A case study of air quality control in Beijing and the surrounding area during the 2015 World Championships and Parade

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ABSTRACT

Based on satellite observations, the effects of emission reduction measures on air pollutants (NO$_2$ (nitrogen dioxide), SO$_2$ (sulfur dioxide), and aerosols) were estimated in Beijing and its surroundings during the 2015 World Championships and Parade (WCP) held in Beijing. Compared with the same period in the previous three years (2012–2014), the tropospheric vertical column densities of NO$_2$ and SO$_2$ in 2015 were significantly reduced in Beijing and its surroundings. During the WCP, aerosol optical depth was reduced most significantly in Beijing, while NO$_2$ and SO$_2$ were reduced most significantly in Hebei and Tianjin, respectively. The meteorological conditions were also favorable during this period. During the WCP, the North China Plain was located under high pressure from the north of China. A southward pressure gradient force and weak northerly and northeasterly winds blocked the transport of pollution from southern and western parts of the industrial area (Hebei, Shanxi and Shandong provinces). Cold air masses pushed southwards weakly. These conditions were beneficial to the removal of air pollutants in Beijing.

1. Introduction

During major societal events, the air quality of the particular region where an event is taking place will generally receive more attention from the public and the government than it would at other times (Han et al. 2014). This is because pollutant emissions into the atmosphere result in low visibility and human health problems — particularly for the respiratory system (He et al. 2001). In China, visibility is usually low in the Jing–Jin–Ji (Beijing, Tianjin, and Hebei) region due to air pollution (Wang et al. 2014).

Emission control measures reduce pollution and improve air quality; for instance, there was a 30% reduction in vehicle emissions during the 2008 Olympics in Beijing (Guo et al. 2012). Another case of administratively imposed emissions control was during APEC (Asia-Pacific Economic Cooperation Summit) 2014 in Beijing, which showed AOD in Beijing was reduced by 34% (Huang, Zhang, and Lin 2015).

Based on previous successful emission control cases, the government formulated a plan to guarantee the air quality in Beijing during the 2015 World Championships and Parade (WCP). In this work, both the nitrogen dioxide (NO$_2$) and sulfur dioxide (SO$_2$) were retrieved from the Ozone Monitoring Instrument, and the aerosol optical depth (AOD) was retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS). They were used to assess the effects of the emissions reduction program in the north of China.

2. Data and methodology

The tropospheric vertical column density (VCD) of NO$_2$ data used in this paper parallel those of Huang, Zhang, and Lin (2015). The noise plumes from strong
3.1. Variation in ground-based observations of air pollutants

Figure 2 shows the temporal variation of pollutants (NO$_2$, SO$_2$, and PM$_{2.5}$ (fine particulate matter)) at Beijing, Tianjin, Shijiazhuang, Zhangjiakou, and Chengde, during pre-WCP, WCP, and post-WCP. In general, the pollutants at these five sites have consistent trends. When the pollution remains at a higher level in the surroundings, the pollution in Beijing is relatively more severe. However, apparently, the pollution level during WCP was lower than during the other two periods, especially in Beijing. Further discussion on this is provided later in the paper.

3.2. Variation in satellite-based observations of air pollutants

3.2.1. NO$_2$

In the troposphere, NO$_2$ is an important indicator of air pollution. Thus, the temporal trend and spatial distribution of NO$_2$ and other atmospheric trace gases are key topics in atmospheric chemistry (Boersma et al. 2008).

Based on satellite observations, the average NO$_2$ VCD for adjacent provinces is calculated (Figure 3). Before WCP, the maximum NO$_2$ VCD was located at Tangshan and Tianjin, with a mean value of $9.34 \times 10^{15}$ molec cm$^{-2}$.
in Tianjin. Compared with the mean values in the same period, only Tangshan was more heavily polluted than in previous years. During pre-WCP, the NO$_2$ VCD for 2015 in Beijing did not change significantly compared with the same period in previous years. During the activity, the NO$_2$ VCD levels maintained at a lower level compared to the previous three years. NO$_2$ (VCD) reduced by 8.1% in Beijing, 3.4% in Tianjin, 18.3% in Hebei, 9.8% in Shanxi, 15% in Shandong, and 4.4% in Henan. However, there was a slight increase in Inner Mongolia (Figures 3 and 4). During the Olympic Games in 2008, the mean concentration of NO$_2$ fell by 13.0% in Beijing (Xin et al. 2010). During World Expo 2010, tropospheric NO$_2$ reduced by about 8% in Shanghai (Hao et al. 2011), and NO$_2$ decreased by 47% in Beijing during APEC (Huang, Zhang, and Lin 2015).

After the activity, emissions were no longer controlled, and thus it is expected that the NO$_2$ VCD would have increased again. Compared with the post-WCP means in previous years (2012–2014), the NO$_2$ in 2015 was still low. However, the regions of Beijing, Tianjin, and Hebei showed increases of NO$_2$ compared with the WCP period. This indicates that the temporary control of emissions is only a transient measure, leading to improved air quality for just a short period.

3.2.2. SO$_2$

SO$_2$ is also an important atmospheric pollutant, being a dominant source of anthropogenic emissions. Also, if there is further oxidation of SO$_2$, usually in the presence of a catalyst, it will quickly and efficiently form sulfuric acid. Generally speaking, the lifetime of SO$_2$ is 13 h in summer.
Another similar example is that the SO\textsubscript{2} concentration was reduced by 51.0% during the Olympic Games (Xin et al. 2010).

3.2.3. AOD
To a certain extent, the AOD can reflect the amount of particulate matter in the atmosphere. It is a good complement to the use of ground-based observations (Che et al. 2015).

During the WCP period, as shown in Figure 4, the mean SO\textsubscript{2} content in Beijing was 0.27 DU, as compared to that of 0.45 DU for the same period in 2012–2014. On average, the SO\textsubscript{2} emission levels maintained at a lower level compared to the previous three years (2012–2014), with the SO\textsubscript{2} VCD reduced by 40.8% in Beijing, 62.3% in Tianjin, 43.4% in Hebei, 8.5% in Shanxi, 35.2% in Shandong, and 5.8% in Henan. Emission reductions are particularly remarkable in Beijing, Tianjin, Hebei, and Shandong. Another similar example is that the SO\textsubscript{2} concentration was reduced by 51.0% during the Olympic Games (Xin et al. 2010).

3.2.3. AOD
To a certain extent, the AOD can reflect the amount of particulate matter in the atmosphere. It is a good complement to the use of ground-based observations (Che et al. 2015).

During the activity, aerosols remained at a lower level over the North China Plain compared to the previous three years (2012–2014), with AOD reduced by 59.1% in Beijing, 55.7% in Tianjin, 44.7% in Hebei, 25.3% in Inner Mongolia, and about three times as long in winter. The oxidation of SO\textsubscript{2} forms sulfuric acid mist or sulfate aerosols in the atmosphere, which cause acid deposition. Therefore, the reduction of SO\textsubscript{2} is a highly important task (Lee et al. 2011).

Figure 3. Averages of (a) NO\textsubscript{2} VCD, (b) SO\textsubscript{2} VCD, and (c) AOD, for the pre-WCP, WCP, and post-WCP periods, in each year from 2012 to 2015, based on satellite observations, for Beijing, Tianjin, and adjacent provinces.
3.3. Impact of weather conditions

The meteorological factors before, during, and after WCP were also analyzed (Figure 5). The southern part of Beijing is an industrial area (Hebei and Shandong provinces). During WCP, the northerly wind was so weak that it was almost stationary; therefore, the transportation of pollution from this southern industrial area can be neglected. Before WCP, the mean air temperature was above 22 °C in the North China Plain region, with a weak temperature gradient. During WCP, the temperature was 18–20 °C in Beijing and 20–22 °C in Tianjin–Tangshan region, which was about 2 °C lower than that before WCP. Also, the temperature gradient was stronger than that before WCP. After the activity, the temperature was 16–18 °C in Beijing and 20.8% in Shanxi, and 6.7% in Shandong. However, Henan was different, showing a 40.7% increase, most probably resulting from unfavorable meteorological conditions (poor diffusion conditions) compared with other provinces, as discussed further in Section 3.3. Emission reductions were most remarkable in Beijing and Tianjin, showing that the emission control measures achieved great success. However, another study reported a decrease in AOD of ~69% in Beijing during the WCP (Zheng et al. 2016), most likely because of the different data sampling, data sources, and calculation methods used. Meanwhile, downstream of the Yangtze River Basin, the aerosol loading was higher than that in the previous three years (2012–2014). The AOD in Beijing during the post-WCP period in 2015 returned to the level of 2013, and it was the same in Tianjin.

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During WCP, the North China Plain was near high pressure from Mongolia. The high pressure over the sea had completely disappeared. Based on the combined distribution of relative humidity and temperature, the air mass was moving southwards during WCP, meaning the levels of NO$_2$, SO$_2$, and AOD were relatively low (Figure 2). After WCP, the dominant wind was divergent and anticyclonic.

As Figure 5 shows, before WCP, the north of China was near the edge of a high pressure system over the sea in the east and another area of high pressure over land in the west. During WCP, the North China Plain was near high pressure from Mongolia. The high pressure over the sea had completely disappeared. Based on the combined distribution of relative humidity and temperature, the air mass was moving southwards during WCP, meaning the levels of NO$_2$, SO$_2$, and AOD were relatively low (Figure 2). After WCP, the dominant wind was divergent and anticyclonic.
anticyclonic over the North China Plain. Under such flow conditions, it is difficult for pollutants to disperse. Once the emission control measures came to an end after the event, the air quality in industrial area deteriorated rapidly, resulting from both the continued emissions of pollutants and the unfavorable circulation conditions.

We also analyzed the weather systems during the period from 20 August to 4 September (i.e. the WCP period), from 2012 to 2015, based on daily NCEP reanalysis data. In the same period of 2012, the air mass from the north to the south was inhibited by a high-pressure system at sea. The conditions were not favorable for the proliferation of pollutants because of relatively stable air flow in Beijing and its surroundings. In the same period of 2013, cold air from the north passed through Beijing and its surrounding areas on two occasions, and the wind direction changed frequently. As for 2014, the atmospheric circulation was similar to that in 2013. During WCP in 2015, the region experienced slow and persistent southward movement of cold air from the north, was affected by the edge of a typhoon over the Pacific Ocean, and northerly wind was dominant. This indicates that the meteorological conditions were more conducive to clear air pollution in Beijing area in the WCP period of 2015.

3.4. Emission source analysis

Both \( \text{SO}_2 \) and \( \text{NO}_2 \) can be emitted from natural as well as anthropogenic sources. For \( \text{SO}_2 \), volcanic eruptions are the main natural source (Casadevall et al. 1994; Elias and Sutton 2007), while its anthropogenic sources (Klimont, Smith, and Cofala 2013) are dominated by coal combustion (Abelson 1975; Rokni et al. 2016). For \( \text{NO}_2 \), lightning is a major natural source, while its anthropogenic sources are fuel combustion, including coal power plants, steel plants, vehicle exhaust fumes, and other industrial processes (AlNaimi, Balakrishnan, and Goktepe 2015; Bishop and Stedman 2008; Burgard et al. 2006; Feng et al. 2014; Zhang et al. 2013). Because of their short lifetimes, \( \text{SO}_2 \) and \( \text{NO}_2 \) can be indicative of the level of pollution from local emissions, and based on their concentrations the locations of their primary sources can be estimated. Atmospheric aerosols can be solid or liquid particles suspended in the atmosphere, and are composed of six main components: dust, carbon (Bond et al. 2007), sulfate (Brühl et al. 2013; Park et al. 2004), nitrate, ammonium, and sea salt (Gong et al. 1997). Generally, \( \text{PM}_{2.5} \) is generated by coagulation and accumulation in gaseous vapor (Whitby 1978). High AOD results from multiple emission sources — natural sources included.

According to the estimates of Cao et al. (Forthcoming), during WCP, the reduction rate for emission sources in Beijing was 40%, and that of the surrounding provinces (Tianjin, Hebei, Shandong, Shanxi, Henan, and Inner Mongolia) was 30%. The main emission reduction measures included coal-fired power plants being temporarily closed, vehicle use being managed, the production of industrial enterprises being stopped or limited, and dust pollution being controlled. These measures played direct and indirect roles in the reduction of particulate matter, \( \text{NO}_2 \) and \( \text{SO}_2 \).

According to satellite observations, the VCD of \( \text{NO}_2 \) was kept very low in Beijing, being reduced by 8.1% compared to previous three years. Meanwhile, \( \text{SO}_2 \) reduced by 40.8% and AOD reduced by 59.1%. As for the surrounding provinces, taking Hebei as an example, the reduction rate of \( \text{NO}_2 \) was 18.3%, while that for \( \text{SO}_2 \) was 43.4% and AOD was 44.7%. So, the reduction rates of \( \text{SO}_2 \) and AOD in Beijing and its surrounding area were found to be similar to the estimated reduction of gaseous pollutant emissions and particulate matter of Cao et al. (Forthcoming), and emissions reduction in surrounding provinces cannot be ignored. According to satellite observations (Figure 4), the main emission sources were Tianjin, at the edge of Hebei and Henan provinces, and the center of Shandong Province, despite these areas having taken measures to reduce emissions. Again, this is consistent with the findings of Cao et al. (Forthcoming).

4. Conclusions

In this work, satellite observations and ground measurements were applied to estimate the effects of emission reduction measures on the levels of atmospheric pollutants (\( \text{NO}_2 \), \( \text{SO}_2 \) and particulate matter) in Beijing and its surroundings during the 2015 WCP held in Beijing. The meteorological conditions were also analyzed, based on NCEP reanalysis data, to investigate the diffusion and transport of air pollution.

1. During WCP, \( \text{NO}_2 \) (VCD) was reduced by 8.1% in Beijing, 3.4% in Tianjin, 15% in Hebei, 4.4% in Henan, 25.3% in Shandong, and 8.5% in Shanxi. \( \text{SO}_2 \) was reduced by 40.8% in Beijing, 62.3% in Tianjin, 43.4% in Hebei, 55.7% in Henan, 35.2% in Shandong, and 5.8% in Shanxi. During the activity, the aerosol levels maintained at a lower level over the North China Plain compared to the previous three years (2012–2014). AOD reduced by 59.1% in Beijing, 44.7% in Tianjin, and 25.3% in Shandong. Conversely, Henan showed a 40.7% increase, due to unfavorable meteorological conditions. Emission reductions were most remarkable in Beijing and Tianjin.
(2) During WCP, a southward pressure gradient and weak northerly and northeasterly winds blocked the transportation of pollution from the southern and western industrial areas (Hebei, Shanxi, and Shandong provinces). Cold air masses pushed southwards weakly. These conditions benefitted the removal of pollutants from Beijing. During WCP, NO$_2$, SO$_2$ and AOD remained at low levels (Figure 2), due to favorable weather conditions and the emission reduction measures. Clearly, meteorological conditions play a key role in air quality improvement.

Disclosure statement
No potential conflict of interest was reported by the authors.

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