily concentrations for SO₂, NO₂, PM_{2.5}, and PM₁₀ decreasing by 42.6%, 57.1%, 38.5%, and 36%, respectively; the O₃ concentration, however, significantly increased (by 19%). In addition, the concentrations of most of the chemical components of PM_{2.5} decreased, with sulfate and nitrate exhibiting the largest reductions. The AOD and the columnar NO₂ in the region of 29.5–30.5°N and 119.4–120.4°E during

the G20 period also displayed a trend similar to that of the observed surface pollutant concentrations.

Based on our comprehensive results and observational analysis, emission reduction measures implemented on the regional scale effectively improved the air quality during the G20 period, suggesting that regional jointly emission reduction are ideal for controlling air pollution in megacities such as Hangzhou, and even the entire YRD region. Moreover, the effects of O₃-VOCs-NO_x sensitivity must be fully considered, particularly for VOCs-limited cities, e.g., Hangzhou; specifically, to prevent a significant increase in O₃, emission control measures should ensure that the reduction in VOCs exceeds that of NO_x. Finally, collaborative efforts in pollutant emission and control between adjacent regions should be intensified a few days in advance—before the occurrence of adverse weather conditions—to maintain low pollutant concentrations during major events. The strategies implemented during the G20 Summit can be used as a reference when devising air quality improvement measures for similar activities in the future.

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DISCLAIMER

The authors declare that they have no conflicts of interest.

SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <http://www.aaqr.org>.

REFERENCES

An, J., Zou, J., Wang, J., Lin, X. and Zhu, B. (2015).

- Differences in ozone photochemical characteristics between the megacity Nanjing and its suburban surroundings, Yangtze river delta, China. *Environ. Sci. Pollut. Res. Int.* 22: 19607–19617.
- Aw, J. and Kleeman, M.J. (2003). Evaluating the first-order effect of interannual temperature variability on urban air pollution. *J. Geophys. Res. Atmos.* 108: 4365.
- Baek, B.H. and Aneja, V.P. (2004). Measurement and analysis of the relationship between ammonia, acid gases, and fine particles in eastern North Carolina. *J. Air Waste Manage. Assoc.* 54: 623–633.
- Chan, C.K. and Yao, X. (2008). Air pollution in mega cities in China. *Atmos. Environ.* 42: 1–42.
- Chang, W.L., Brown, S.S., Stutz, J., Middlebrook, A.M., Bahreini, R., Wagner, N.L., Dubé, W.P., Pollack, I.B., Ryerson, T.B. and Riemer, N. (2016). Evaluating N_2O_5 heterogeneous hydrolysis parameterizations for CalNex 2010. *J. Geophys. Res. Atmos.* 121: 5051–5070.
- Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., Pope, C.A., III, Shin, H., Straif, K., Shaddick, G., Thomas, M., van Dingenen, R., van Donkelaar, A., Vos, T., Murray, C.J.L. and Forouzanfar, M.H. (2017). Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *Lancet* 389: 1907–1918.
- Ding, J., van der A, R.J., Mijling, B., Levelt, P.F. and Hao, N. (2015). NO_x emission estimates during the 2014 Youth Olympic Games in Nanjing. *Atmos. Chem. Phys.* 15: 9399–9412.
- Dong, X., Gao, Y., Fu, J.S., Li, J., Huang, K., Zhuang, G. and Zhou, Y. (2013). Probe into gaseous pollution and assessment of air quality benefit under sector dependent emission control strategies over megacities in Yangtze River Delta, China. *Atmos. Environ.* 79: 841–852.
- Feng, R., Wang, Q., Huang, C.C., Liang, J., Luo, K., Fan, J.R. and Cen, K.F. (2019). Investigation on air pollution control strategy in Hangzhou for post-G20/pre-Asian-games period (2018–2020). *Atmos. Pollut. Res.* 10: 197–208.
- Geng, F., Tie, X., Guenther, A., Li, G., Cao, J. and Harley, P. (2011). Effect of isoprene emissions from major forests on ozone formation in the city of Shanghai, China. *Atmos. Chem. Phys.* 11: 10449–10459.
- Hu, J., Chen, J., Ying, Q. and Zhang, H. (2016). One-year simulation of ozone and particulate matter in China using WRF/CMAQ modeling system. *Atmos. Chem. Phys.* 16: 10333–10350.
- Hu, J., Li, X., Huang, L., Ying, Q., Zhang, Q., Zhao, B., Wang, S. and Zhang, H. (2017). Ensemble prediction of air quality using the WRF/CMAQ model system for health effect studies in China. *Atmos. Chem. Phys.* 17: 13103–13118.
- Huang, Q., Wang, T., Chen, P., Huang, X., Zhu, J. and Zhuang, B. (2017). Impacts of emission reduction and meteorological conditions on air quality improvement during the 2014 Youth Olympic Games in Nanjing, China. *Atmos. Chem. Phys.* 17: 13457–13471.
- Jansen, R.C., Shi, Y., Chen, J., Hu, Y., Xu, C., Hong, S., Li, J. and Zhang, M. (2014). Using hourly measurements to explore the role of secondary inorganic aerosol in $\text{PM}_{2.5}$ during haze and fog in Hangzhou, China. *Adv. Atmos. Sci.* 31: 1427–1434.
- Ji, Y., Qin, X., Wang, B., Xu, J., Shen, J., Chen, J., Huang, K., Deng, C., Yan, R., Xu, K. and Zhang, T. (2018). Counteractive effects of regional transport and emission control on the formation of fine particles: A case study during the Hangzhou G20 summit. *Atmos. Chem. Phys.* 18: 13581–13600.
- Jin, X. and Holloway, T. (2015). Spatial and temporal variability of ozone sensitivity over China observed from the ozone monitoring instrument. *J. Geophys. Res. Atmos.* 120: 7229–7246.
- Li, K., Chen, L., Ying, F., White, S.J., Jang, C., Wu, X., Gao, X., Hong, S., Shen, J., Azzi, M. and Cen, K. (2017). Meteorological and chemical impacts on ozone formation: A case study in Hangzhou, China. *Atmos. Res.* 196: 40–52.
- Li, K., Chen, L., White, S.J., Zheng, X., Lv, B., Lin, C., Bao, Z., Wu, X., Gao, X., Ying, F., Shen, J., Azzi, M. and Cen, K. (2018). Chemical characteristics and sources of PM_{10} during the 2016 summer in Hangzhou. *Environ. Pollut.* 232: 42–54.
- Liang, P., Zhu, T., Fang, Y., Li, Y., Han, Y., Wu, Y., Hu, M. and Wang, J. (2017). The role of meteorological conditions and pollution control strategies in reducing air pollution in Beijing during APEC 2014 and Victory Parade 2015. *Atmos. Chem. Phys.* 17: 13921–13940.
- Liu, H., Ma, W., Qian, J., Cai, J., Ye, X., Li, J. and Wang, X. (2015). Effect of urbanization on the urban meteorology and air pollution in Hangzhou. *J. Meteorol. Res.* 29: 950–965.
- Liu, Y., Li, L., An, J., Huang, L., Yan, R., Huang, C., Wang, H., Wang, Q., Wang, M. and Zhang, W. (2018). Estimation of biogenic VOC emissions and its impact on ozone formation over the Yangtze River Delta region, China. *Atmos. Environ.* 186: 113–128.
- Louie, P.K., Chow, J.C., Chen, L.W., Watson, J.G., Leung, G. and Sin, D.W. (2005). $\text{PM}_{2.5}$ chemical composition in Hong Kong: Urban and regional variations. *Sci. Total Environ.* 338: 267–281.
- Ni, Z.Z., Luo, K., Gao, X., Gao, Y., Fan, J.R., Fu, J.S. and Chen, C.H. (2019). Exploring the stratospheric source of ozone pollution over China during the 2016 Group of Twenty summit. *Atmos. Pollut. Res.* 10: 1267–1275.
- Quan, J. and Zhang, X. (2008). Assessing the role of ammonia in sulfur transformation and deposition in China. *Atmos. Res.* 88: 78–88.
- Riemer, N., Vogel, H., Vogel, B., Schell, B., Ackermann, I., Kessler, C. and Hass, H. (2003). Impact of the heterogeneous hydrolysis of N_2O_5 on chemistry and nitrate aerosol formation in the lower troposphere under photochemical conditions. *J. Geophys. Res. Atmos.* 108: 291–302.
- Situ, S., Wang, X., Guenther, A., Zhang, Y., Wang, X.,

- Huang, M., Fan, Q. and Xiong, Z. (2014). Uncertainties of isoprene emissions in the MEGAN model estimated for a coniferous and broad-leaved mixed forest in Southern China. *Atmos. Environ.* 98: 105–110.
- Su, W., Liu, C., Hu, Q., Fan, G., Xie, Z., Huang, X., Zhang, T., Chen, Z., Dong, Y., Ji, X., Liu, H., Wang, Z. and Liu, J. (2017). Characterization of ozone in the lower troposphere during the 2016 G20 conference in Hangzhou. *Sci. Rep.* 7: 17368.
- Sun, Y., Wang, Z., Fu, P., Jiang, Q., Yang, T., Li, J. and Ge, X. (2013). The impact of relative humidity on aerosol composition and evolution processes during wintertime in Beijing, China. *Atmos. Environ.* 77: 927–934.
- Tang, G., Wang, Y., Li, X., Ji, D., Hsu, S. and Gao, X. (2012). Spatial-temporal variations in surface ozone in Northern China as observed during 2009–2010 and possible implications for future air quality control strategies. *Atmos. Chem. Phys.* 12: 2757–2776.
- Tao, J., Shen, Z., Zhu, C., Yue, J., Cao, J., Liu, S., Zhu, L. and Zhang, R. (2012). Seasonal variations and chemical characteristics of sub-micrometer particles (PM₁) in Guangzhou, China. *Atmos. Res.* 118: 222–231.
- Tao, J., Zhang, L., Cao, J. and Zhang, R. (2017). A review of current knowledge concerning PM_{2.5} chemical composition, aerosol optical properties and their relationships across China. *Atmos. Chem. Phys.* 17: 9485–9518.
- Wang, T., Xue, L., Brimblecombe, P., Lam, Y.F., Li, L. and Zhang, L. (2017a). Ozone pollution in China: A review of concentrations, meteorological influences, chemical precursors, and effects. *Sci. Total Environ.* 575: 1582–1596.
- Wang, Z., Li, Y., Chen, T., Li, L., Liu, B., Zhang, D., Sun, F., Wei, Q., Jiang, L. and Pan, L. (2015). Changes in atmospheric composition during the 2014 APEC conference in Beijing. *J. Geophys. Res. Atmos.* 120: 12695–12707.
- Wang, Z.S., Li, Y.T., Zhang, D.W., Chen, T., Wei, Q., Sun, T.H., Wang, B.Y., Pan, J.X., Cui, J.X. and Pi, S. (2017b). Analysis on air quality in Beijing during the military parade period in 2015. *China Environ. Sci.* 37: 1628–1636.
- Wu, D., Lin, S.L., Yang, H.Q., Du, R.G., Xia, J.R., Qi, B., Liu, G., Li, F.Y., Yang, M. and Gai, X.L. (2017). Pollution characteristics and light extinction contribution of water-soluble ions of PM_{2.5} in Hangzhou. *Environ. Sci.* 38: 2656–2666.
- Wu, K., Yang, X., Chen, D., Gu, S., Lu, Y., Jiang, Q., Wang, K., Ou, Y., Qian, Y., Shao, P. and Lu, S. (2020). Estimation of biogenic VOC emissions and their corresponding impact on ozone and secondary organic aerosol formation in China. *Atmos. Res.* 231: 104656.
- Xing, J., Wang, S.X., Jang, C., Zhu, Y. and Hao, J.M. (2011). Nonlinear response of ozone to precursor emission changes in China: A modeling study using response surface methodology. *Atmos. Chem. Phys.* 11: 5027–5044.
- Xu, Y., Ying, Q., Hu, J., Gao, Y., Yang, Y., Wang, D. and Zhang, H. (2018). Spatial and temporal variations in criteria air pollutants in three typical terrain regions in Shaanxi, China, during 2015. *Air Qual. Atmos. Health* 11: 95–109.
- Yan, R.S., Li, L., An, J.Y., Lu, Q., Wang, S., Zhu, Y., Jang, C.J. and Fu, J.S. (2016). Establishment and application of nonlinear response surface model of ozone in the Yangtze river delta region during summertime. *Acta Sci. Circumstant.* 36: 1383–1392.
- Yarwood, G., Emery, C., Jung, J., Nopmongkol, U. and Sakulyanontvittaya, T. (2013). A method to represent ozone response to large changes in precursor emissions using high-order sensitivity analysis in photochemical models. *Geosci. Model Dev.* 6: 1601–1608.
- Zhang, G., Xu, H., Qi, B., Du, R., Gui, K., Wang, H., Jiang, W., Liang, L. and Xu, W. (2018). Characterization of atmospheric trace gases and particulate matter in Hangzhou, China. *Atmos. Chem. Phys.* 18: 1705–1728.

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