Trends of surface PM$_{2.5}$ over Beijing–Tianjin–Hebei in 2013–2015 and their causes: emission controls vs. meteorological conditions

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ABSTRACT

The PM$_{2.5}$ (particulate matter with a diameter of less than 2.5 μm) trends during the period 2013–2015, in 13 cities over the Beijing–Tianjin–Hebei region, and their causes, were investigated using observations at 75 stations and a regional air quality model. It was found that annual PM$_{2.5}$ in this region experienced a significant decrease in 2014 and 2015, compared with 2013. PM$_{2.5}$ in 2015 almost met the target on air quality in the 13th Five-Year Plan (2012–2017). In southern cities (e.g. Xingtai, Handan, Shijiazhuang, and Cangzhou), this PM$_{2.5}$ decreasing trend was caused by both meteorological conditions and regional emission controls in 2014 and 2015. Contributions from regional emission controls were more significant than meteorological conditions. In Tianjin and Langfang, the impact of regional emission controls was partly offset by the meteorological conditions in 2014. In 2015, meteorological conditions turned favorable for a PM$_{2.5}$ decrease, but emission controls were still the dominant cause. Compared with polluted cities in Hebei and Tianjin, the decreasing trend in Beijing was small (4% and 9% in 2014 and 2015). This reflects the competition between adverse meteorological conditions and emission controls. In northern cities (Tangshan, Qinhuangdao, and Zhangjiakou), regional emission controls dominated the PM$_{2.5}$ decreasing trend in 2014 and 2015, although they were partly offset by meteorological conditions. In all cities during the heating season in 2015, a more significant decreasing trend of high PM$_{2.5}$ from emission controls was found than low and middle PM$_{2.5}$. This indicates that air pollution controls are developing towards refined management (e.g. the Heavy Air Pollution Emergency Response Program) in this region.

1. Introduction

With urbanization and industrialization, substantial megacities in China are undergoing severe air pollution, especially Beijing and in the North China Plain region (Tao et al. 2014; Wu, Xu, and Zhang 2015). As the predominant wind direction is obstructed by the Yanshan and Taihang Mountains, diffusion in this area is hindered (Miao et al. 2015). Accordingly, haze events have occurred frequently in the past five years in this region. In 2014, eight of the ten Chinese cities with the worst air quality belonged to this megacity cluster, with an annual PM$_{2.5}$ concentration exceeding 100 μg m$^{-3}$ (http://jcs.mep.gov.cn). Extensive research has been conducted to investigate the source and formation of haze in this region. These studies have found that regional transport plays an important role in haze episodes, as well as local emissions (Wang, Li et al. 2014). Besides emissions, meteorological factors (low wind speed, high relative humidity, and stable atmospheric
stratification) in the atmospheric boundary layer can cause accumulation of air pollutants (Yang et al. 2014). Additionally, local atmospheric circulations (urban heat island, sea–land breezes, and mountain–valley breezes) can spur pollutant accumulation and aggravate the air quality in the Beijing–Tianjin–Hebei (BTH) area (Wang, Wang et al. 2014).

The State Council of China published the Air Pollution Prevention Action in September 2013, setting a 25% PM$_{2.5}$ reduction by 2017 from the 2012 level for the BTH area, and a target for Beijing's PM$_{2.5}$ annual average to drop below 60 μg m$^{-3}$. During the past three years, many policies to reduce emissions have been implemented. Previous studies have tried to elucidate the effects of emission control measures, but often in a specific and short period of time, such as during the APEC (Asia-Pacific Economic Cooperation) event and the Military Parade, by using statistical prognosis methods or source apportionment (Liang et al. 2015; Shen et al. 2016). Studies on PM$_{2.5}$ trends over longer periods, such as in the past three years (2013–2015), and their causes, are limited. In the first part of 2016, Chinese Academy of Engineering academicians reported that there has been a general decreasing trend in PM$_{2.5}$ since 2013, but that stricter control measures are still needed to further improve the situation (http://www.cae.cn/cae/html/main/col66/2016-07/05/20160705160522816693277_1.html). Clearly, more detailed studies are needed. In the present study, we used observations at 75 stations, along with the Nested Air Quality Prediction Modeling System (NAQPMS), to investigate the PM$_{2.5}$ trends in 13 cities in BTH and quantify the impacts of meteorological conditions and emission controls.

2. Methodology, observation, and model description

In this study, we employed surface PM$_{2.5}$ observations and NAQPMS to analyze the trends of PM$_{2.5}$ during the period 2013–2015 in 13 cities within BTH and investigate the impacts of meteorological fields and emission controls on these trends. Three steps were included in this analysis procedure: Firstly, we treated the year 2013 as the base year, and calculated the difference between 2014 and 2015 with the base year from the city-averaged PM$_{2.5}$ observations (Diff$_{obs}$). Secondly, we employed NAQPMS to simulate the PM$_{2.5}$ in 2013–2015 using varying meteorology and the same emissions inventory (for the year 2013). The relative impact of meteorological fields (Cont$_{emis}^{i}$ in 2014 and 2015 on the PM$_{2.5}$ difference with the base year was calculated as per Equation (1):

$$\text{Cont}_{i}^{\text{net}} = \frac{(\text{Sim}_{i} - \text{Sim}_{2013})}{\text{Sim}_{2013}}$$  

(1)

where $i$ represents the target year (2014 and 2015 in this study), and Sim$_{i}$ and Sim$_{2013}$ represent the simulated PM$_{2.5}$ (μg m$^{-3}$) in the $i$th year and 2013, respectively.

In NAQPMS, the contribution of regional transport has already been simulated by the advection and diffusion. So, the effects of transport driven by changes of winds in 2013–2015 were considered as one part of the meteorological impact in this study. Lastly, the relative impact of emission controls (Cont$_{i}^{\text{emis}}$) was calculated by Equation (2):

$$\text{Cont}_{i}^{\text{emis}} = 1 - \text{Cont}_{i}^{\text{net}}.$$  

(2)

2.1. Observational data

PM$_{2.5}$ data from 75 stations in 13 cities within BTH were obtained from http://www.cnemc.cn. The 13 cities were: Beijing (Bj), Tianjin (Tj), Shijiazhuang (Sjz), Tangshan (Ts), Qinhuangdao (Qhd), Handan (Hd), Xingtai (Xt), Baoding (Bd), Zhangjiakou (Zjk), Chengde (Cd), Cangzhou (Cz), Langfang (Lf), and Hengshui (Hs). These stations are routinely operated by the Chinese National Environmental Monitoring Center. We calculated the mean concentrations of national control monitoring stations as the city-averaged PM$_{2.5}$.

2.2. Model description and setup

NAQPMS is a 3D Eulerian chemical transport model, developed by the Institute of Atmospheric Physics, Chinese Academy of Sciences. NAQPMS includes fully coupled ozone–nitrogen oxides–hydrocarbon chemistry and aerosols, including sulfate/nitrate/ammonium, black and organic carbon, and other primary aerosols like dust and sea salts (Li et al. 2011, 2012). WRFv3.6 provides the meteorological fields, derived from National Centers for Environmental Prediction Final Operational Global Analysis data.

Anthropogenic emissions (fossil fuels, biofuels, industrial, transportation, and power plants), at a resolution of 5 km, were taken from the Multi-resolution Emissions Inventory for China, developed by Tsinghua University and Peking University, for the year 2015 (Li et al. 2015). The biogenic emissions inventory was calculated using the Model of Emissions of Gases and Aerosols from Nature (Guenther et al. 2006). The biomass-burning emissions in 2013 were projected onto a 0.25° × 0.25° grid, based on the Global Fire Emissions Database, version 4.1 (Giglio, Randerson, and van der Werf 2013).

The model domain covered the whole of East Asia at a resolution of 5 km. We applied a vertical resolution of 20 levels from the surface to 20 km above sea level. The first level from the surface was 30 m in height. The average vertical layer spacing between 30 m and 1 km was ~100 m. The simulated period was 2013–2015.
Figure 1. Boxplot of the diurnal mean concentration of PM$_{2.5}$ for both observations (blue) and simulations (red). MO and MM stand for the annual mean concentration of the observation and simulation, respectively. ‘R’ is the correlation coefficient.
2.3. Model validation

As shown in Figure 1, NAQPMS reproduced the general variation of monthly PM$_{2.5}$ at the 13 cities in 2015 reasonably well. The correlation coefficients, based on daily mean concentrations, ranged from 0.52 (Zjk) to 0.75 (Cz and Hs). In particular, the simulated median and 75th percentile PM$_{2.5}$ in December–January–February in Bj and the southern Hebei cities reached ~150 μg m$^{-3}$ and 150–250 μg m$^{-3}$, respectively, which were close to observations. Note that a small underestimation in winter was found, but this is quite normal for current air quality models in China (Zheng et al. 2015), caused by uncertainties relating to emissions and missing mechanisms in these models.

2.4. Spatial distribution of PM$_{2.5}$

Figure 1 shows that the concentrations of PM$_{2.5}$ differed dramatically among cities in BTH in the past three years (2013–2015). In the southern cities (Sjz, Bd, Hd, and Xt), annual PM$_{2.5}$ reached over 100 μg m$^{-3}$, which is about three times the National Grade II standard (35 μg m$^{-3}$). In central cities (Bj, Tj, Ts, Lf, Cz, and Hs), PM$_{2.5}$ ranged from 70 to 110 μg m$^{-3}$. In the northern cities (Zjk, Qhd, and Hs), annual PM$_{2.5}$ concentrations were only 30–50 μg m$^{-3}$.

3. Results

3.1. Observed PM$_{2.5}$ trends from 2013 to 2015

Figure 2 shows a decrease of annual PM$_{2.5}$ in 2014 and 2015, compared with 2013. In order to investigate the possible causes of PM$_{2.5}$ trends, the decrease in mean PM$_{2.5}$ during the heating season (November–December–January–February–March) and non-heating season (April to October) is also shown (Figure 3). The annual PM$_{2.5}$ at most polluted cities in southern Hebei (Sjz, Hd, Xt, and Cz) decreased by 10%–20% (10–30 μg m$^{-3}$) and 30%–40% (30–60 μg m$^{-3}$) in 2014 and 2015, respectively. The magnitude of the PM$_{2.5}$ decrease in central cities like Bd, Lf, Tj, Ts, and Qhd, ranged from 5%–15% and 20%–30% in 2014 and 2015, respectively. The 25th–75th (main body) and 75th–100th (high concentrations) percentiles of PM$_{2.5}$ contributed the most to the decreased concentrations in these cities. Compared with these cities, the annual PM$_{2.5}$ in Bj decreased far less, with magnitudes of 4% (3.6 μg m$^{-3}$) and 9% (8.9 μg m$^{-3}$) in 2014 and 2015 compared with 2013, respectively (Figure 2(a) and (d)). The trends of PM$_{2.5}$ in high concentrations partly explain this difference between Hebei and Bj. In Bj, high PM$_{2.5}$ only contributed 3.5% to this decrease of annual PM$_{2.5}$ in 2015, and even increased (negative value in Figure 3(c)) in 2014.

For most polluted cities in Hebei, PM$_{2.5}$ showed a similar decreasing magnitude (10%–20% in 2014 and 20%–40% in 2015), in both the heating and non-heating season. In the heating season, the decrease was mostly from the 75th–100th percentile PM$_{2.5}$, while it was from the 25th–75th percentiles in the non-heating season in 2014 (Figure 3(g) and (k)). In 2015, the 75th–100th and 25th–75th PM$_{2.5}$ almost equally contributed to the PM$_{2.5}$ decrease (Figure 3(h) and (l)). In Bj, the PM$_{2.5}$ in the heating season in 2014 slightly decreased, and increased in the non-heating season. This is in contrast with the situation...
in 2015, in which PM\textsubscript{2.5} increased by ~10% in the heating season and decreased by ~20% in the non-heating season. Note that the increase in PM\textsubscript{2.5} does not mean emissions in the city increased; rather, it was likely caused by meteorological factors. So, in the next part of the study, we analyzed the impacts of meteorology and emission controls.

### 3.2. Impact of meteorological fields

Figure 2 presents the relative contribution of meteorological fields and emission controls to the PM\textsubscript{2.5} trends in 2013–2015. Meteorological fields in 2014 showed a different impact on PM\textsubscript{2.5} trends compared with 2013. In BJ, TJ, and cities of northern Hebei, the meteorological fields in 2014 were more unfavorable for air quality, compared with 2013, contributing −20% to −100% to the PM\textsubscript{2.5} decrease in 2014, partly offsetting the efforts of emission controls (Figure 2c). As shown in Figure 4a, the negative impact of the meteorological fields on the PM\textsubscript{2.5} decreasing trends was mostly concentrated in the 75th–100th and 25th–75th percentiles of PM\textsubscript{2.5}. On the contrary, the meteorological fields in 2014 were more favorable to PM\textsubscript{2.5} dispersion in southern cities in Hebei, which contributed to 15%–50% of the decreased PM\textsubscript{2.5}. In 2015, the favorable meteorological fields extended northwardly from southern cities to BJ and TJ, which accounted for 8%–30% of the decreased PM\textsubscript{2.5} relative to 2013. Northern cities like TS, QHD, CD, and ZJK still showed an adverse impact on the PM\textsubscript{2.5} decrease, similar to the situation in 2014 (Figure 2c). Comparing 2014 and 2015, the contribution of the meteorological fields...
meteorological fields in the non-heating season of 2015, the PM$_{2.5}$ in all cities decreased relative to 2013 (Figure 4(f)). In the heating season, however, the 25th–75th and 75th–100th percentiles of PM$_{2.5}$ significantly increased in most cities relative to 2013 (Figure 4(e), negative values). In Bj, the increased mean concentration of the 25th–75th and 75th–100th PM$_{2.5}$ reached 200% of the PM$_{2.5}$ changes to the PM$_{2.5}$ decrease in southern cities was less in 2015 than in 2014 (8%–36% vs. 16%–51%). This suggested the meteorological fields in 2015 were more adverse than in 2014 in these cities.

The impact of meteorological fields on PM$_{2.5}$ trends was very different in the heating and non-heating seasons (Figure 4(b), (c), (e), and (f)). Benefiting from the meteorological fields in the non-heating season of 2015, the PM$_{2.5}$ in all cities decreased relative to 2013 (Figure 4(f)). In the heating season, however, the 25th–75th and 75th–100th percentiles of PM$_{2.5}$ significantly increased in most cities relative to 2013 (Figure 4(e), negative values). In Bj, the increased mean concentration of the 25th–75th and 75th–100th PM$_{2.5}$ reached 200% of the PM$_{2.5}$ changes to the PM$_{2.5}$ decrease in southern cities was less in 2015 than in 2014 (8%–36% vs. 16%–51%). This suggested the meteorological fields in 2015 were more adverse than in 2014 in these cities.

Figure 4. Contributions of meteorological fields and emission controls to the PM$_{2.5}$ decrease in 2014 and 2015 relative to 2013. The left-hand column stands for 2014 and the right-hand column for 2015. The first, second, and third rows show the situation for the whole year, for the heating season, and for the non-heating season, respectively. A positive value indicates a reduction. The abbreviations '0–25th mete' (dark blue bars), '25th–75th mete' (cyan bars), and '75th–100th mete' (red bars) refer to the meteorological fields’ contribution to the decreases of the 0–25th, 25th–75th, and 75th–100th percentile of PM$_{2.5}$, respectively. Similarly, '0–25th emis' (blue bars), '25th–75th emis' (yellow bars), and '75th–100th emis' (brown bars) refer to the emission controls’ contribution to the decreases of the 0–25th, 25th–75th, and 75th–100th percentile of PM$_{2.5}$, respectively. The ratios of Beijing (Bj) in (a), Qinhuangdao (Qhd) in (b), and Beijing and Chengde (Cd) in (e) are curtailed by several multiples (red numbers), in order to provide a better display for all cities (see Section 2.1 for the city abbreviations).
between 2014 and 2013. In southern cities (Sjz, Hd, and Xt), the meteorological fields almost had no impact on PM$_{2.5}$. In 2014, the meteorological fields increased the 25th–75th and 75th–100th percentiles in most cities in the non-heating season (Figure 4(c)). In the heating season, high PM$_{2.5}$ in northern cities like Bj, Bd, Zjk, and Cd increased, while it decreased in southern cities (Figure 4(b)).

### 3.3. Impact of emission controls

In BTH, high emission rates were mainly located in the central and southern cities (Hd, Xt, Sjz, Bd, Bj, Lf, Tj, and Ts), with magnitudes of 0.3–1 μg m$^{-2}$. The northern cities, like Zjk, Cd, and Qhd, emitted fewer pollutants than southern cities (figure not shown). The PM$_{2.5}$ in most cities in both 2014 and 2015 exhibited a decreasing trend compared with 2013 (except Cd). In 2015, this decreasing trend was more significant than in 2014. It cannot be totally accounted for by the changes in meteorological fields, which even increased PM$_{2.5}$ in northern cities in 2014. This indicates that regional emission controls in BTH have had significant positive effects on air quality. In 2014, emission controls contributed 51%–97% to the annual PM$_{2.5}$ decreasing trend in southern cities (Bd, Sjz, Xt, Hd, and Cz), which indicates emission controls were more effective than the meteorological conditions (Figure 2(c)). In northern cities (Bj, Tj, Lf, Ts, Qhd, and Zjk), regional emission controls contributed 108%–187% of the PM$_{2.5}$ decreasing trend, which indicated emission controls were partly offset by the meteorological conditions. In Cd, emission changes in 2014 resulted in a PM$_{2.5}$ increase. As shown in Figure 4(a), the impact of emission controls concentrated in the 25th–75th percentiles of PM$_{2.5}$. In 2015, emission controls had a more significant impact on the PM$_{2.5}$ decreasing trends in southern cities compared with 2014 (Figure 2(f)). This explains why PM$_{2.5}$ decreased more than 2014 in the adverse meteorological fields of 2015. In Bj, Tj, and Lf, both emission controls and meteorological conditions decreased PM$_{2.5}$ concentrations, but the former were more effective. In northern cities (Zjk, Ts, and Qhd), emission controls dominated the PM$_{2.5}$ decreasing trend, although they were partly offset by the meteorological conditions. Figure 4(d) clearly shows that not only the 25th–75th, but also the 75th–100th percentiles, significantly decreased in all cities.

The different impact of controls on PM$_{2.5}$ trends in the heating season in 2014 and 2015 clearly reflected the evolution of regional emission controls towards refined management (Figure 4(b) and (e)). In 2014, the most effective impact of controls focused on the 25th–75th percentiles of PM$_{2.5}$, while it switched to the 75th–100th percentiles in 2015. The Heavy Air Pollution Emergency Response Program was called into action in almost all cities in 2015. For example, Bj had one orange and two red alerts in 2015, when PM$_{2.5}$ reached 250–700 μg m$^{-2}$. Previous studies have shown that emergency response measures can decrease PM$_{2.5}$ by 20%–30% (Cheng et al. 2016). In the non-heating season, the 25th–75th percentiles of PM$_{2.5}$ decreased more than the 75th–100th percentiles in 2014 and 2015 (Figure 4(c) and (f)). This is related to the fact that heavy pollution episodes mostly appear in the heating season in BTH.

### 4. Discussion

It has been a confusing problem for policy-makers to explore the possible causes of secondary pollutant trends in BTH. In this study, we employed observations at 75 stations as well as a nested air quality model (NAQPMS) to quantify the impacts of meteorological conditions and regional emission controls. However, there are still some uncertainties. Firstly, the PM$_{2.5}$ trends were simply attributed to the sum of the impacts of meteorological conditions and regional emission controls in this study. In fact, the interaction between meteorological conditions and emission controls also affects PM$_{2.5}$ concentrations. For example, a two-way feedback mechanism between boundary layer height and PM$_{2.5}$ concentrations has been previously reported (Wang, Wang et al. 2014). In this study, this interaction was only attributed to the contribution of emission controls. Secondly, the impacts of emission controls were the net sum of controls in all cities in this study. We did not distinguish the contribution of control measures in each city, which will be studied in future work.

### 5. Conclusions

In this study, we investigated the trends of PM$_{2.5}$ in 13 cities in BTH during the period 2013–2015 and quantified the relative contributions of meteorological conditions and regional emission controls, using observations at 75 stations and a nested air quality model (NAQPMS). We found that the annual PM$_{2.5}$ in southern Hebei (Sjz, Hd, Xt, and Cz) decreased by 10%–20% and 30%–40% in 2014 and 2015, relative to 2013, respectively. In central cities (Bd, Lf, Tj, Ts, and Qhd), PM$_{2.5}$ decreased by 5%–15% and 20%–30% in 2014 and 2015. Compared with these cities, PM$_{2.5}$ in Bj decreased least, with magnitudes of 4% and 9% in 2014 and 2015 relative to 2013, respectively.

In southern cities, both meteorological conditions and regional emission controls in 2014 and 2015 were favorable to the PM$_{2.5}$ decreasing trend. In 2014, the impact of regional emission controls was more significant than meteorological conditions. They decreased PM$_{2.5}$ by 50%–85% and 15%–50%, respectively. In 2015, regional emission controls were even the dominant cause of the PM$_{2.5}$ decrease, accounting for 60%–90%.
In Tj and Lf, regional emission controls in 2014 decreased PM$_{2.5}$ compared with 2013, contributing to 105%–120% of the observed PM$_{2.5}$ decrease. However, these impacts were partly offset by the meteorological conditions, which increased PM$_{2.5}$ by 6%–20%. Consequently, the magnitude of the decrease was less than in southern cities. In 2015, meteorological conditions turned favorable to a PM$_{2.5}$ decrease, but emission controls were still the dominant cause of this decreasing trend.

In Bj, the magnitude of the PM$_{2.5}$ decrease in 2014 was small. This reflects the competition between meteorological conditions and emission controls. In the meteorological conditions in 2014, both the 25th–75th and 75th–100th percentile PM$_{2.5}$ significantly increased. In 2015, meteorological conditions were favorable to the annual PM$_{2.5}$ decrease, but it significantly increased PM$_{2.5}$ in the heating season. This indicates that more strict control measures should be applied in Bj to reach the target (30% decrease in 2017 relative to 2013).

In northern cities (Ts, Qhd, and Zjk), regional emission controls dominated the PM$_{2.5}$ decreasing trend in 2014 and 2015, although they were partly offset by meteorological conditions.

Finally, a more significant decreasing trend of high PM$_{2.5}$ (75th–100th percentiles) from emission controls was found in all cities in the heating season in 2015, compared with the 0–25th and 25th–75th percentiles. This did not occur in the non-heating season and the whole year in 2014. This indicates that air pollution controls are developing towards refined management (e.g. the Heavy Air Pollution Emergency Response Program) in this region.

**Disclosure statement**

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