# 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 pollution emissions. However, air quality can still be affected by synoptic weather. 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 hourly mean observational concentration of $SO_2$, $NO_2$, $PM_{10}$, $PM_{2.5}$, CO and $O_3$ was 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. 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%, 19.0%, 19.5%, 7.8% and 0.8%, respectively. Taking account of local emission abatement only, simulated $SO_2$, $NO_2$, $PM_{10}$, $PM_{2.5}$ and CO was decreased by 24.6%, 12.1%, 14.8%, 7.3% and 7.2%, respectively. Consequently, stringent emission control measures can reduce the concentrations of air pollutants in short term, and emission reduction is the dominant factor of 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 stringent environmental quality assurance work plan 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 heavy pollution vehicles called “yellow label buses” were prohibited in Nanjing during 10-28 Aug.. Oil loading and unloading operations were strictly controlled. Construction process was forced to stop.

It is well known that air quality can be affected by both meteorological factors and pollutant emissions. Many cases verified that both emission abatement efforts and weather conditions do influence the air quality improvement. 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 transportation control measures 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 as 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 compared 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 cut down anthropogenic emissions could increase $PM_{2.5}$ 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 construction dust contributes the most in coarse particles, and 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 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 YOG with those a year ago 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 dominant factor of the air quality promotion during 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 from Nanjing Environmental Monitoring Center (http://222.190.111.117:8023/). Both of the two stations are state controlling air sampling 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. Here 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 research 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. And there is no traffic congestion problem in Qixia District. 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 research. 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 atmospheric complicated physical and chemical processes and the relative contribution of different species (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 (Skamarocket al., 2008) model was run to provide meteorology fields for CMAQ. Four nested domains were set for both models, with horizontal resolutions of 81km, 27km, 9km, 3km, with the innermost domain covering Nanjing (Fig.1). For all domains, 23 vertical sigma layer 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 the research of Shu et al. (2016) and were proven to have good simulation performance. As for the innermost domain, Nanjing Municipal Environmental Protection Bureau chooses the local 9 state controlling air sampling sites (See Fig.1, Table1) to represent the whole Nanjing city. In conformity with this, the 9 state controlling air sampling sites in domain4 were chosen to represent the whole Nanjing while analyzing model simulation impacts.

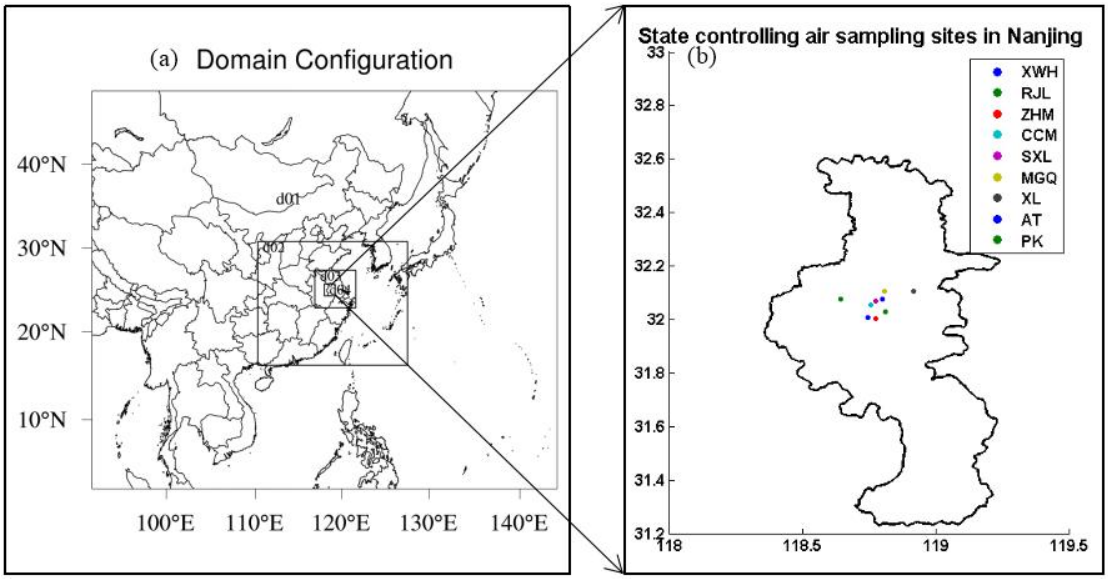

**Fig.1.** Modeling domains and state controlling air sampling sites in Nanjing. ((a) The four nested modeling domains at 81km (D01: East Asia), 27km (D02: East China), 9km (D03: Yangtze River Delta), and 3km (D04: Nanjing), (b) Locations of 9 state controlling air sampling sites in Nanjing).

**Table 1**
The air sampling sites in Nanjing

| Air sampling sites | Abbreviations | 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, form 4 sectors: industry, power plants, transportation, and residential. What's more, the innermost domain used the local emission inventory before and after emission reduction, with a horizontal resolution of 3km × 3km.

The innermost domain emission inventory before emission control was based on the local emissions in 2012 (basic emission inventory), and the emissions outside Nanjing city were from MEIC. Besides, the emissions outside Nanjing city were set the same before and after emission control in Nanjing. According to the local emission control program, we adjusted the basic emission inventory and got the emission inventory under emission control. 5 major categories: industry, power plants, traffic, VOC product-related sources and others were in the emission sources 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 during Aug. 2014. Moreover, heavy pollution vehicles were prohibited in Nanjing during 10-28 Aug. 2014 to reduce traffic pollution. 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 sources 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 were showed in Fig.2. For $SO_2$, $NO_x$, $PM_{10}$ and $PM_{2.5}$, the emission reduction area centered in the middle of Nanjing city. And for CO, the emission reduction centered in several points.

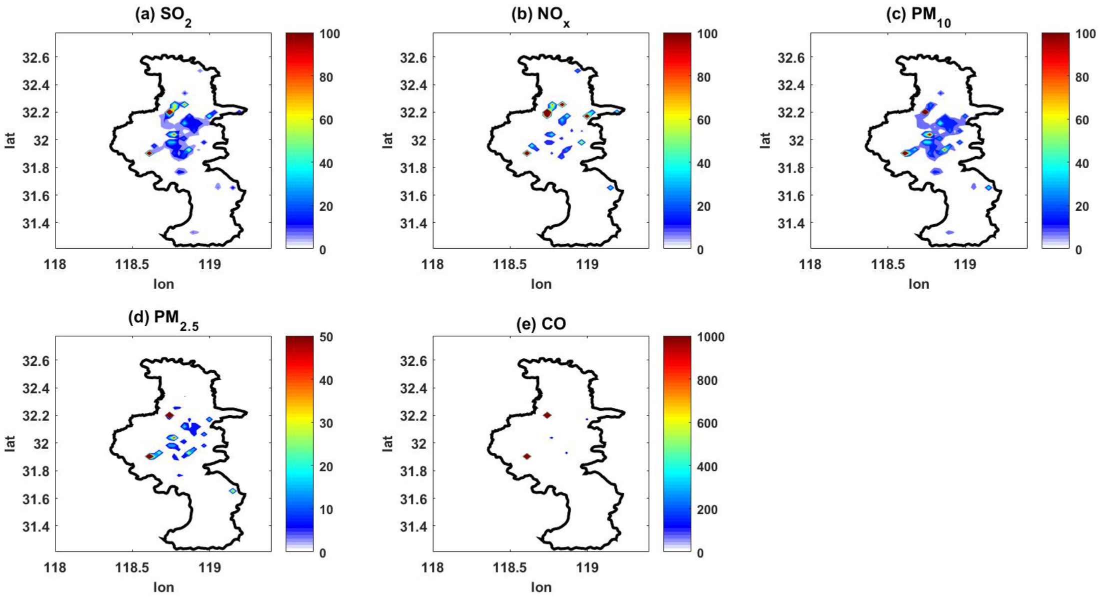

**Fig.2.** Emission reduction in domain4 ((a) $SO_2$, (b) $NO_X$, (c) $PM_{10}$, (d) $PM_{2.5}$, (e) CO (unit: t/month)).

The simulated period was from Jul. 27 to Sept. 1 (China standard time, CST), but only the holding month (1 Aug. to 31 Aug.) was focused on. 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 while Exp.2 used the same weather conditions with the emission inventory before reduction. Exp.3 had the same inventory as Exp.2 but used the weather conditions during Aug. 2013 (CST). Besides, Exp.2 acted as the control experiment. What's more, Exp.1 and Exp.2 were set to study the influence of emission reduction on pollutants only. Similarly, Exp.2 and Exp.3 were conducted to understand the impact of meteorology on air quality only.

## 3 Results and discussion

### 3.1 Observed air quality during YOG

In the most strictly emission control month Aug.2014, emission sources including 5 major categories were reduced, and the air quality had great promotion compared to Aug. 2013. Firstly, it 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 pollutant concentration of the two sites during Aug. 2014 is 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 concentration of the six major species ($SO_2$, $NO_2$, $PM_{10}$, $PM_{2.5}$, CO and $O_3$) 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. However, the drop of pollutant concentration could be caused mainly by meteorology conditions or emission reductions. And we will discuss the reason based on model simulations in Section 3.2 and Section 3.3.

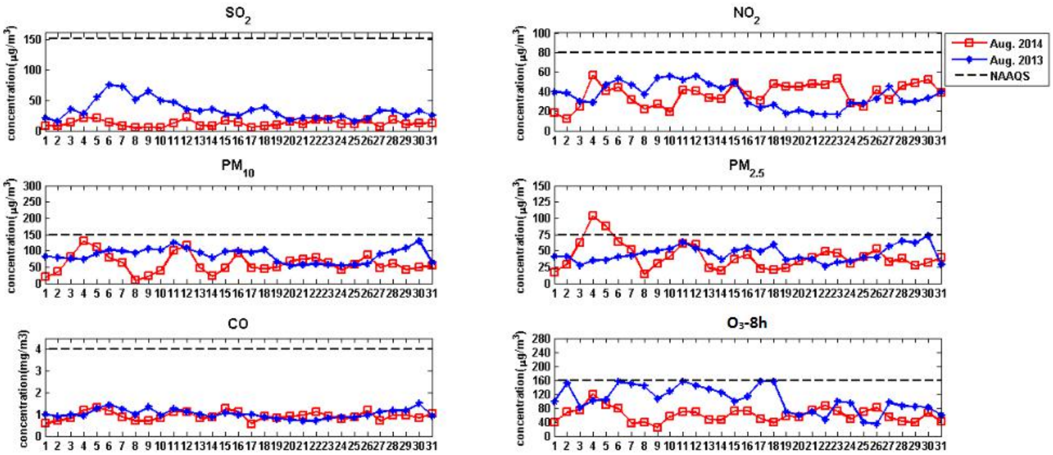

**Fig.3.** Day-to-day variations in $SO_2$, $NO_2$, $PM_{10}$, $PM_{2.5}$, CO and $O_3$-8h at CCM station in Aug. 2013 and Aug. 2014 (CST). Observed data in Aug. 2013 are indicated in blue. Observed data in Aug.2014 are indicated in red. NAAQS are indicated in black dotted line.

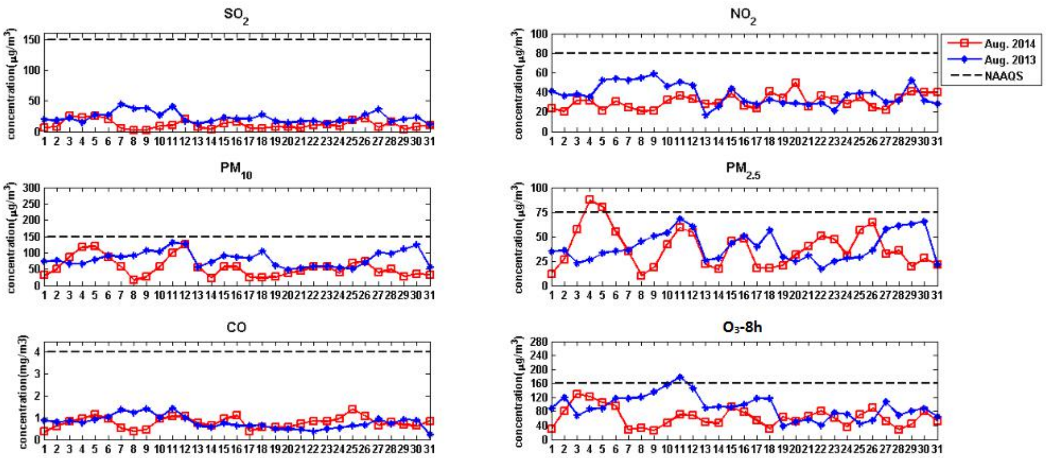

**Fig.4.** Day-to-day variations in $SO_2$, $NO_2$, $PM_{10}$, $PM_{2.5}$, CO and $O_3$-8h at XL station in Aug. 2013 and Aug. 2014 (CST). Observed data in Aug. 2013 are indicated in blue. Observed data in Aug. 2014 are indicated in red. NAAQS are indicated in black dotted line.

**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, compared 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 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 $PM_{2.5}$ and $O_3$. As shown in Table 4 and Table5, 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 with 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). Besides, 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 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, they could rebound without emission control. Besides, Section

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

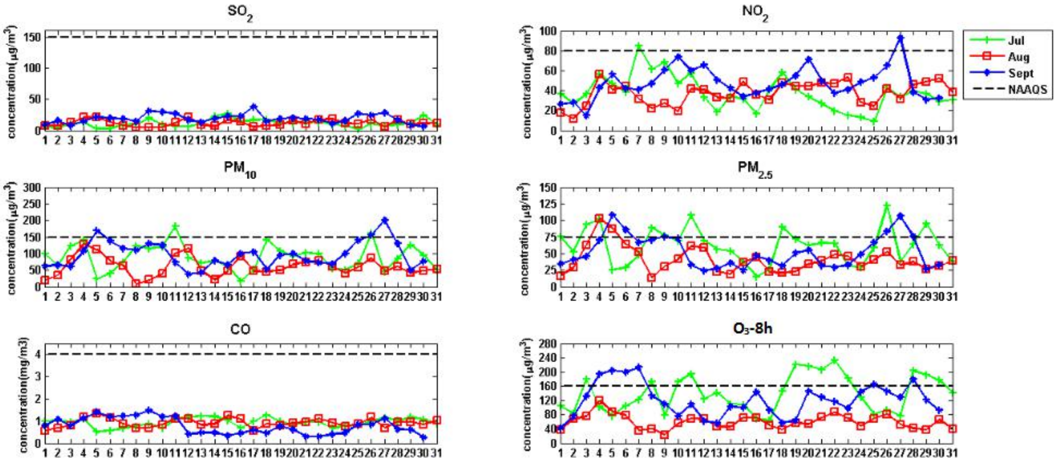

**Fig.5.** Day-to-day variations in $SO_2$, $NO_2$, $PM_{10}$, $PM_{2.5}$, CO and $O_3$-8h at CCM station in Jul., Aug. and Sept. 2014 (CST). Observed data in Jul., Aug. and Sept. 2014 are indicated in green, red and blue, respectively. NAAQS are indicated in black dotted line.

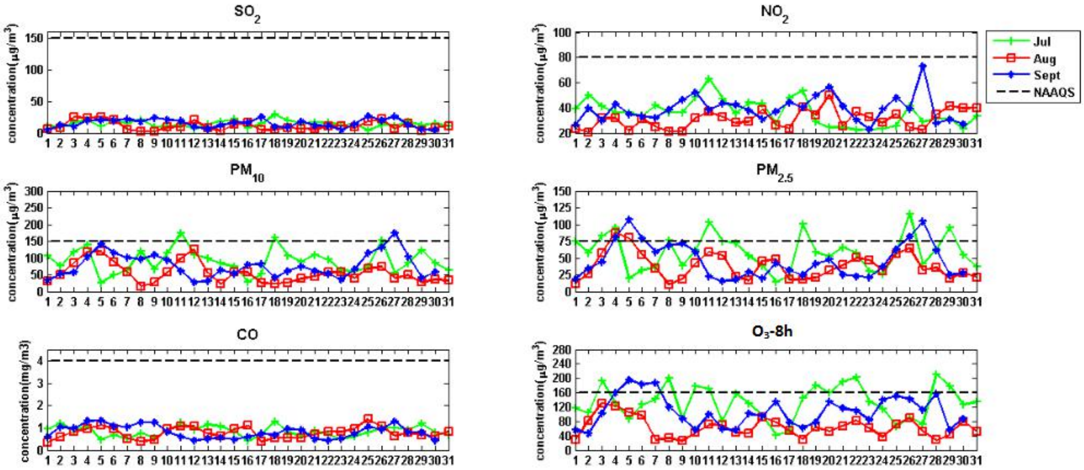

**Fig.6.** Day-to-day variations in $SO_2$, $NO_2$, $PM_{10}$, $PM_{2.5}$, CO and $O_3$-8h at XL station in Jul., Aug. and Sept. 2014 (CST). Observed data in Jul., Aug. and Sept. 2014 are indicated in green, red and blue, respectively. NAAQS are indicated in black dotted line.

**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 | | |
| $NO_2$ | Jul. 2014 | 161.0 | 1.0 | 37.5 | 32.0 | 28.3 | -0.7% | -19.8% |
| | Aug. 2014 | 110.0 | 1.0 | 37.3 | 35.0 | 18.6 | | |
| | 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 | | |
| $PM_{10}$ | Jul. 2014 | 255.0 | 6.0 | 88.5 | 88.0 | 50.7 | -31.8% | -37.6% |
| | Aug. 2014 | 198.0 | 6.0 | 60.4 | 54.0 | 36.6 | | |
| | 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 | | |
| $PM_{2.5}$ | Jul. 2014 | 171.0 | 1.0 | 61.5 | 58.0 | 33.9 | -33.7% | -22.3% |
| | Aug. 2014 | 165.0 | 3.0 | 40.7 | 36.0 | 23.8 | | |
| | 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 | | |
| CO | Jul. 2014 | 2.7 | 0.2 | 0.9 | 0.9 | 0.3 | -1.1% | 21.1% |
| | Aug. 2014 | 2.2 | 0.3 | 0.9 | 0.9 | 0.3 | | |
| | 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 | | |
| $O_3$ | Jul. 2014 | 281.0 | 4.0 | 82.4 | 69.0 | 57.6 | -52.8% | -47.2% |
| | Aug. 2014 | 150.0 | 9.0 | 38.9 | 34.0 | 22.6 | | |
| | 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 $\mu g/m^3$ except CO ($mg/m^3$) )

| species | month | max | min | mean | median | std | Δa | Δb |
|---|---|---|---|---|---|---|---|---|
| $SO_2$ | Jul. 2014 | 61.0 | 1.0 | 14.5 | 12.0 | 10.3 | -21.2% | -24.6% |
| | Aug. 2014 | 71.0 | 1.0 | 11.4 | 8.0 | 10.4 | | |
| | 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 | | |
| $NO_2$ | Jul. 2014 | 123.0 | 9.0 | 36.4 | 33.0 | 18.9 | -15.8% | -21.8% |
| | Aug. 2014 | 95.0 | 7.0 | 30.7 | 27.0 | 15.0 | | |
| | 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 | | |
| $PM_{10}$ | Jul. 2014 | 300.0 | 4.0 | 91.3 | 85.0 | 48.9 | -39.6% | -28.7% |
| | Aug. 2014 | 196.0 | 6.0 | 55.2 | 47.0 | 35.9 | | |
| | 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 | | |
| $PM_{2.5}$ | Jul. 2014 | 158.0 | 2.0 | 58.2 | 51.0 | 34.8 | -34.6% | -17.7% |
| | Aug. 2014 | 157.0 | 3.0 | 38.0 | 34.0 | 24.1 | | |
| | 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 | | |
| CO | Jul. 2014 | 2.0 | 0.3 | 0.8 | 0.8 | 0.4 | -7.1% | -4.9% |
| | Aug. 2014 | 2.0 | 0.3 | 0.8 | 0.7 | 0.3 | | |
| | 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 | | |
| $O_3$ | Jul. 2014 | 238.0 | 2.0 | 78.4 | 67.0 | 55.6 | -50.7% | -39.9% |
| | Aug. 2014 | 148.0 | 2.0 | 38.7 | 32.0 | 28.3 | | |
| | 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 | | |

### 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.

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 meteorology conditions. According to model simulation, Exp.2 exhibited higher pollutant concentrations for all species 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%, 19.0%, 19.5%, 7.8% and 0.8% during Aug. 2014 compared to Aug. 2013. That is to say, the diffusion conditions in Aug. 2014 were worse than those in Aug. 2013. The simulated hourly mean 10-m wind speed in Nanjing was larger in Aug. 2013, especially in 16-28 Aug., and it was 1.5 m/s larger than that of 16-28 Aug., 2014 (Fig.8). Also, the simulated 2-m temperature was higher in Aug. 2013, especially in 16-28 Aug., and it was 2.0 K larger than that of 16-28 Aug., 2014 (Fig.8). Besides, 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.8). Larger wind speed and higher PBLH benefited the diffusion. Warming on the ground surface was conductive to the promotion of convective instability and was also good for the dilution and diffusion of pollutant. Thus, the simulation meteorological conditions in Aug. 2013 were better than those in Aug. 2014. Rather worse meteorological conditions in Aug. 2014 implied that abatement controls might play a decisive role in improving air quality in YOG compared with the same period in 2013.

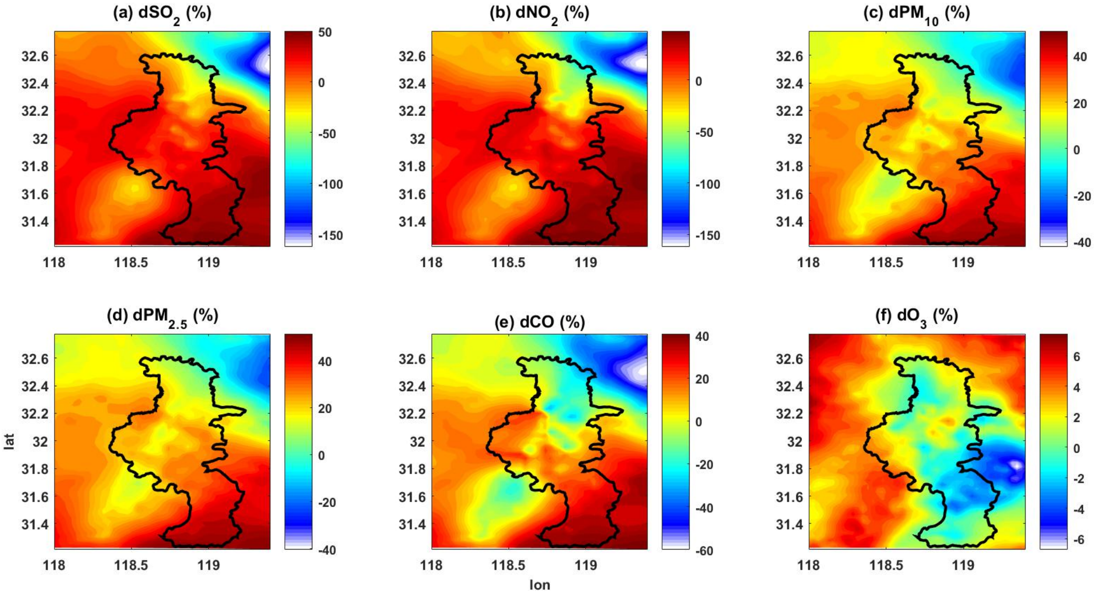

**Fig. 7.** Influence of meteorology on hourly mean concentrations of pollutants in Aug. 2014 compared with Aug. 2013. (Black thick lines draw the outline of Nanjing. Picture a - f are hourly average values of impact percentage (dspecies (%)= (Exp.2 - Exp.3)/Exp.2 * 100%) of $SO_2$, $NO_2$, $PM_{10}$,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

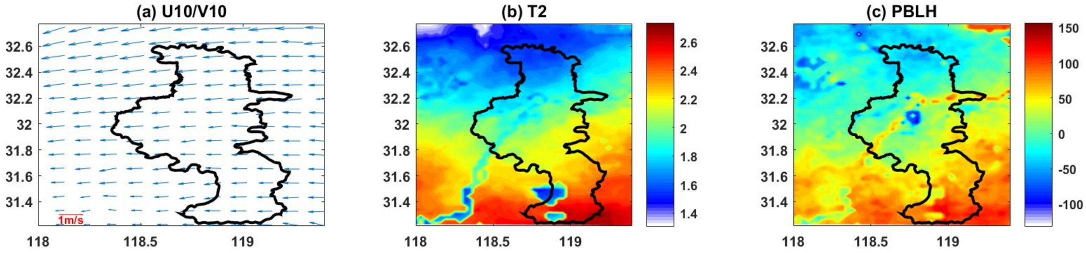

**Fig. 8.** Bias of simulated hourly mean meteorological conditions during the YOG. (Bias = Meteorological Factors in 16-28 Aug., 2013 - Meteorological Factors in 16-28 Aug., 2014. (a) Bias of Wind at 10m during 16-28 Aug. (unit: m/s), (b) Bias of temperature at 2m during 16-28 Aug. (unit: K), (c) Bias of planetary boundary layer height during 16-28 Aug. (unit: m)).

### 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 the distributions of their sources and sinks. As seen in Fig.9, 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). Besides, 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%, 14.8%, 7.3% and 7.2% during Aug. 2014. As for $O_3$, the variation was positive (1.3%), especially in the downwind area of $NO_x$ heavy reduction region, which might due to the less titration of $O_3$ by $NO_x$ (Liu et al., 2013; Dong et al., 2013).

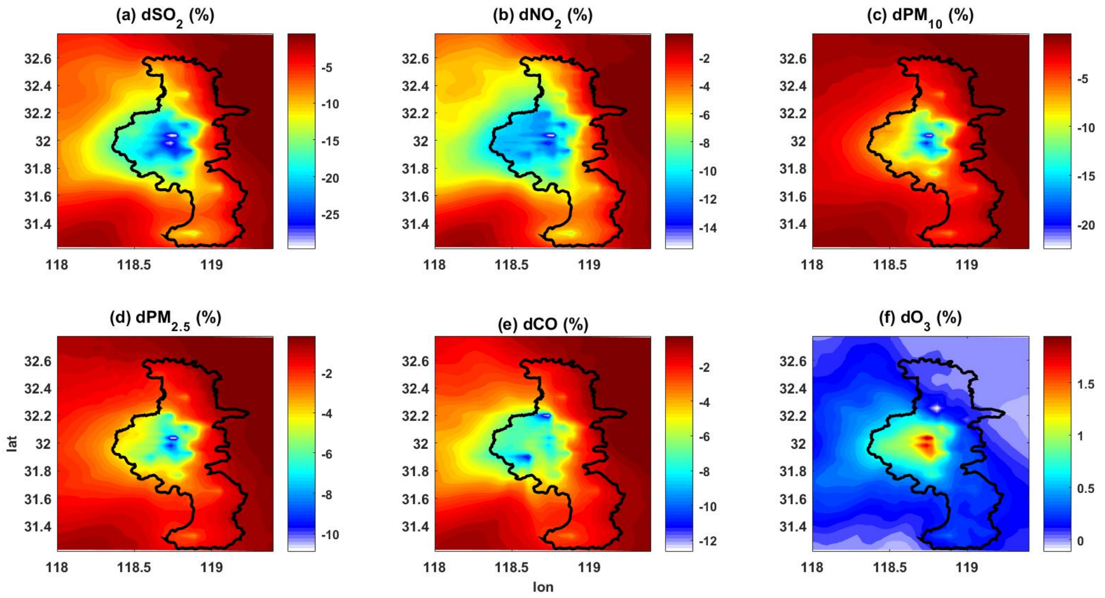

**Fig. 9.** Influence of emission reduction on hourly mean concentrations of pollutants in Aug. 2014. (Black thick lines draw the outline of Nanjing. Picture a - f are hourly average values of impact percentage (dspecies (%) = (Exp.1 - Exp.2)/ Exp.2*100%) of $SO_2$, $NO_2$, $PM_{10}$, $PM_{2.5}$, CO and $O_3$, respectively.).

### 3.4 Comparison of simulated meteorological factors and emission reduction

Fig.10 displays the simulated effect of meteorological factors and emission reduction in Nanjing on air quality improvement during YOG (16-28 Aug., 2014). Disadvantage meteorology played a negative role in air quality promotion for all of the six species in most of time, while emission reduction attributed to the decline of $SO_2$, $NO_2$, $PM_{10}$, $PM_{2.5}$, and CO, but caused a slight rise of $O_3$. This signifies that emission abatement was the crucial factor of the air quality promotion during YOG.

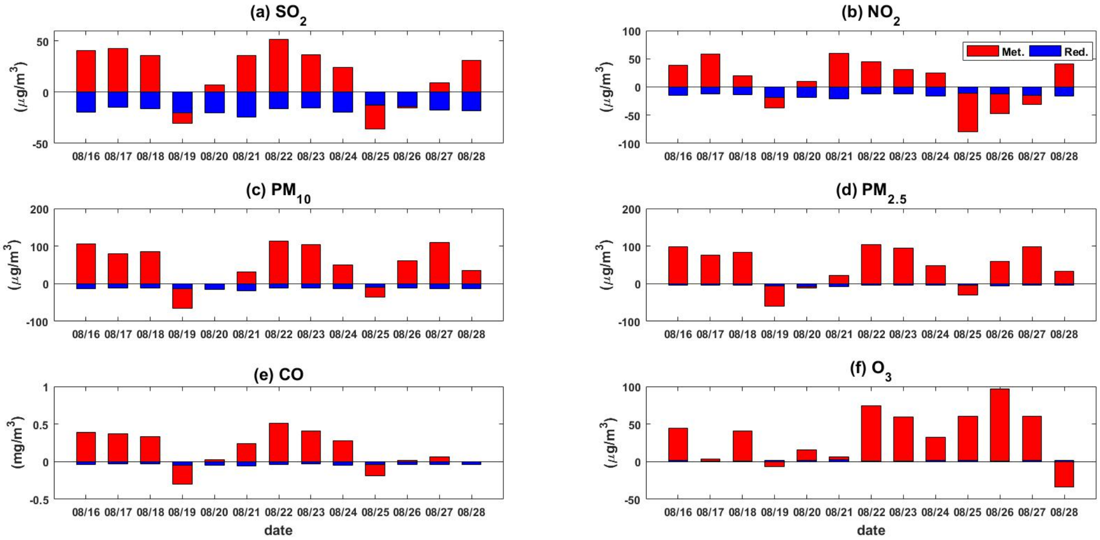

**Fig. 10.** The simulated effect of meteorology and reduction on pollutant concentrations in Nanjing during the YOG (16-28 Aug. , 2014), Met. (Exp.2-Exp.3) represents the effect of meteorology, while Red. (Exp.1-Exp.2) represents the simulated effect of reduction.

Besides, their opposite effects were more apparent at specific sites as listed in Table 6. CCM station represents the urban status and XL station represents the suburban status. Adverse meteorology was found to raise the concentration of the six pollutants as 17.4% for $SO_2$, 15.1% for $NO_2$, 15.9% for $PM_{10}$, 15.4% 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 $NO_2$, 23.2% for $PM_{10}$, 25.6% 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 semms that air pollutants reduced with more extent at CCM station. Emission abatement independently led to a 24.3% decrease in $SO_2$ at CCM station, which was 5.1% higher than that at XL station. Moreover, the cutbacks of $NO_2$, $PM_{10}$, $PM_{2.5}$ and CO were 11.7%, 13.7%, 6.8% and 7.0%, respectively at CCM station, whose decrease range was 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.

**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) |
|---|---|---|---|---|
| $SO_2$ | 17.4% | -24.3% | 14.1% | -19.2% |
| $NO_2$ | 15.1% | -11.7% | 12.4% | -10.2% |
| $PM_{10}$ | 15.9% | -13.7% | 23.2% | -11.7% |
| $PM_{2.5}$ | 15.4% | -6.8% | 25.6% | -5.8% |
| CO | 6.4% | -7.0% | 2.3% | -5.5% |
| $O_3$ | 0.9% | 1.3% | 1.6% | 0.9% |

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 due to the limit and halt of power plants and improvement of coal-combustion. The cut of particulate matter might due to the stop of construction process and use of low ash content coal. Besides, 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. $O_3$ response under emission control could be complicated to predict due to its non-linearity chemistry (Fu et al., 2012), and reducing $NO_2$ pollution 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, and emission reduction played a decisive role in the air quality promotion.

## 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 was effective to ambient air quality promotion during the Youth Olympic Games, especially to $SO_2$, $NO_2$, $PM_{10}$, $PM_{2.5}$ and CO. The simulated impact percentage of emission reductions were -24.6%, -12.1%, -14.8%, -7.3% and -7.2% for $SO_2$, $NO_2$, $PM_{10}$, $PM_{2.5}$, and CO, respectively.

The meteorological conditions in the holding time were inferior to those of the same period in 2013, with lower temperature and weaker winds, especially during the YOG. Model simulations show that less favorable weather conditions caused higher concentrations for all species. Thus, emission reduction control is the decisive factor of the air quality improvement during the YOG.

In general, better air quality during 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 YOG (in Sept. 2014) suggest that short-term emission control can only ease air pollution effectively but temporarily. Long-term control policies are necessary to ensure pleasant future air quality.

## Acknowledgements

This work was supported by the National Natural Science Foundation of China (91544230, 41575145, 41621005), the National Key Research Development Program of China (2016YFC0203303, 2016YFC0208504, 2014CB441203), the National Special Fund for the Weather Industry (GYHY201206011) and the National Special Fund for the Environmental Protection Industry (GYHY201409008) . We are grateful to Prof. Yu Zhao from School of Environment of Nanjing University for supply the emission data of Nanjing. The contents of this paper are solely the responsibility of the authors and do not necessarily represent the official views of sponsors.

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