Characteristics of heavy air pollution in Beijing-Tianjin-Hebei and the surrounding areas during autumn and winter and policy recommendations

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Abstract. Beijing-Tianjin-Hebei and its surrounding areas is the most polluted region in China. Autumn and winter are the most heavily polluted seasons. It is essential to reduce the PM$_{2.5}$ pollution in autumn and winter in this region for winning the blue sky defense war. The characteristics of PM$_{2.5}$ pollution during autumn and winter in this region were analysed and crucial issues in atmospheric pollution prevention were identified from the perspectives of time, space and pollution sources, using a combination of techniques including air quality observation, emission inventory, PM$_{2.5}$ source apportionment and air quality model simulation. The results showed that average PM$_{2.5}$ concentrations in autumn and winter were twice that in spring and summer, and frequent heavy pollution elevated PM$_{2.5}$ concentration significantly. Six cities including Handan, Xingtai, Shijiazhuang, Xinxiang, Anyang and Baoding, located along the south-western transport channel in the region, have great effects on regional air quality. The severe PM$_{2.5}$ pollution in this region could be attributed to heavy industrial structure, large NOx emissions from mobile sources, re-burn of loose coal, insufficient dust control and impacts from cities out of the region. Suggestions for air pollution control in autumn and winter in this region were proposed. More efforts should be devoted to the most vulnerable links in the key cities.

1. Introduction

In recent years, Beijing-Tianjin-Hebei (BTH) and its surrounding areas has experienced heavy pollution and attracted attention all over the world. Since the implementation of the Action Plan for Prevention and Control of Air Pollution in 2013, the air quality in this region has notably improved. The annual average concentration of PM$_{2.5}$ in Beijing-Tianjin-Hebei region in 2018 was 48% lower than that of 2013. However, the performance of the efforts to improve air quality remains unstable. The PM$_{2.5}$ concentration in BTH and its surrounding regions rose again in autumn and winter during 2018-2019. It is therefore imperative to deeply analyze the atmospheric pollution characteristics in this region from the perspectives of time, space, pollution sources etc., identify key factors affecting the atmospheric environment and adopt more accurate measures to achieve constant improvement of ambient air quality and environmental, economic and social multi-win results.

Currently, many scholars at home and abroad have conducted huge amount of studies on characteristics of air pollution in BTH and its surrounding areas based on atmospheric circulation[1], meteorological impacts [2], regional pollution transport [3-5], pollutant emissions [6], chemical composition of PM$_{2.5}$ and source apportionment [7-9]. The results suggest southerly low-speed air
masses intensify pollution accumulation in this region, leading to obviously heavier pollution than affected by north-western air masses [5,10]. Regional transport contributes to the formation of PM$_{2.5}$ and even more to heavy pollution episodes [4]. In terms of PM$_{2.5}$ composition characteristics, nitrate, sulphate and ammonium salt are the most important secondary inorganic components [1] and the share of nitrate is on the rise [11-13]. However, most of the existing studies merely probed into a single city or several typical cities or analysed a single pollution process, while few conducted comprehensive and systematic research on characteristics and sources of PM$_{2.5}$ pollution in this region from multiple angles or identify key problems in air pollution control there.

This paper analysed the characteristics of PM$_{2.5}$ pollution in the BTH and its surrounding areas from the perspectives of time, space and pollution sources, identified key problems in air pollution control in autumn and winter in the region based on emission inventory, PM$_{2.5}$ source apportionment and regional PM$_{2.5}$ transport, and proposed suggestions and recommendations for air pollution prevention and control in this region during autumn and winter seasons.

2. Materials and methods

2.1. Research methods
In order to identify key problems in the prevention and control of air pollution in BTH and its surrounding areas, this research established a systematic methodology propped up by air quality observation technique, pollution source emission inventory characterization technique and air quality model simulation technique, which enabled comprehensive analysis from the perspectives of time, space and pollution sources. Temporally, seasonal variation of pollution was analyzed based on air quality observation data, with emphasis placed on heavy pollution seasons and particulate pollutants; spatially, sensitive zones significantly affecting regional air quality were identified through emission inventories and air quality model simulation; with respect to pollution sources, a combination of emission inventories and source apportionment techniques were used to analyze the characteristics of pollution emission in this region, and identify critical problems in key sectors in the region. Based on the analysis above, suggestions to air pollution prevention in the region during autumn and winter were proposed in a problem-oriented manner. See Figure 1 for the framework of the research.

2.2. Data sources
In this study, ‘2+26’ cities, namely Beijing, Tianjin, Shijiazhuang, Tangshan, Langfang, Baoding, Cangzhou, Hengshui, Xingtai, Handan, Taiyuan, Yangquan, Changzhi, Jincheng, Jinan, Zibo, Jining, Dezhou, Liaocheng, Binzhou, Heze, Zhengzhou, KaiFeng, Anyang, Hebi, Xinxiang, Jiaozuo and Puyang, were studied. The concentration data of 6 conventional pollutants in the 28 cities from 2015 to 2019 were collected from the National Urban Air Quality Real-Time Publishing Platform Centre (http://106.37.208.233:20035/). The annual average PM$_{2.5}$ concentrations from 2015-2019 were published on Ministry of Ecology and Environment (MEE) official website.

3. Results and discussions

3.1. Temporal distribution characteristics of air pollution
The average concentrations of PM$_{2.5}$ in BTH and its surrounding areas showed significant seasonal variations, as displayed in Figure 2. The values in autumn and winter (October to March), were twice that in spring and summer (April to September). Although the annual average PM$_{2.5}$ concentrations showed a decrease trend, the average PM$_{2.5}$ concentrations in autumn and winter fluctuated, which rose by 6.5% during 2018-2019 over 2017-2018. Air pollution control is more challenging in autumn and winter than spring and summer, and more efforts should be devoted.

The number of days with heavy or severe pollution in autumn and winter took up more than 90% of the total heavy and severe pollution days throughout the year. Frequent heavy pollution increased the average PM$_{2.5}$ concentration significantly. The average number of days with heavy pollution or above
was 21.4 in 2018-2019 autumn and winter, resulting in an increase of 14.6μg/m³, or 18.2%, in the regional average PM$_{2.5}$ concentration. Specifically, the average number of days with heavy pollution or above in the six cities along the south-western transport channel, including Handan, Xingtai, Shijiazhuang, Xinxiang, Anyang and Baoding, was 33.3, which was 55.6% higher than the regional average, directly resulting in an increase of 5.1μg/m³, or 6.4%, in the regional average PM$_{2.5}$ concentration. Heavy pollution days in autumn and winter remarkably raised the average PM$_{2.5}$ concentration in the region.

3.2. Spatial distribution characteristics of air pollution

The inter-city air pollution transport in the region from October 1, 2018 to March 31, 2019 was simulated and analysed using the WRF-CAMx model. The results indicated that 6 cities including Handan, Xingtai, Shijiazhuang, Xinxiang, Anyang and Baoding contribute most to the regional PM$_{2.5}$ pollution. These cities, situated along the eastern side of the Taihang Mountains, constitute a transport channel featuring notable mutual transport and obvious cumulative superposition (details will be published elsewhere). Air quality monitoring data also showed that in autumn and winter during 2018-2019, 11 regional heavy pollution processes occurred in the region, of which nine were generated and intensified in that very channel. This agreed with the research results that PM$_{2.5}$ concentrations are high in the south and low in the north in the region and that southerly transport channels are more likely to cause heavy pollution [5].

![Figure 1. The framework of the research.](image1)

![Figure 2. Seasonal variations of PM$_{2.5}$ concentrations in ‘2+26’ cities from 2015-2019.](image2)
The air quality in the surrounding out-region cities was compared with that of the in-region cities. Due to the great efforts on air pollution control in the region, pollution in the surrounding out-region cities has exceeded the average level within the region. In the seven out-region cities (including Zaozhuang, Tai’an, Rizhao, Linyi, Xuchang, Shangqiu and Zhoukou), the average PM$_{2.5}$ concentration was 81$\mu$g/m$^3$ in autumn and winter during 2018-2019, higher than the average level of 80$\mu$g/m$^3$ within the region. These out-region cities lag far behind in terms of the four structures adjustment, pollution control in key enterprises, mobile source pollution control and emergency responses to heavy pollution, and may become sources of inferior oil products and other pollution factors, impeding the air quality improvement in BTH and its surrounding areas.

3.3. Characteristics and problems of air pollution sources

Recently, with further advancement of emission reduction projects in this region, great changes have taken place in air pollution sources. In this research, we deeply analysed the characteristics of air pollution sources from the perspectives of PM$_{2.5}$ source apportionment and pollutant emissions, and root causes of severe PM$_{2.5}$ pollution in the region were addressed.

PM$_{2.5}$ chemical composition studies in this region revealed a decrease in the sulphate content in PM$_{2.5}$ and an increase in the share of nitrate since 2015[14]. The absolute concentration and proportion of nitrate was far higher than that of sulphate in the autumn and winter during 2018 and 2019, making it the most important secondary inorganic component of PM$_{2.5}$ [11,13]. During heavy pollution episodes, the concentration of nitrate increases more rapidly and nitrate is the major driving factor for high PM$_{2.5}$ concentration[12,15]. Nitrate is mainly from the NOx emission in industry and mobile sources, and NOx emission control becomes top priority.

The industrial structure in the region is heavy and the production output of the four major industrial sectors, namely iron and steel, coking, clinker and flat glass, stay high. In 2017, the outputs of crude steel, coke, cement and flat glass in Beijing, Tianjin, Hebei, Shanxi, Shandong and Henan, six municipalities and provinces in the region, took up 41%, 45%, 19% and 35% of the national total, respectively. In addition, the output of main products exhibited a clear rising trend. In 2018, the crude steel production in Hebei and Shanxi grew by over 20%. Crude steel production in Hebei registered up to 237 million tons, more than twice that of the second largest steel producing country in the world. Cement production in Tianjin and Shanxi rose by 48% and 17.4%, respectively. Heavy industrial structure lead to a large quantity of pollutant emissions. The Multi-resolution Emission Inventory of China (MEIC, http://www.meicmodel.org/) demonstrated that the emissions of NOx from industry sector in Beijing, Tianjin, Hebei, Shanxi, Shandong and Henan reached 2.92 million tons, which was 42.8% of the total in the six municipalities and provinces. Considering the implementation of technical reform for ultra-low emission in coal-fired power plants and the increasing main product outputs, the contribution of industry sector to NOx emission was probably more prominent. Among the industrial sectors, iron and steel exerted the highest influence, The iron and steel sector contributed 8-14% to the PM$_{2.5}$ concentration in different seasons in the Beijing-Tianjin-Hebei region [16].

NOx emissions from mobile sources remains at a high level in the region. In 2017, NOx emissions from mobile sources were roughly 1.26 million tons, which was approximately half of the total in ‘2+26’ cities [11]. The contribution of mobile sources to PM$_{2.5}$ is between 10%-50%, and it is actually the largest PM$_{2.5}$ source in some cities [17,18]. Rapid growth of highway freight transportation has led to an increase in emissions from diesel trucks. In 2018, the highway freight volume and turnover in the 6 cities and provinces in the region including Beijing, Tianjin, Hebei, Shanxi, Shandong and Henan rose by 9.7% and 7.1%, respectively year-on-year. Moreover, off-spec diesel with excessively high level of sulphur aggravated pollution from diesel vehicles. The region was challenged by the serious black petrol station problem, with sulphur content in off-spec diesels being hundreds of times higher[19]. Diesel vehicles subject to China’s IV and V standards using diesel with sulphur content of 500ppm could generate over 30% more NOx emissions than diesel subject to China’s VI standards [20]. NOx emissions from non-road mobile machinery (NRMM) in this region are high. In 2017, NOx
emissions from NRMM accounted for about 17% of NOx emissions in ‘2+26’ cities [19]. Many cities had not calibrated their detecting instruments or maintained effective regulation due to an absence of the Limits and Measurement Methods for Exhaust Smoke from Non-Road Mobile Machinery Equipped with Diesel Engine (GB36886-2018) at that time. Excessive sulphur in diesel can also cause a rise in pollutant emissions from NRMM.

The concentrations of carbonaceous components in PM$_{2.5}$ in autumn and winter were higher than in spring and summer, which was probably resulted from larger amount of coal consumption for heating purpose[9]. The contribution of residential coal consumption to monthly average PM$_{2.5}$ concentrations during heating season ranged from 20-60%[21]. The promotion of clean heating project alleviated residential pollution effectively. However, loose coal was still found in use in villages which had completed the shift. Take Baoding as an example, 36% villages which had completed clean energy substitution switched back to loose coal in heating season during 2018-2019.

4. Conclusions and recommendations

(1) Temporally, PM$_{2.5}$ pollution is prominent in autumn and winter seasons in BTH and its surrounding areas, while heavy pollution weather occurs more frequently. The average PM$_{2.5}$ concentrations and number of days under heavy pollution or above in autumn and winter were twice and 9 times that in spring and summer, respectively. In 2018-2019 autumn and winter, PM$_{2.5}$ concentration rose instead of falling, bouncing by 6.5%, and days of heavy pollution or above resulted in an increase of 14.6μg/m$^3$, or 18.2%, in the average PM$_{2.5}$ concentration in the region.

(2) Spatially, the six cities along the south-western transport channel in the region, including Handan, Xingtai, Shijiazhuang, Xinxiang, Anyang and Baoding, have great effects on regional air quality. The surrounding out-region cities lag behind in pollution control, which retards the process of regional pollution prevention and control.

(3) In terms of pollution sources, root causes of heavy pollution in BTH and its surrounding areas are heavy industrial structure with a large quantity of pollutant emissions, large NOx emissions from mobile sources, attributed to high volume of highway transportation, off-spec oils with excessive sulphur and lack of supervision on NRMM, and re-burn of loose coal and insufficient supervision of dust

(4) In order to improve the air quality in this region, management should be strengthened and more resources should be devoted in key cities, which are along the south-western transport channel, including Baoding, Shijiazhuang, Xingtai, Handan, Anyang and Xinxiang. Efforts should focus on solving critical problems in the vulnerable links, such as pushing forward ultra-low emission reform in the iron and steel sector; promoting clean heating and controlling pollution from mobile sources.

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