Impacts of emission reduction and meteorological conditions on air quality improvement during the 2014 Youth Olympic Games in Nanjing, China

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Abstract

As the holding city of the 2nd Youth Olympic Games (YOG), Nanjing is highly industrialized and urbanized facing with several air pollution issues. In order to ensure better air quality during the event, the local government took great efforts to control the emissions from pollutant sources. However, air quality can still be affected by synoptic weather, not only emission. In this paper, the influences of meteorological factors and emission reductions were investigated using observational data and numerical simulations with WRF/CMAQ. During the YOG holding month (Aug., 2014), the observed hourly mean concentrations of SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO and O_3 were 11.6 μg/m^3, 34.0 μg/m^3, 57.8 μg/m^3, 39.4 μg/m^3, 0.9 mg/m^3, and 38.8 μg/m^3, respectively, which were below China National Ambient Air Quality Standard (Level

2). However, model simulation showed that the weather conditions such as weaker winds during the holding time were adverse for better air quality, and could increase SO_2, NO_2, PM_{10}, $PM_{2.5}$ and CO by 17.5%, 16.9%, 18.5%, 18.8%, 7.8% and 0.8%, respectively. Taking account of local emission abatement only, the simulated SO_2, NO_2, PM_{10}, $PM_{2.5}$ and CO was decreased by 24.6%, 12.1%, 15.1%, 8.1% and 7.2%, respectively. Consequently, stringent emission control measures can reduce the concentrations of air pollutants in short term, and emission reduction is the very important factor for the air quality improvement during the YOG, which has set up a good example in air protection for important social events.

KEY WORDS: Youth Olympic Games; Emission reduction; Meteorological conditions; WRF/CMAQ; Nanjing

1 Introduction

As located in the economically developed Yangtze River Delta (YRD) region of China, Nanjing successfully hosted the second Youth Olympic Games (YOG) during 16 - 28 Aug., 2014. Nanjing is a highly urbanized city and its GDP ranked the 12th of all the cities in China by 2013 (National Bureau of Statistics of China, 2014). Due to fast urbanization and industrialization, heavy motor vehicles and construction dust, Nanjing has long been suffered from air pollution (Dong et al., 2013; Chen et al., 2015).

In order to realize the promise of “Green YOG”, the local government had taken a series of measures to reduce emissions of air pollutants. The preparatory work started from 1 Jul., 2014. Besides, the local government performed the work plan for stringent environmental quality assurance from 1 Aug. (National Bureau of Statistics of China, 2014). The controlled emissions include 5 major categories: industry, power plants, traffic, VOC product-related sources and others. Some local petrochemical, chemical and steel industries were forced to limit or halt the production. Coal-combustion enterprises were required to use high-quality coals with low sulfur content and ash content. And vehicles with heavy pollution called “yellow label buses” were prohibited in Nanjing during 10-28 Aug.. Oil loading and unloading operations were strictly controlled. All construction processes in the city were forced to stop. The ground surface with bare soil was covered.

It is well known that air quality can be affected by both meteorological factors and pollutant emissions. Many cases verified that both emission abatement and weather conditions can influence the improvement of local air quality. Emission control has been taken in many social events, like Beijing Olympic Games in 2008 and Shanghai Expo in 2010. Xing et al. (2011) suggested that emission controls benefit for pollutants reduction, but meteorological effects can be either ways at different locations. Cermak and Knutti (2009), Wang et al. (2009b, 2010) and Xing et al. (2011) reported that typical meteorological conditions accounted more for air improvement during 2008 Beijing Olympics than emission reductions. Zhou et al. (2010) concluded that control measures for transportation resulted in a reduction of 44.5% and 49.0% in daily CO and NO_x emission from motor vehicles during the 2008 Olympics. Cai et al. (2011) and Wang et al. (2009a) also studied the transportation controls on improving air quality during Beijing Olympic Games. Okuda et al. (2011) argued that sources control during Beijing Olympics significantly reduced PM_{10}, NO_2 and SO_2, but did not effectively reduce $PM_{2.5}$. Streets et al. (2007) proposed that local sources controlling is inadequate for heavily populated, urbanized, and industrialized city, regional air quality management is in urgent need. Lin et al. (2013) applied monitoring data to analyze the weather impacts on air quality of the World Expo in YRD and concluded that high frequency of marine winds during the Expo had a positive effect on the air quality of coastal cities, but a negative effect on some inland cities in YRD. Satellite data reflected that the tropospheric NO_2 column, aerosol optical thickness (AOT), and CO concentration dropped by 8%, 14% and 12%, respectively over Shanghai during the Expo period, compared to the past three years (Hao et al., 2011). Liu et al. (2013) compared the contributions of long-term and short-term emission control via CMAQ simulation and investigated their effects on air quality in Guangzhou during the Asian Games. Xu et al. (2013) concluded that $PM_{2.5}$ was mainly emitted from anthropogenic sources other than biogenic sources and indicated that cutting down anthropogenic emissions could decrease $PM_{2.5}$ effectively.

Dong et al. (2013) found that independent NO_x emission reduction would strengthen O_3 as a side effect in YRD. Chen et al. (2015, 2017) studied the source apportionment of size-fractionated particles in Nanjing, and found that fugitive and construction dust decreased significantly in YOG.

There have been some studies on air quality during the 2nd YOG (Ding et al., 2015; Chen et al., 2017; Zhou et al., 2017), but few work focused on the relative contributions of meteorology and control efforts. This study takes the air quality monitoring data and applies WRF/CMAQ model to estimate the effect of meteorological factors and emission reduction on air quality of Nanjing during the 2nd YOG. Data and model descriptions as well as simulation scenarios are described in Section 2. Section 3 examines the characteristics of six major air pollutants (SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO and O_3) and compares their concentrations during the YOG with those a year ago (Aug., 2013) and the months without emission reduction (Jul. and Sept., 2014). Besides, this section discusses the separate effect of weather conditions and emission abatement qualitatively and quantitatively based on the simulation results. Section 4 summaries the main conclusions, emphasizes the important factor of the air quality promotion during the YOG, and provides some advice for ensuring pleasant future air quality.

2 Methodology

2.1 Data description

Hourly observed air quality data during Jul.-Sept. 2014 and Aug. 2013 of two representative stations was collected from Nanjing Environmental Monitoring Center (http://222.190.111.117:8023/). Both of the two stations are state controlling air monitoring sites. The data quality assurance and quality control procedures for monitoring strictly follow the national standards (State Environmental Protection Administration of China, 2006). Caochangmen (CCM) Station (118.75° E, 32.06° N) locates in Gulou District, the city center of Nanjing. Gulou District is the center of economy, politics, culture and education in Nanjing, where gathers many East China’s high-end industrial and corporate headquarters. Besides, over 90% provincial authorities, more than 20 colleges and universities, and more than 120 institutes situate in Gulou District. It’s the most populated area in Nanjing, with lively commercial hub and heavy traffic. Thus, CCM station was chosen to represent the urban status of Nanjing. The other site calls Xianlin (XL) Station (118.92° E, 32.11° N), which locates in Qixia District, the suburb of Nanjing. Compared to Gulou District, Qixia District is much more sparsely populated with few traffic congestion problems. Thus, XL station was chosen to represent the suburban status of Nanjing.

2.2 Model description

The integrated modeling system WRF/CMAQ was employed in this study. Community Multiscale Air Quality (CMAQ) is a third-generation regional air quality model developed by the Environmental Protection Agency of USA (USEPA). It incorporates a set of up-to-date compatible modules and control equations for the atmosphere, and can fully consider complicated physical and chemical processes (Byun and Schere, 2006; Foley et al., 2010). Many applications have proven that CMAQ is a reliable tool in simulating air quality from city scale to mesoscale (Xing et al., 2011; Dong et al., 2013; Liu et al., 2013; Xu et al. 2013; Shu et al., 2016). Community Multiscale Air Quality (CMAQ v4.7.1, Binkowski and Roselle, 2003) model includes the 2005 Carbon Bond gas-phase mechanism (CB05) (Yarwood et al., 2005) and the fourth-generation CMAQ aerosol module (AERO4) (Byun and Schere, 2006). And it was applied to simulate the pollutant distribution over Nanjing in this paper. Weather Research and Forecasting (WRF) is a new generation of mesoscale weather forecast model and assimilation system, developed by the National Center for Atmospheric Research (NCAR). It has been widely applied in China and shows a good performance in all kinds of weather forecasts (Jiang et al., 2008, 2012; Xu et al.,2013; Liao et al., 2014, 2015; Xie et al., 2014, 2016; Li et al., 2016; Shu et al., 2016). WRF v3.2.1 (Skamarock et al., 2008) model was run to provide meteorological fields for CMAQ. Four nested domains were set for both models, with horizontal resolutions of 81km, 27km, 9km, 3km, and the innermost domain covering Nanjing (Fig. 1). For all domains, 23 vertical sigma layers from the surface to the top pressure of 100 hpa was set, with about 10 layers in the planetary boundary layer. The detail dynamic parameterization in WRF as well as the physical and chemical schemes of CMAQ applied in this research were the same as those in Shu et al. (2016)'s work and were proven to have good performance. As for the innermost domain, Nanjing Environmental Protection Bureau chooses the local 9 state controlling air monitoring sites (See Fig. 1, Table 1) to represent the whole Nanjing (NJ) city. In conformity with this, the 9 sites in domain 4 were chosen to represent the whole Nanjing when analyzing the impacts of weather conditions and emission reduction.

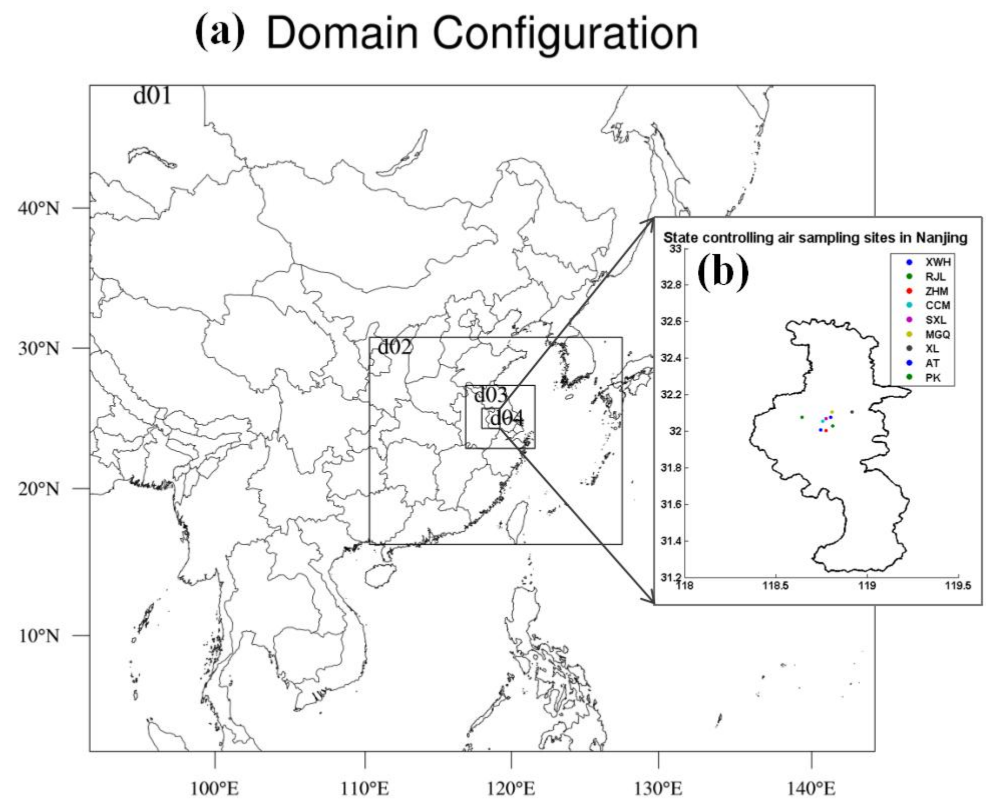

Fig. 1. Modeling domains and state controlling air monitoring sites in Nanjing. ((a) The four nested modeling domains at 81km (d01: East Asia), 27km (d02: East China), 9km (d03: Yangtze River Delta), and 3km (d04: Nanjing), (b) Locations of 9 sites in Nanjing).

Table 1

The air monitoring sites in Nanjing

Site	Abbreviation	Location
Xuanwuhu Station	XWH	32.08° N, 118.80° E
Ruijinlu Station	RJL	32.03° N, 118.82° E
Zhonghuamen Station	ZHM	32.00° N, 118.76° E

Caochangmen Station	CCM	32.06° N, 118.75° E
Shanxilu Station	SXL	32.07° N, 118.77° E
Maigaoqiao Station	MGQ	32.11° N, 118.81° E
Xianlin Station	XL	32.11° N, 118.92° E
Aoti Station	AT	32.01° N, 118.74° E
Pukou Station	PK	32.07° N, 118.64° E

2.3 Emissions and simulation scenarios

In this study, Multi-resolution Emission Inventory for China (MEIC v1.2, http://www.meicmodel.org/) with a resolution of 0.25° × 0.25° was employed to provide the anthropogenic emissions for species including SO_2, NO_x, CO, NMVOC, NH_3, CO_2, $PM_{2.5}$, PM_{10}, BC, and OC, which form 4 sectors as industry, power plants, transportation, and residential.

For the innermost domain, the local emission inventory before and after emission control was used with a horizontal resolution of 3km × 3km. The base year of the local emission is 2012. According to the local emission control program, 5 major categories: industry, power plants, traffic, VOC product-related sources and others were in the control list. In Aug. 2014, all coal-combustion enterprises must use high-quality coals with low sulfur content less than 0.5% and ash content less than 13%. Besides, the local government ordered over 100 local petrochemical, chemical and steel enterprises to cut or halt their production. Moreover, heavy pollution vehicles were prohibited in Nanjing during 10-28 Aug. 2014 to reduce traffic emission. To reduce emissions of volatile organic compounds, loading and unloading oil operations were prohibited at the docks in Nanjing section of Yangtze River. What's more, local construction work was halted during Aug. 2014. With these efforts, the emission would be cut by 25.0% for SO_2, 15.0% for NO_x, 42.8% for PM_{10}, 36.2% for $PM_{2.5}$, and 20.0% for CO. The spatial distributions of emission reduction for different species were showed in Fig. 2. For SO_2, NO_x, PM_{10} and $PM_{2.5}$, they centered in the middle of Nanjing city and for CO, it centered in several points.

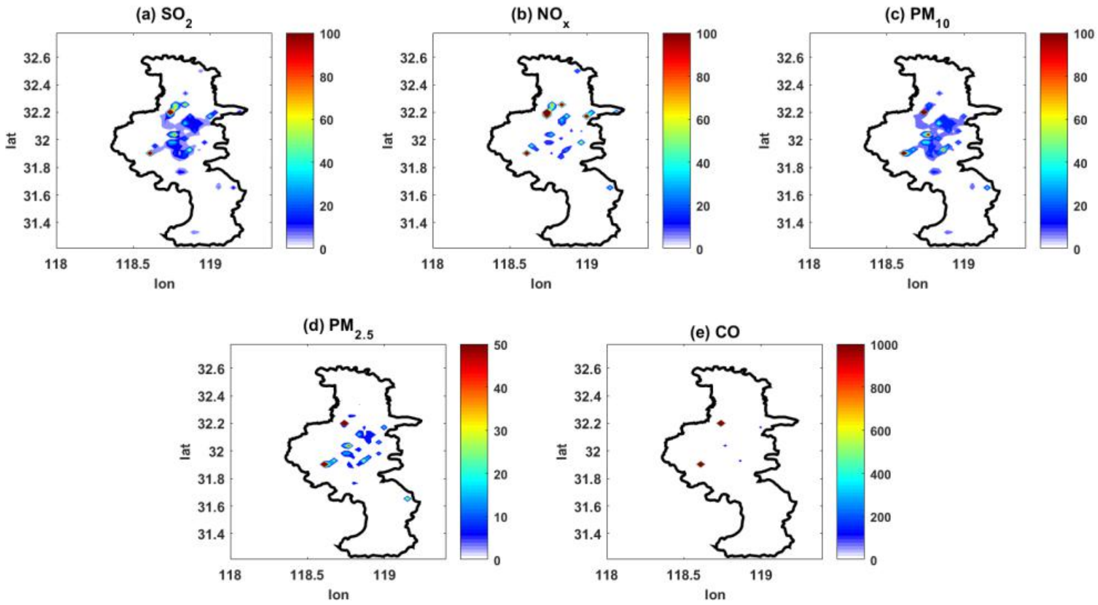

Fig. 2. Emission reduction in domain 4 ((a) SO_2, (b) NO_X, (c) PM_{10}, (d) $PM_{2.5}$, (e) CO (unit: t/month)).

The simulated period was from 27 Jul. to 1 Sept. (China standard time, CST), but only the holding month (1 Aug. to 31 Aug.) was focused on for discussion. In order to better understand the influence of meteorological factors and emission abatement, three experiments were carried out. Exp. 1 used the weather conditions during Aug. 2014 (CST) and the emission inventory after reduction. Exp. 2 used the same weather conditions as Exp. 1 with the emission inventory before reduction. Exp. 3 used the same inventory as Exp. 2 and the weather conditions during Aug. 2013 (CST). Besides, Exp. 2 acted as the control experiment. Therefore, Exp. 1 and Exp. 2 were performed to investigate the influence of emission reduction on pollutant levels. Similarly, Exp. 2 and Exp. 3 were conducted to understand the impact of meteorology on air quality.

3 Results and discussions

3.1 Observed air quality during the YOG

In Aug. 2014, emission sources including 5 major categories were strictly reduced, and the air quality had great promotion compared to Aug. 2013. Firstly, air quality was good during the Games in accordance with China's National Ambient Air Quality Standards (NAAQS) (Ministry of Environmental Protection of the People's

Republic of China, 2012) (Fig. 3, Fig. 4). The hourly mean concentrations of pollutants at the two sites during Aug. 2014 are 11.6 μg/m^3 for SO_2, 34.0 μg/m^3 for NO_2, 57.8 μg/m^3 for PM_{10}, 39.4 μg/m^3 for $PM_{2.5}$, 0.9 mg/m^3 for CO, and 38.8 μg/m^3 for O_3. Secondly, as showed in Table 2 and Table 3, the mean concentrations of the six major species dropped by 64.7% for SO_2, 29.8% for PM_{10}, 9.8% for $PM_{2.5}$, 8.9% for CO and 31.7% for O_3 at CCM station, while 50.0% for SO_2, 18.6% for NO_2, 32.8% for PM_{10}, 4.1% for $PM_{2.5}$, and 31.7% for O_3 at XL station. Besides, the smaller standard deviation (std) of SO_2, NO_2, CO and O_3 revealed that concentrations of these air pollutants varied more steadily in Aug. 2014. Actually, the drop of pollutant concentrations could be caused mainly by meteorological conditions or emission reduction, which will be discussed based on model simulations in Section 3.2 and Section 3.3.

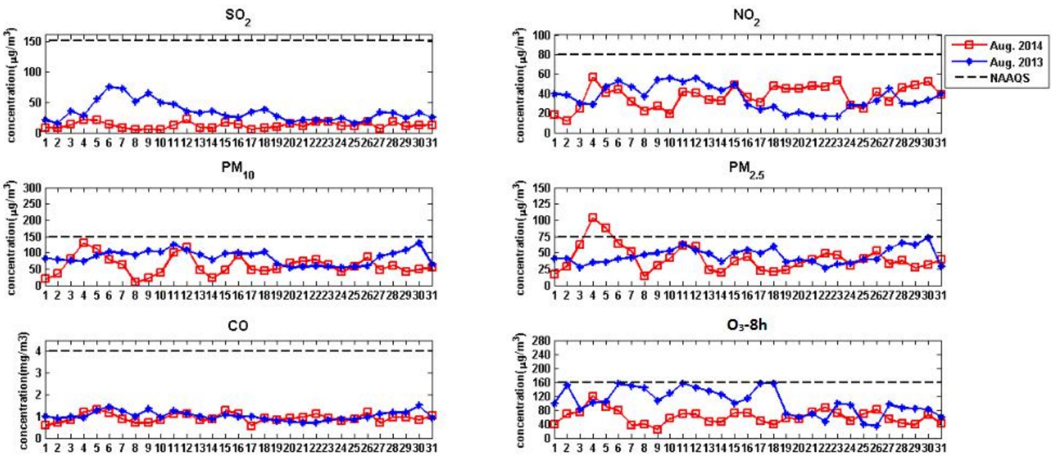

Fig. 3. Day-to-day variations in SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO and O_3-8h at CCM station in Aug. 2013 and Aug. 2014 (CST). Observed data in Aug. 2013 and Aug. 2014 are indicated in blue and red, respectively. NAAQS are indicated in black dotted line.

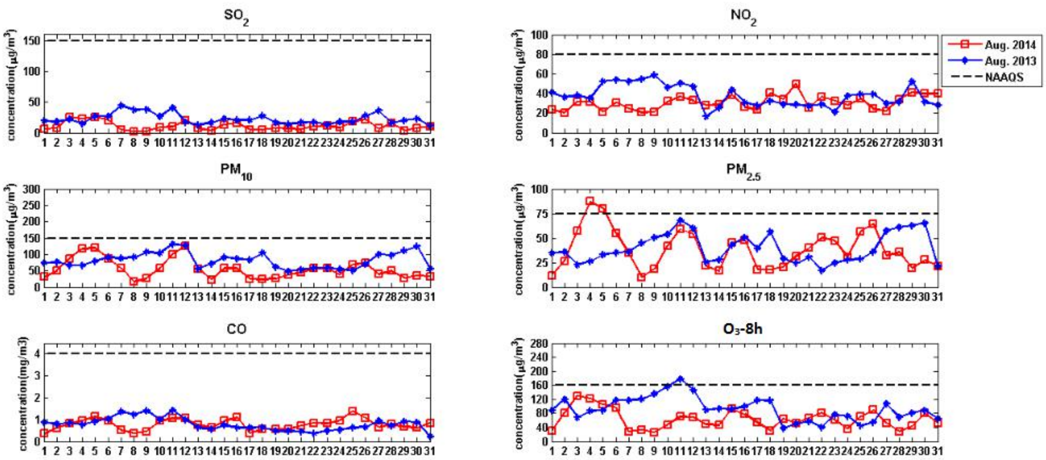

Fig. 4. Day-to-day variations in SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO and O_3-8h at XL station in Aug. 2013 and Aug. 2014 (CST). Observed data in Aug. 2013 and Aug. 2014 are indicated in blue and red, respectively. NAAQS are indicated in black dotted line.

Table 2

Statistical analysis of hourly data in Aug. 2013 and Aug. 2014 at CCM station (The unit is μg/m^3 except CO (mg/m^3))

Species	Time	Max	Min	Mean	Median	Std	Δ
SO_2	Aug. 2013	169.0	1.0	33.7	27.0	23.7	
	Aug. 2014	72.0	2.0	11.9	10.0	7.8	-64.7%
NO_2	Aug. 2013	111.0	1.0	35.4	32.0	19.4	
	Aug. 2014	110.0	1.0	37.3	35.0	18.6	5.0%
PM_{10}	Aug. 2013	213.0	19.0	86.0	84.0	29.5	
	Aug. 2014	198.0	6.0	60.4	54.0	36.6	-29.8%
$PM_{2.5}$	Aug. 2013	123.0	10.0	45.2	43.5	16.2	
	Aug. 2014	165.0	3.0	40.7	36.0	23.8	-9.8%
CO	Aug. 2013	3.1	0.4	1.0	0.9	0.4	
	Aug. 2014	2.2	0.3	0.9	0.9	0.3	-8.9%
O_3	Aug. 2013	198.0	1.0	56.9	42.0	46.2	
	Aug. 2014	150.0	9.0	38.9	34.0	22.6	-31.7%

Δ : The change percentage of species in Aug. 2014 based on Aug. 2013.

Table 3

Statistical analysis of hourly data in Aug. 2013 and Aug. 2014 at XL station (The unit is μg/m^3 except CO (mg/m^3))

Species	Time	Max	Min	Mean	Median	Std	Δ
SO_2	Aug. 2013	139.0	0.0	22.8	19.0	16.1	
	Aug. 2014	71.0	1.0	11.4	8.0	10.4	-50.0%
NO_2	Aug. 2013	129.0	0.0	37.7	32.0	21.7	

	Aug. 2014	95.0	7.0	30.7	27.0	15.0	-18.6%
PM_{10}	Aug. 2013	215.0	0.0	82.1	79.0	32.4	
	Aug. 2014	196.0	6.0	55.2	47.0	35.9	-32.8%
$PM_{2.5}$	Aug. 2013	122.0	0.0	39.7	37.5	18.9	
	Aug. 2014	157.0	3.0	38.0	34.0	24.1	-4.1%
CO	Aug. 2013	3.2	0.0	0.8	0.7	0.4	
	Aug. 2014	2.0	0.3	0.8	0.7	0.3	<0.1%
O_3	Aug. 2013	193.0	0.0	56.6	44.0	37.5	
	Aug. 2014	148.0	2.0	38.7	32.0	28.3	-31.7%

Δ : The change percentage of species in Aug. 2014 based on Aug. 2013.

Analogously, when comparing the observational data in Aug. 2014 with that in Jul. and Sept. 2014 (the months before and after the most aggressive abatement), the concentrations of most species also decreased obviously. As presented in Fig. 5 and Fig. 6, without abatement, NO_2, PM_{10}, $PM_{2.5}$ and O_3 were likely to exceed NAAQS, especially for $PM_{2.5}$ and O_3. As shown in Table 4 and Table 5, compared with Jul. 2014, the concentration of NO_2, PM_{10}, $PM_{2.5}$, CO and O_3 dropped by 0.7%, 31.8%, 33.7%, 1.1%, and 52.8%, respectively at CCM station in Aug. 2014, while the concentration of SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO and O_3 decreased by 15.8%, 39.6%, 34.6%, 7.1%, and 50.7%, respectively at XL station in Aug. 2014. Without emission control, the concentration of air pollutants rebounded in Sept. 2014. Compared to Aug., the concentration of SO_2, NO_2, PM_{10}, $PM_{2.5}$ and O_3 increased by 37.4%, 19.8%, 37.6%, 22.3%, and 47.2%, respectively at CCM station in Sept. 2014 (Table 4), while the concentration of SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO and O_3 increased by 24.6%, 21.8%, 28.7%, 17.7%, 4.9%, and 39.9%, respectively at XL station in Sept. 2014 (Table 5). In addition, for most species, the standard deviation was the lowest in Aug., which meant that the potential of extreme events was the least in Aug.. Assume that the weather conditions in Jul., Aug., Sept., 2014 were nearly similar, it can be estimated that emission sources could be the major impact factor of explaining the concentration changes during the three months. These results proved that concentrations of most species decreased and had less potential in extreme events after aggressive emission abatement. However, the concentration became higher without emission control.

Section 3.3 would further discuss the change of pollutant concentration with and without emission reduction based on model simulation.

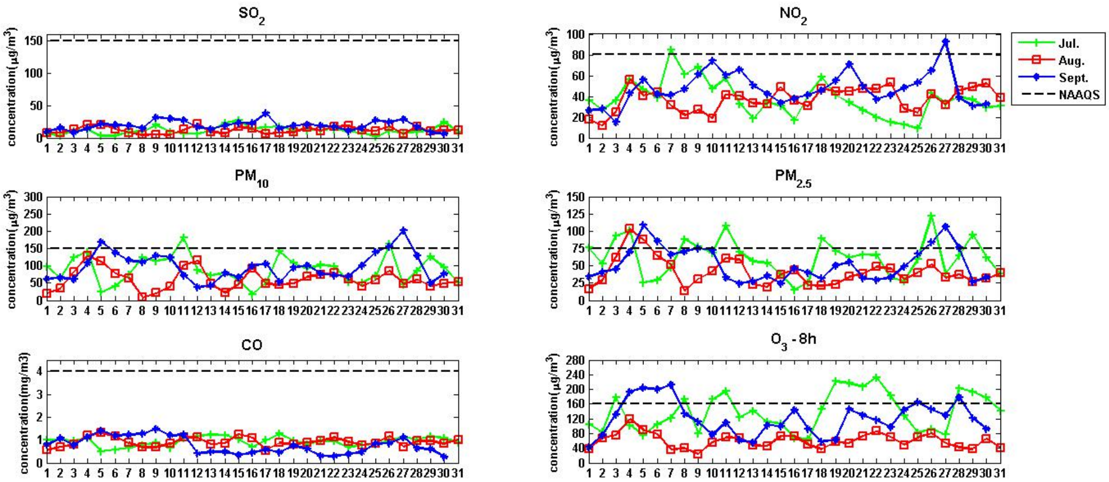

Fig. 5. Day-to-day variations in SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO and O_3-8h at CCM station in Jul., Aug. and Sept. 2014 (CST). Observed data in Jul., Aug. and Sept. 2014 are indicated in green, red and blue, respectively. NAAQS are indicated in black dotted line.

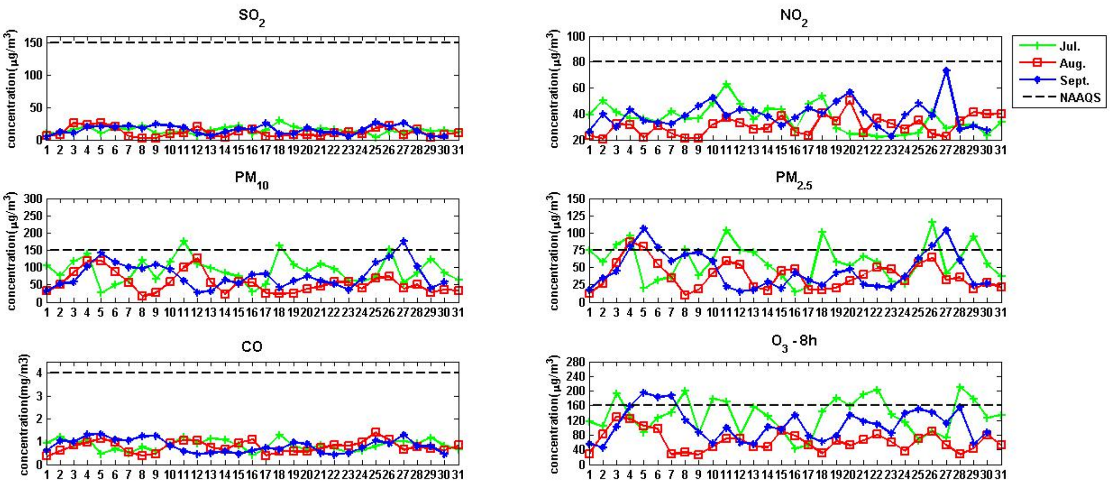

Fig. 6. Day-to-day variations in SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO and O_3-8h at XL station in Jul., Aug. and Sept. 2014 (CST). Observed data in Jul., Aug. and Sept. 2014 are indicated in green, red and blue, respectively. NAAQS are indicated in black dotted line.

Table 4

Statistical analysis of hourly data in Jul. - Sept. 2014 at CCM station (The unit is μg/m^3 except CO (mg/m^3))

Species	Month	Max	Min	Mean	Median	Std	Δa	Δb

	Jul. 2014	83.0	1.0	11.3	9.0	9.8		
SO_2	Aug. 2014	72.0	2.0	11.9	10.0	7.8	5.1%	-37.4%
	Sept. 2014	70.0	4.0	19.0	18.0	9.9		
	Jul.-Sept. 2014	83.0	1.0	14.0	12.0	9.8		
	Jul. 2014	161.0	1.0	37.5	32.0	28.3		
NO_2	Aug. 2014	110.0	1.0	37.3	35.0	18.6	-0.7%	-19.8%
	Sept. 2014	151.0	8.0	46.5	42.0	24.5		
	Jul.-Sept. 2014	161.0	1.0	40.2	37.0	24.4		
	Jul. 2014	255.0	6.0	88.5	88.0	50.7		
PM_{10}	Aug. 2014	198.0	6.0	60.4	54.0	36.6	-31.8%	-37.6%
	Sept. 2014	243.0	6.0	96.7	90.0	45.8		
	Jul.-Sept. 2014	255.0	6.0	81.7	76.0	47.4		
	Jul. 2014	171.0	1.0	61.5	58.0	33.9		
$PM_{2.5}$	Aug. 2014	165.0	3.0	40.7	36.0	23.8	-33.7%	-22.3%
	Sept. 2014	143.0	3.0	52.4	46.0	27.2		
	Jul.-Sept. 2014	171.0	1.0	51.5	45.0	29.9		
	Jul. 2014	2.7	0.2	0.9	0.9	0.3		
CO	Aug. 2014	2.2	0.3	0.9	0.9	0.3	-1.1%	21.1%
	Sept. 2014	2.1	0.1	0.8	0.7	0.4		
	Jul.-Sept. 2014	2.7	0.1	0.9	0.8	0.4		
	Jul. 2014	281.0	4.0	82.4	69.0	57.6		
O_3	Aug. 2014	150.0	9.0	38.9	34.0	22.6	-52.8%	-47.2%
	Sept. 2014	240.0	6.0	73.6	61.0	49.2		
	Jul.-Sept. 2014	281.0	4.0	64.7	51.0	49.3		

Δa: The change percentage of species in Aug.2014 based on Jul. 2014.

Δb: The change percentage of species in Aug. 2014 based on Sept. 2014.

Table 5

Statistical analysis of hourly data in Jul. - Sept.2014 at XL station (The unit is μg/m^3 except CO (mg/m^3))

Species	Month	Max	Min	Mean	Median	Std	Δa	Δb
	Jul. 2014	61.0	1.0	14.5	12.0	10.3		
SO_2	Aug. 2014	71.0	1.0	11.4	8.0	10.4	-21.2%	-24.6%
	Sept. 2014	75.0	1.0	15.1	14.0	10.3		
	Jul.-Sept. 2014	75.0	1.0	13.7	11.0	10.4		
	Jul. 2014	123.0	9.0	36.4	33.0	18.9		
NO_2	Aug. 2014	95.0	7.0	30.7	27.0	15.0	-15.8%	-21.8%
	Sept. 2014	127.0	11.0	39.2	36.0	18.7		
	Jul.-Sept. 2014	127.0	7.0	35.4	32.0	18.0		
	Jul. 2014	300.0	4.0	91.3	85.0	48.9		

PM_{10}	Aug. 2014	196.0	6.0	55.2	47.0	35.9	-39.6%	-28.7%
	Sept. 2014	226.0	9.0	77.3	70.0	40.3		
	Jul.-Sept. 2014	300.0	4.0	74.5	64.0	44.6		
	Jul. 2014	158.0	2.0	58.2	51.0	34.8		
$PM_{2.5}$	Aug. 2014	157.0	3.0	38.0	34.0	24.1	-34.6%	-17.7%
	Sept. 2014	144.0	3.0	46.2	38.0	29.0		
	Jul.-Sept. 2014	158.0	2.0	47.4	40.5	30.7		
	Jul. 2014	2.0	0.3	0.8	0.8	0.4		
CO	Aug. 2014	2.0	0.3	0.8	0.7	0.3	-7.1%	-4.9%
	Sept. 2014	2.8	0.3	0.8	0.7	0.4		
	Jul.-Sept. 2014	2.8	0.3	0.8	0.7	0.4		
	Jul. 2014	238.0	2.0	78.4	67.0	55.6		
O_3	Aug. 2014	148.0	2.0	38.7	32.0	28.3	-50.7%	-39.9%
	Sept. 2014	226.0	2.0	64.4	54.0	46.4		
	Jul.-Sept. 2014	238.0	2.0	60.3	48.0	47.7		

Δa: The change percentage of species in Aug.2014 based on Jul. 2014.

Δb: The change percentage of species in Aug. 2014 based on Sept. 2014.

3.2 Simulated impact of meteorological conditions

In this paper, the model configurations were the same as those set by Shu et al. (2016), who has evaluated the model performance of WRF/CMAQ and proved the model's reliability in simulating air quality in Nanjing.

As we know, meteorology is an important impact factor on air quality. Good diffusion conditions can alleviate air pollution in the short term (Cermak and Knutti, 2009; Wang et al., 2009b). In this premise, if two experiments (Exp. 2 and Exp. 3) use the same emission inventory but different weather conditions, it can be concluded that the higher concentrations may result from poor meteorological conditions. According to model simulation, Exp. 2 exhibited higher pollutant concentrations for all species in most part of Nanjing as shown in Fig. 7. For SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO, and O_3, their concentrations were increased by 17.5%, 16.9%, 18.5%, 18.8%, 7.8% and 0.8% during Aug. 2014 compared to Aug. 2013. Additionally, the contributions of meteorological conditions to primary and secondary particulate matters differed (See Fig. 8). Secondary PM_{10} (PM_{10s}) was raised by 21.5%, while primary PM_{10} (PM_{10p}) rose by 12.6% during Aug. 2014 compared to Aug. 2013. And secondary $PM_{2.5}$

($PM_{2.5s}$) was increased by 21.5%, while primary $PM_{2.5}$ ($PM_{2.5p}$) was enhanced by 9.5%. Thus, the weather conditions had a slightly greater impact on secondary fine particulate matters. Moreover, for SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO, PM_{10p}, PM_{10s}, $PM_{2.5p}$, and $PM_{2.5s}$, there were some small decreasing areas in the northeast Nanjing (Fig. 7 and Fig. 8). In domain 4, the simulated predominant wind was northeast wind in Aug. 2014, while that was southeast wind in Aug. 2013. So, the diffusion condition of northeast Nanjing might be better in Aug. 2014 and resulted in small decrease in these areas.

The overall increasing pollutant levels in Aug. 2014 suggested that the diffusion conditions in Aug. 2014 were worse than those in Aug. 2013. Focus on the weather conditions during the YOG holding period (16-28 Aug., 2014) and the same period in 2013, the simulated hourly mean 10-m wind speed in Nanjing was 1.5 m/s larger in 16-28 Aug., 2013 than that of 16-28 Aug., 2014 (Fig. 9). Also, the simulated 2-m temperature was 2.0 K higher in 16-28 Aug., 2013 than that of 16-28 Aug., 2014 (Fig. 9). Also, the simulated planetary boundary layer height (PBLH) was higher in Aug. 2013, especially in 16-28 Aug., and it was 27.5 m higher than that of 16-28 Aug., 2014 (Fig. 9). Larger wind speed and higher PBLH benefited the diffusion of air pollutants. Warming on the ground surface was conductive to the promotion of convective instability and was also good for the vertical dilution and diffusion of pollutant. Thus, the diffusion conditions in 16-28 Aug. 2013 were better than those in 16-28 Aug. 2014. Rather worse meteorological conditions in 16-28 Aug. 2014 implied that abatement controls might play a more important role in improving air quality in YOG compared with the same period in 2013. What's more, relative humidity, cloud cover and shortwave solar radiation all affect ozone chemical reaction (Katragkou et al., 2011; Pu et al., 2017). The generation and photochemical reaction of surface ozone depends on the availability of solar radiation. During the heat wave period, less relative humidity leads to less cloud cover, which could result in more net downward shortwave solar radiation and more production of O_3 (Pu et al., 2017). For ordinary O_3, its production also corresponded well to the cloud cover. As shown in Fig. 9, more relative humidity resulted in more cloud cover in northern and eastern Nanjing during

16-28 Aug., 2013, which resulted in less O_3 in Aug. 2013, but more O_3 in Aug. 2014 (Fig. 7).

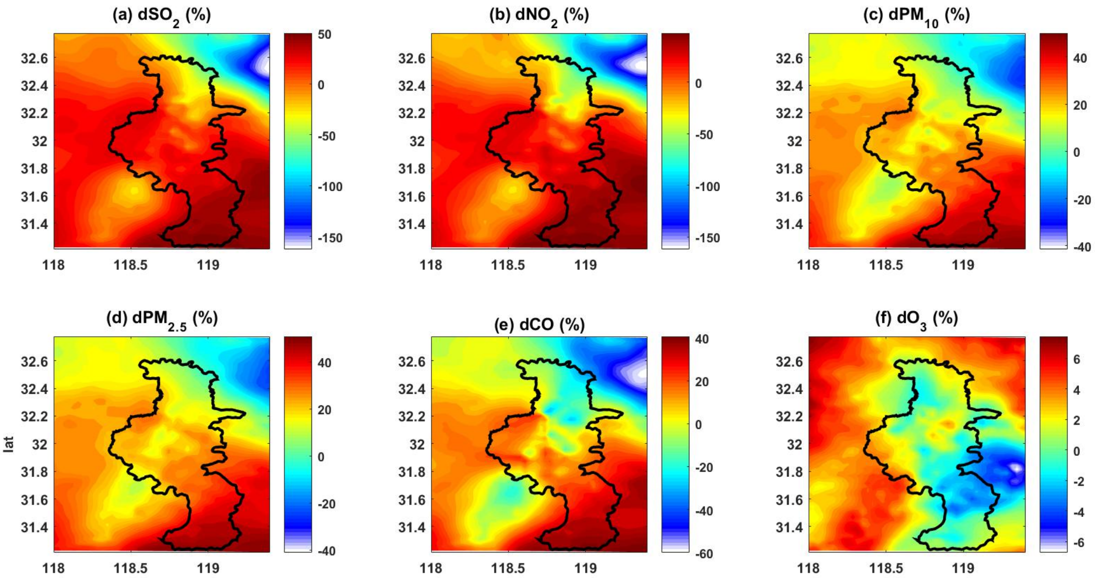

Fig. 7. Influence of meteorology on hourly mean concentrations of air pollutants in Aug. 2014 compared with Aug. 2013. (Black thick lines draw the outline of Nanjing. Picture a - f are hourly average values of impact percentage (dspecies (%)= (Exp. 2 - Exp. 3)/Exp. 2 * 100%) of SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO, and O_3, respectively.).

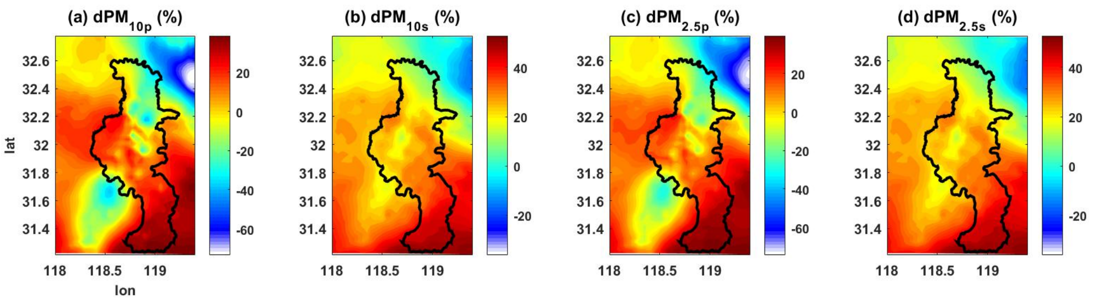

Fig. 8. Influence of meteorology on hourly mean concentrations of primary and secondary particulate matters in Aug. 2014 compared with Aug. 2013. (Black thick lines draw the outline of Nanjing. Picture a - d are hourly average values of impact percentage (dspecies (%)= (Exp. 2 - Exp. 3)/Exp. 2 * 100%) of PM_{10p}, PM_{10s}, $PM_{2.5p}$, and $PM_{2.5s}$, respectively.)

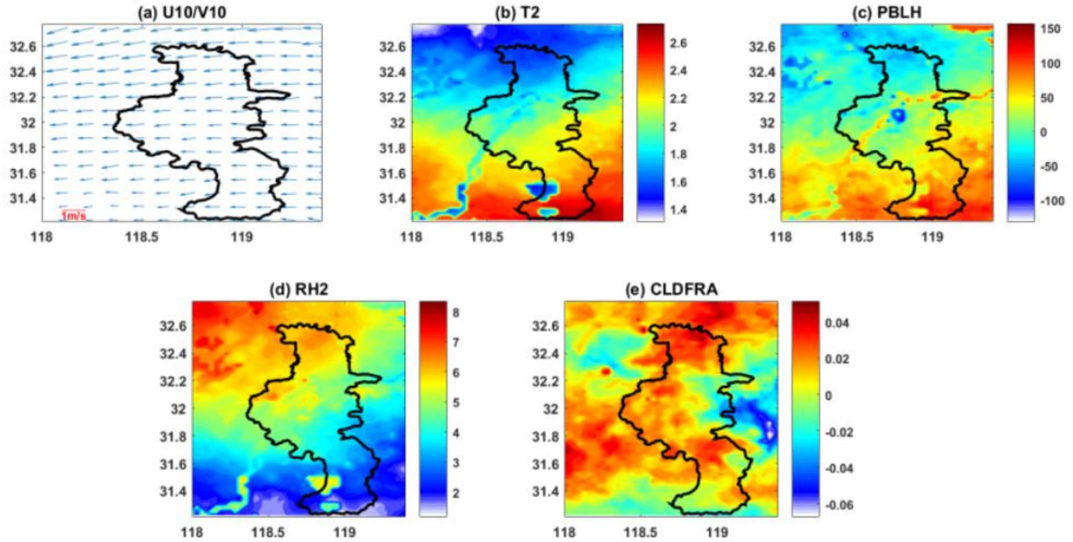

Fig. 9. Bias of simulated hourly mean meteorological conditions during the YOG. (Bias = Meteorological Factors in 16-28 Aug., 2013 - Meteorological Factors in 16-28 Aug., 2014. (a) Bias of Wind at 10m during 16-28 Aug. (unit: m/s), (b) Bias of temperature at 2m during 16-28 Aug. (unit: K), (c) Bias of planetary boundary layer height during 16-28 Aug. (unit: m), (d) Bias of relative humidity at 2m during 16-28 Aug. (unit: %), (e) Bias of cloud fraction during 16-28 Aug.).

3.3 Simulated impact of emission reduction

As for SO_2, NO_2, PM_{10}, $PM_{2.5}$, and CO, the distributions of such short-lived chemical compositions are largely affected by their sources and sinks. As seen in Fig. 10, the simulated spatial distributions of concentration changes were uneven, large variations were found in the west of Nanjing corresponding to the downwind regions of heavy reduction districts (See Fig. 2). Impact percentages (dspecies (%) = (Exp. 1 - Exp. 2)/ Exp. 2*100%) of species were negative except O_3, implying that emission regulatory efforts were effective on the other species, but counterproductive to O_3. Statistically, the concentrations of SO_2, NO_2, PM_{10}, $PM_{2.5}$, and CO in Nanjing were reduced by 24.6%, 12.1%, 15.1%, 8.1% and 7.2% during Aug. 2014. As for O_3, the variation was positive (1.3%), especially in the downwind area of NO_x with heavy reduction, which might due to the less titration of O_3 by NO_x (Liu et al., 2013; Dong et al., 2013). For primary and secondary particulate matters, the influence of emission reduction varied dramatically. As shown in Fig. 11, PM_{10p} was dropped by 39.6%, while PM_{10s} only declined by 2.9%. And $PM_{2.5p}$ was decreased by 26.2%, while $PM_{2.5s}$ merely cut down by 2.9%. It seems that emission controls had much more impacts on primary pollutants, especially on coarse particulate matters.

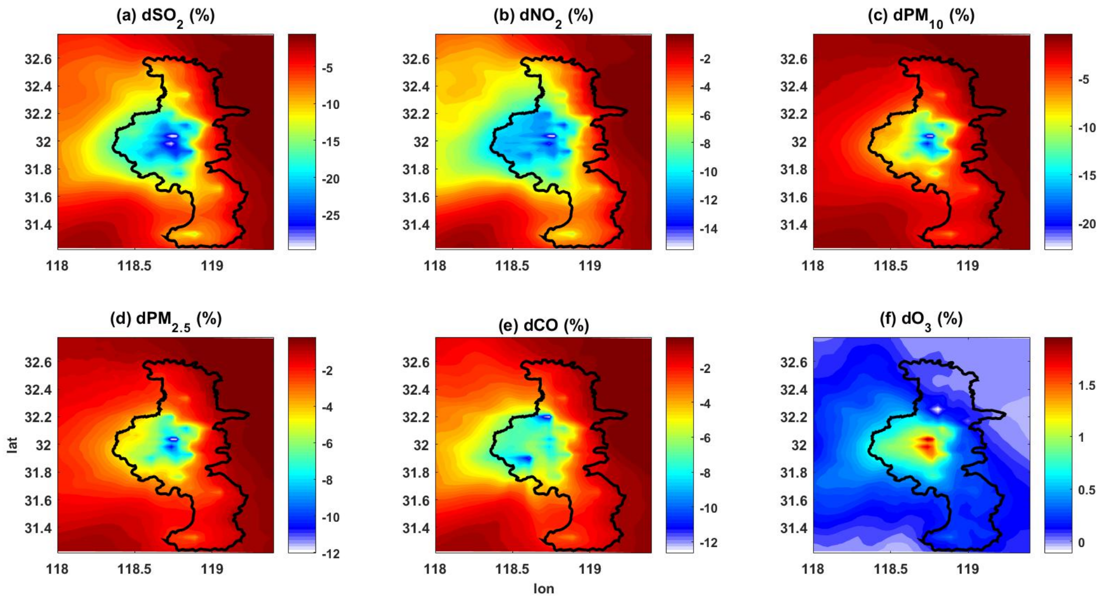

Fig. 10. Influence of emission reduction on hourly mean concentrations of air pollutants in Aug. 2014. (Black thick lines draw the outline of Nanjing. Picture a - f are hourly average values of impact percentage (dspecies (%) = (Exp. 1 - Exp. 2)/ Exp. 2*100%) of SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO and O_3, respectively.).

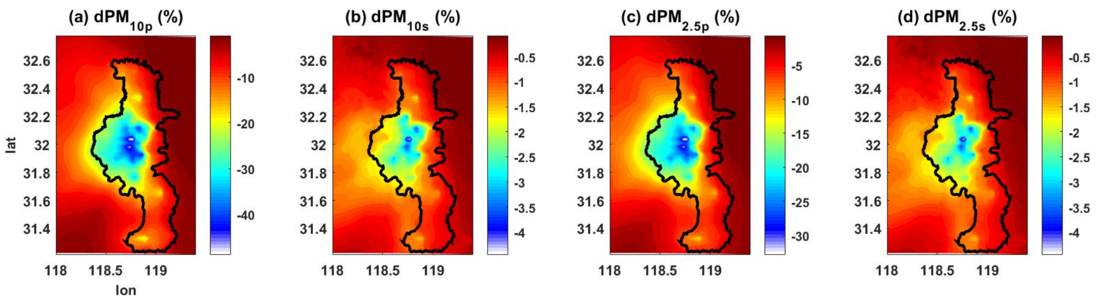

Fig. 11. Influence of emission reduction on hourly mean concentrations of primary and secondary particulate matters in Aug. 2014. (Black thick lines draw the outline of Nanjing. Picture a - d are hourly average values of impact percentage (dspecies (%) = (Exp. 1 - Exp. 2)/ Exp. 2*100%) of PM_{10p}, PM_{10s}, $PM_{2.5p}$ and $PM_{2.5s}$, respectively.).

3.4 Comparison of simulated meteorological factors and emission reduction

Fig. 12 displays the simulated effect of meteorological factors and emission reduction in Nanjing on air quality improvement during Aug. 2014. In general, meteorological conditions played a negative role in air quality promotion in most days, only played a positive role in a few days (See discussion in Section 3.2). On the other hand, emission reduction contributed to the decline of SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO, PM_{10p}, PM_{10s}, $PM_{2.5p}$, and $PM_{2.5s}$ all the time, especially for primary coarse particulate matters. However, reduction of NO_x could cause a slight rise of O_3.

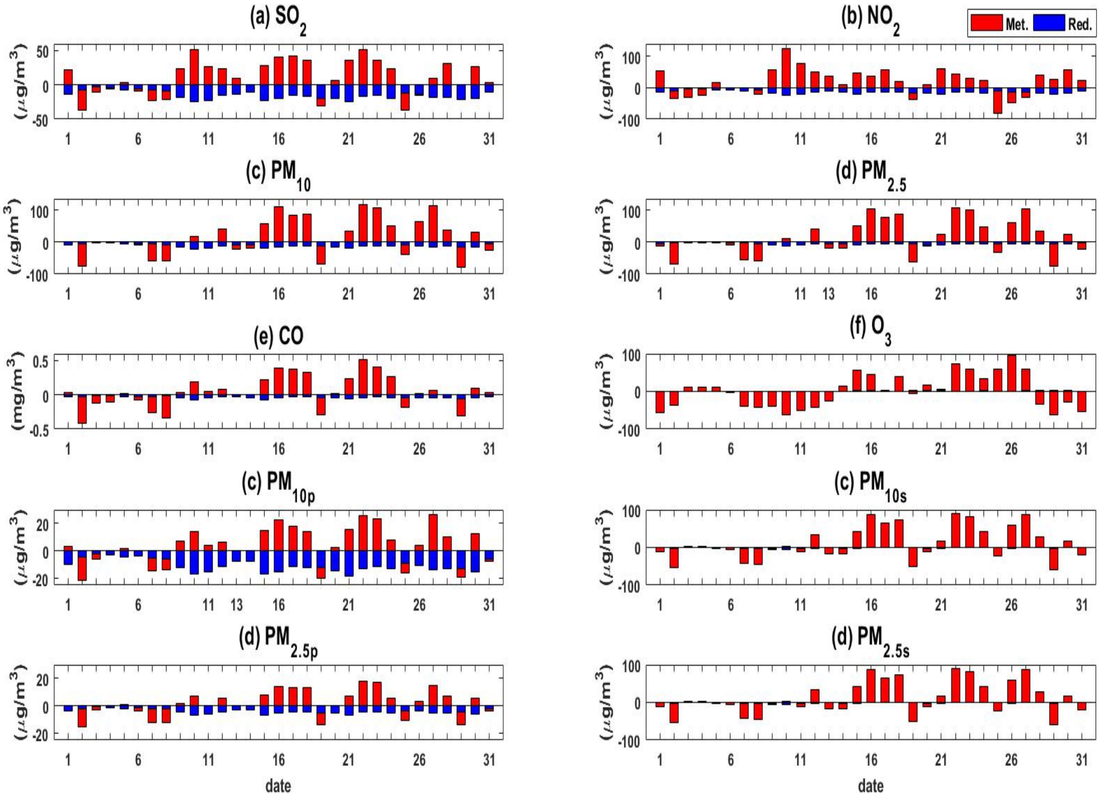

Fig. 12. The simulated effect of meteorology and emission reduction on pollutant concentrations in Nanjing during 1-31 Aug. , 2014, Met. (Exp. 2-Exp. 3) represents the effect of meteorology, while Red. (Exp. 1-Exp. 2) represents the simulated effect of emission reduction.

The opposite effects of meteorology and emission abatement on SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO, PM_{10p}, PM_{10s}, $PM_{2.5p}$ and $PM_{2.5s}$ during the whole month were significant as statistically listed in Table 6. CCM station represents the urban status, XL station represents the suburban status and NJ represents the whole city. Adverse meteorological condition was found to raise the concentrations of the six pollutants as 17.4% for SO_2, 15.1% for NO_2, 15.6% for PM_{10}, 14.9% for $PM_{2.5}$, 6.4% for CO and 0.9% for O_3 at CCM station, and 14.1% for SO_2, 12.4% for NO_2, 22.4% for PM_{10}, 24.5% for $PM_{2.5}$, 2.3% for CO, and 1.6% for O_3 at XL station. On the contrary, emission abatement reduced their levels in most cases, especially in the urban site. It seems that the levels of air pollutants reduced more at CCM station compared to XL station. Emission abatement independently led to a 24.3% decrease in SO_2 at CCM station, which was 5.1% higher compared to XL station. Moreover, the cutbacks of NO_2, PM_{10}, $PM_{2.5}$ and CO were 11.7%, 13.9%, 7.5% and 7.0%, respectively at CCM station, being larger by 1.0% to 2.0% compared with XL station. Though O_3 under emission reduction scenarios resulted in a slightly rise (0.9% to 1.3%) at both sites, the effectiveness of emission abatement was remarkable generally. As for primary and secondary particulate matters, meteorological factors also played a negative role during Aug. 2014, and had slightly more effect on secondary fine particles. Emission controls seemed to cause tremendous impact on primary particulate matters, especially for primary coarse particles. Emission abatement led to a 38.3% decrease in PM_{10p} at CCM station, a 33.2% decrease in PM_{10p} at XL station, and a 39.6% decrease in PM_{10p} for the whole city. For secondary particulate matters, including sulfate, nitrate, and ammonium salt, emission reduction played rather minor role in cutting the pollutants, with merely a 2.4% decrease in PM_{10s} and $PM_{2.5s}$ at CCM station, a 2.9% decrease in PM_{10s} and $PM_{2.5s}$ at XL station.

Table 6

Comparison between the simulated effect of meteorology and emission reduction at CCM and XL station

Species	Met. (CCM)	Red. (CCM)	Met. (XL)	Red. (XL)	Met. (NJ)	Red. (NJ)
SO_2	17.4%	-24.3%	14.1%	-19.2%	17.5%	-24.6%
NO_2	15.1%	-11.7%	12.4%	-10.2%	16.9%	-12.1%
PM_{10}	15.6%	-13.9%	22.4%	-11.9%	18.5%	-15.1%
$PM_{2.5}$	14.9%	-7.5%	24.5%	-6.3%	18.8%	-8.1%
CO	6.4%	-7.0%	2.3%	-5.5%	7.8%	-7.2%
O_3	0.9%	1.3%	1.6%	0.9%	0.7%	1.5%
PM_{10p}	13.2%	-38.3%	5.9%	-33.2%	12.6%	-39.6%
PM_{10s}	16.7%	-2.4%	29.4%	-2.9%	21.5%	-2.9%
$PM_{2.5p}$	8.4%	-25.8%	4.9%	-20.1%	9.5%	-26.2%
$PM_{2.5s}$	16.7%	-2.4%	29.4%	-2.9%	21.5%	-2.9%

Met.: The change percentage of species in Exp. 2 based on Exp3, represents the effect of meteorology.
Red.: The change percentage of species in Exp. 1 based on Exp 2, represents the effect of Nanjing local emission reduction.

The decrease of SO_2 might result from the limit and halt of power plants and improvement of coal-combustion. The prohibition of heavy pollution vehicles could contribute to the drop of NO_2 and CO. Also, limiting the production of industries helped to reduce NO_2 and CO. The cut of particulate matters might be attributable to the stop of construction process and use of low ash content coal for industry. For secondary particulate matters, controlling the emission of SO_2 and NO_x could help to reduce the formation of sulfate and nitrate, but no control on the emission of NH_3 could still result in quite a part of ammonium salt. The response of O_3 to emission control could be due to its non-linearity chemistry (Fu et al., 2012), reducing NO_2 may have side-effect by increasing O_3 because of the titration effect. On the whole, the meteorological factors and emission reduction during the YOG had opposite effects on SO_2, NO_2, PM_{10}, $PM_{2.5}$, and CO, and emission reduction indeed played a very important role in the air quality improvement.

4 Summary and conclusions

The air quality during the 2nd YOG was superior according to the current NAAQS. Both observation and modeling confirmed that stringent emission reductions were effective to ambient air quality promotion during the Youth Olympic Games, especially to SO_2, NO_2, PM_{10}, $PM_{2.5}$ and CO. Compared to Aug. 2013, the observed concentrations in Aug. 2014 were dropped by 64.7% for SO_2, 29.8% for PM_{10}, 9.8% for $PM_{2.5}$, 8.9% for CO and 31.7% for O_3 at CCM station, while 50.0% for SO_2, 18.6% for NO_2, 32.8% for PM_{10}, 4.1% for $PM_{2.5}$, and 31.7% for O_3 at XL station. The simulated impact percentage of emission reductions were -24.6%, -12.1%, -15.1%, -8.1% and -7.2% for SO_2, NO_2, PM_{10}, $PM_{2.5}$, and CO, respectively.

The meteorological conditions in the holding time of the YOG were inferior to those of the same period in 2013, with lower temperature and weaker winds. Model simulations show that unfavorable weather conditions caused higher concentrations for all species, including O_3 which was increased due to less cloud cover. Besides, meteorological conditions had slightly more effect on secondary fine particular matters compared to primary fine particular matters. Emission reduction could cut down the levels of SO_2, NO_2, CO and particular matters, especially for primary coarse particles. Thus, emission reduction control is the very important factor for the air quality improvement during the YOG.

In general, better air quality during the YOG benefit a lot from emission reduction, which has set up a good example in air protection for important social events. However, the enhanced concentrations of air pollutants after the YOG (in Sept. 2014) suggest that short-term emission control can only ease air pollution effectively and temporarily. Long-term control policies are necessary to ensure pleasant future air quality.

5 Data availability

The air quality monitoring records are available at http://222.190.111.117:8023/. The Multi-resolution Emission Inventory for China (MEIC) is available at http://www.meicmodel.org/. The WRF model is available at http://www2.mmm.ucar.edu/wrf/users/downloads.html. The CMAQ model is available at https://www.cmascenter.org/cmaq/.

Competing interests. The authors declare that they have no conflict of interest.

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