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Analysis of air quality characteristics of Beijing–Tianjin–Hebei and its surrounding air pollution transport channel cities in China

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ABSTRACT

Beijing–Tianjin–Hebei (BTH) and its surrounding areas are very important to air pollution control in China. To analyze the characteristics of BTH and its surrounding areas of China, we collected 5,641,440 air quality data from 161 air monitoring stations and 37,123,000 continuous monitoring data from air polluting enterprises in BTH and surrounding cities to establish an indicator system for urban air quality portraits. The results showed that particulate matter with aerodynamic diameters of <2.5 μm ($PM_{2.5}$), particulate matter with aerodynamic diameters of <10 μm (PM_{10}) and SO_2 improved significantly in 31 cities from 2015 to 2018, but ozone deteriorated. Air quality in BTH and the surrounding areas showed obvious seasonal characteristics, among which $PM_{2.5}$, PM_{10}, SO_2, and NO_2 showed a "U" type distribution from January to December, while O_3 had an "inverted U" distribution. The hourly changes in air quality revealed that peaks of $PM_{2.5}$, PM_{10} and NO_2 appeared from 8:00 to 10:00, while those for O_3 appeared at 15:00–16:00. The exposure characteristics of the 31 cities showed that six districts in Beijing had the highest air quality population exposure, and that exposure levels in Zhengzhou, Puyang, Anyang, Jincheng were higher than the average of the 31 investigated cities. Additionally, multiple linear regression revealed a negative correlation between meteorological factors (especially wind and precipitation) and air quality, while a positive correlation existed between industrial pollution emissions and air quality in most of BTH and its surrounding cities.

Introduction

In recent years, regional heavy pollution weather problems have caused widespread concern, and cross-regional joint prevention and control mechanisms have become important to achieve coordinated improvement of atmospheric environmental quality (Chai et al., 2013; Chen et al., 2017; Ning et al., 2012; Wang et al., 2012). High altitude and long range transport of aerosols has important effects on air quality (Li et al., 2015; Guo et al., 2019). To achieve air quality improvement targets and pollution source control targets, the Chinese government has implemented a series of air pollution prevention and control measures including the Air Pollution Prevention Action Plan and the Three-Year Action Plan to Win the Blue Sky Defense War. Air quality has gradually improved in China in recent years, but the Beijing–Tianjin–Hebei (BTH) region is still the most polluted area in China based on particulate matter with aerodynamic diameters of <2.5 μm ($PM_{2.5}$) levels. With 74 cities participating in the air quality composite index in 2017, 9 of the 10 cities with

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Table 1 – Air quality concentration limits (GB 3095-2012).

Pollutant	Index	Limit (μg/m^3)	
		Level I	Level II
Sulfur dioxide (SO_2)	Annual average	20	60
	Daily average	50	150
Nitrogen dioxide (NO_2)	Annual average	40	40
	Daily average	80	80
Ozone (O_3)	1-hr average	160	200
	Maximum eight-hour average	100	160
Particulate matter with aerodynamic diameters of <10 μm (PM_{10})	Annual average	40	70
	Daily average	50	150
Particulate matter with aerodynamic diameters of <2.5 μm ($PM_{2.5}$)	Annual average	15	35
	Daily average	35	75

Levels I and II refer to different air quality functional area, the level I concentration limit applies to the primary air quality functional area and the level II concentration limit applies to the secondary air quality functional area.

the worst air quality are located in the air pollution transmission channel (Ministry of Ecology and Environment, 2018a).

The Ministry of Ecology and Environment of China issued a new Environmental Air Quality Standard (GB 3095-2012) to replace GB 3095-1996 in 2012 (Table 1). According to the Air Pollution Prevention and Control Plan (State Council, 2013), by 2017, the concentration of inhalable particulate matter at the prefecture level and above should be reduced by more than 10% compared with 2012, and the number of fine air quality days should increase annually. Additionally, the concentration of fine particulate matter in Beijing–Tianjin–Hebei, the Yangtze River Delta and the Pearl River Delta should decline by 25%, 20%, and 15%, respectively, and the annual average concentration of fine particulate matter in Beijing should be controlled at about 60 μg/m^3. According to the Three-Year Action Plan to Win the Blue Sky Defense War (State Council, 2018), the ratio of days with good air quality at the prefecture-level and above will reach 80% in 2020.

The World Health Organization (WHO) proposed the concept of population exposure as events in which people come into contact with a pollutant of a certain concentration during a certain period of time. According to a WHO report in 2014, one in eight total global deaths (around 7 million people)

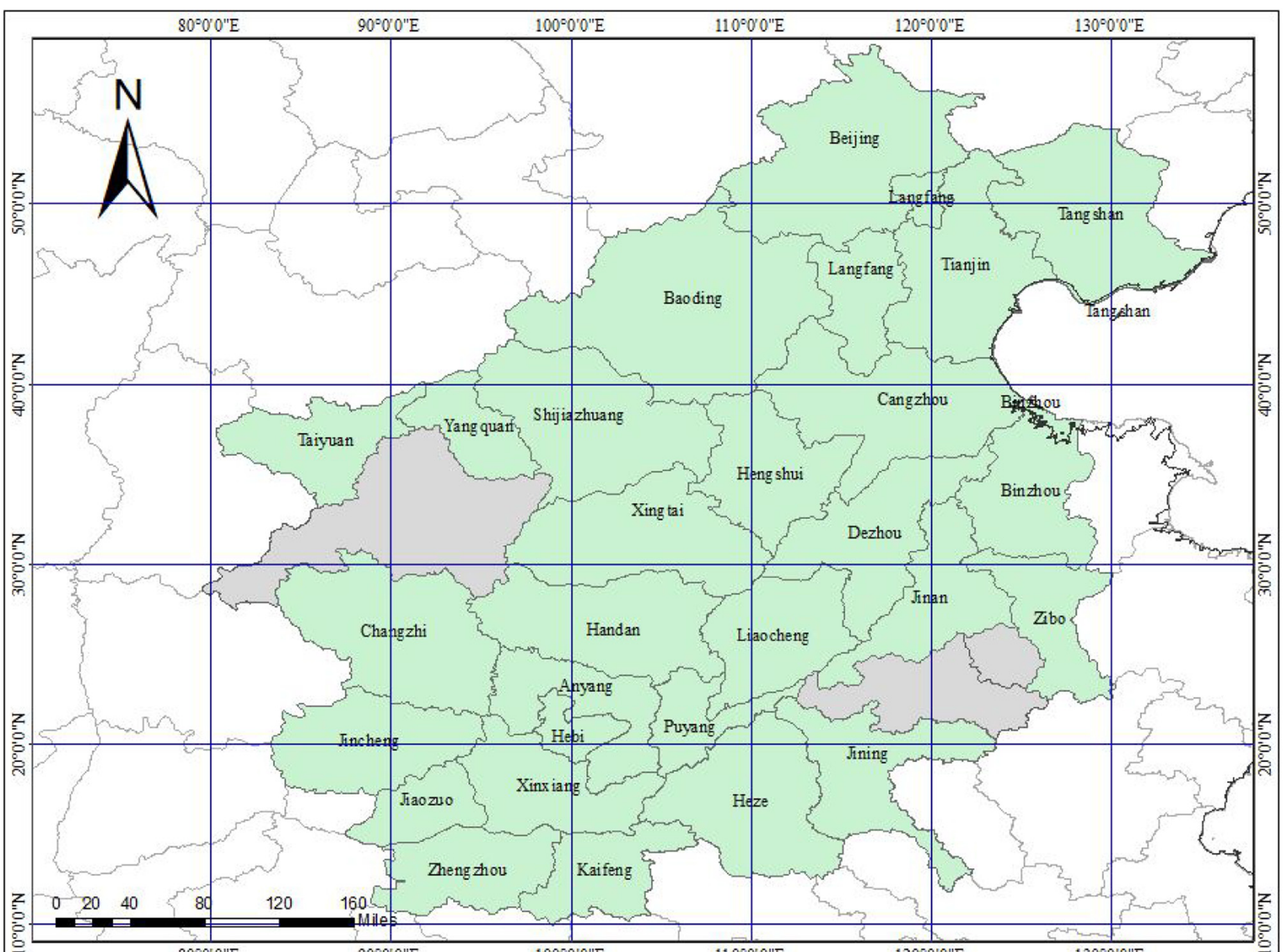

Fig. 1 – Geographical location of Beijing–Tianjin–Hebei (BTH) and surrounding 31 cities.

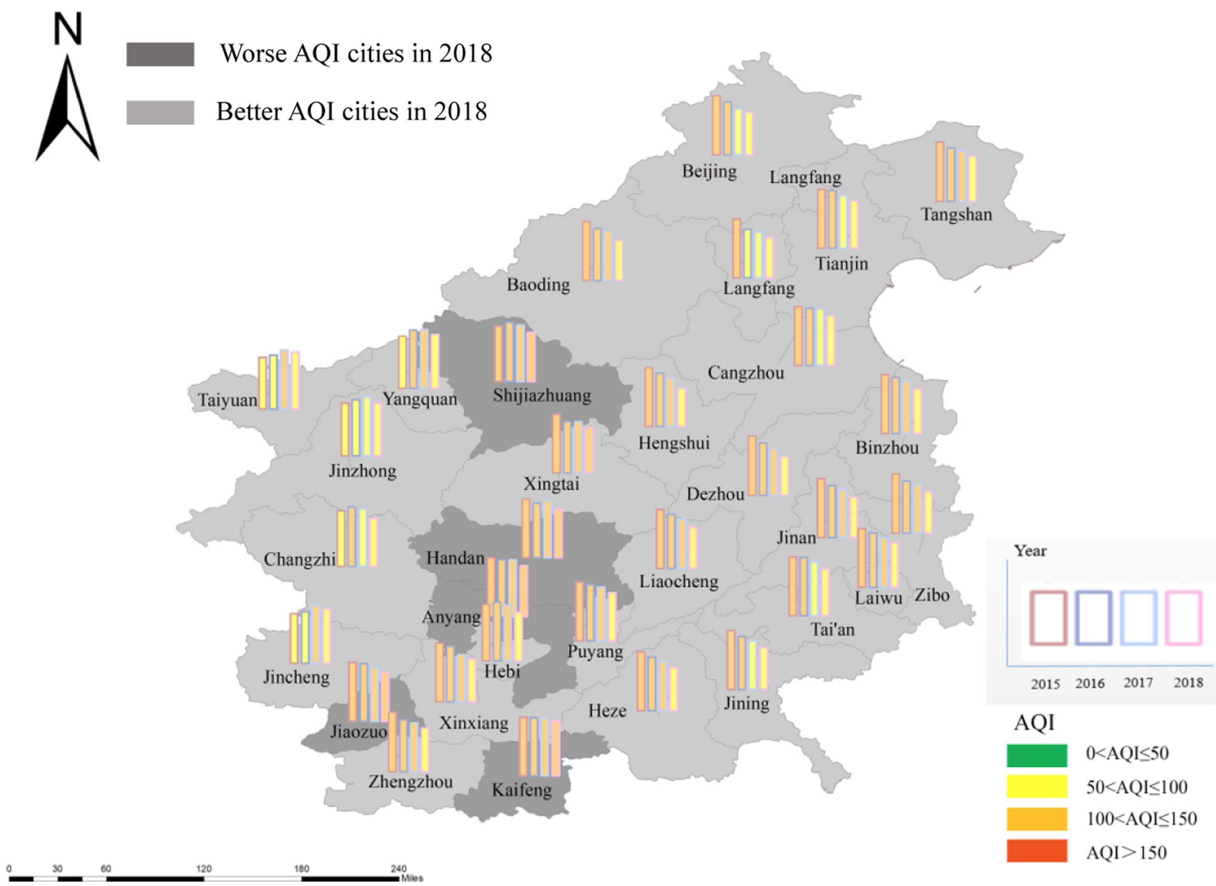

Fig. 2 – Spatial and temporal distribution of air quality index (AQI) of BTH and surrounding cities in 2015–2018.

were a result of air pollution exposure (WHO, 2014; Omidvarborna et al., 2018). Moreover, deaths associated with the economic burden of air pollution cost the global economy about 225 billion USD in lost labor income in 2013 (World Bank, 2016). Additionally, the total economic losses because of ambient air pollution were 154.5–180.3 billion USD, accounting for approximately 5.7%–6.6% of the total Gross domestic product (GDP) of China in 2006 (Miao et al., 2017). The persistent air pollution in China has had great economic and social costs (Hao et al., 2018; Chen et al., 2013; Azam, 2016). Therefore, this study incorporates population indicators into air quality assessments to characterize the impact of air quality on exposed populations.

In recent years, many studies have analyzed the temporal and spatial distribution characteristics of air quality in China (Wang et al., 2014; Song et al., 2017; Filonchyk et al., 2016; Hu et al., 2014; Li et al., 2018a; Yu et al., 2014; Yan et al., 2015; Zhang et al., 2015). Song et al. (2017) proposed a population-weighted air quality index. Other studies (Filonchyk et al., 2016; Hu et al., 2014; Li et al., 2018a) analyzed the correlation between $PM_{2.5}$ and PM_{10} in Gansu, the Yangtze River Delta, and Beijing–Tianjin–Hebei. Yu et al. (2014), Yan et al. (2015), and Zhang et al. (2015) used short-term observation data, and analyzed the heavy haze episode characteristics of cities such as Beijing, Hangzhou and Shanghai. Yu et al. (2018) evaluated a novel precision air pollution control approach (PAPCA) to mitigate severe urban haze events. Additionally, the spatial correlation of air quality between cities in China has been analyzed (Hu et al., 2014; Wang and Zhao, 2018), as has the influence of meteorological factors on $PM_{2.5}$ (Tai et al., 2010; Zhang et al., 2018). Other studies have investigated the correlation between socioeconomic indicators such as population density, unit energy consumption, GDP, and air quality (Li et al., 2018a; Zhu et al., 2017; Wang et al., 2017).

However, few studies have investigated seasonal or hourly trends for different air quality pollutants, and most studies have not considered the amount of population exposed. More importantly, because of the lack of continuous monitoring data for companies responsible for industrial atmospheric emissions, previous studies did not consider the impact of the continuous monitoring data of industrial pollution sources on air quality from the perspective of big data. Therefore, in this study, we used continuous air quality monitoring data (including $PM_{2.5}$, PM_{10}, SO_2, NO_2 and O_3) and pollution source emission monitoring data of the BTH and surrounding cities to establish new indicators for urban air quality portraits, including air quality seasonal indices, air quality population exposure, and hourly mean changes in air quality. Moreover, we analyzed the temporal and spatial distribution characteristics of $PM_{2.5}$, PM_{10}, SO_2, NO_2, and O_3. Furthermore, the effects of industrial pollution source emission and meteorological factors on air quality were investigated. The data generated in this study were then used to provide targeted suggestions for improving the air quality of air pollution transmission channels in BTH and surrounding cities.

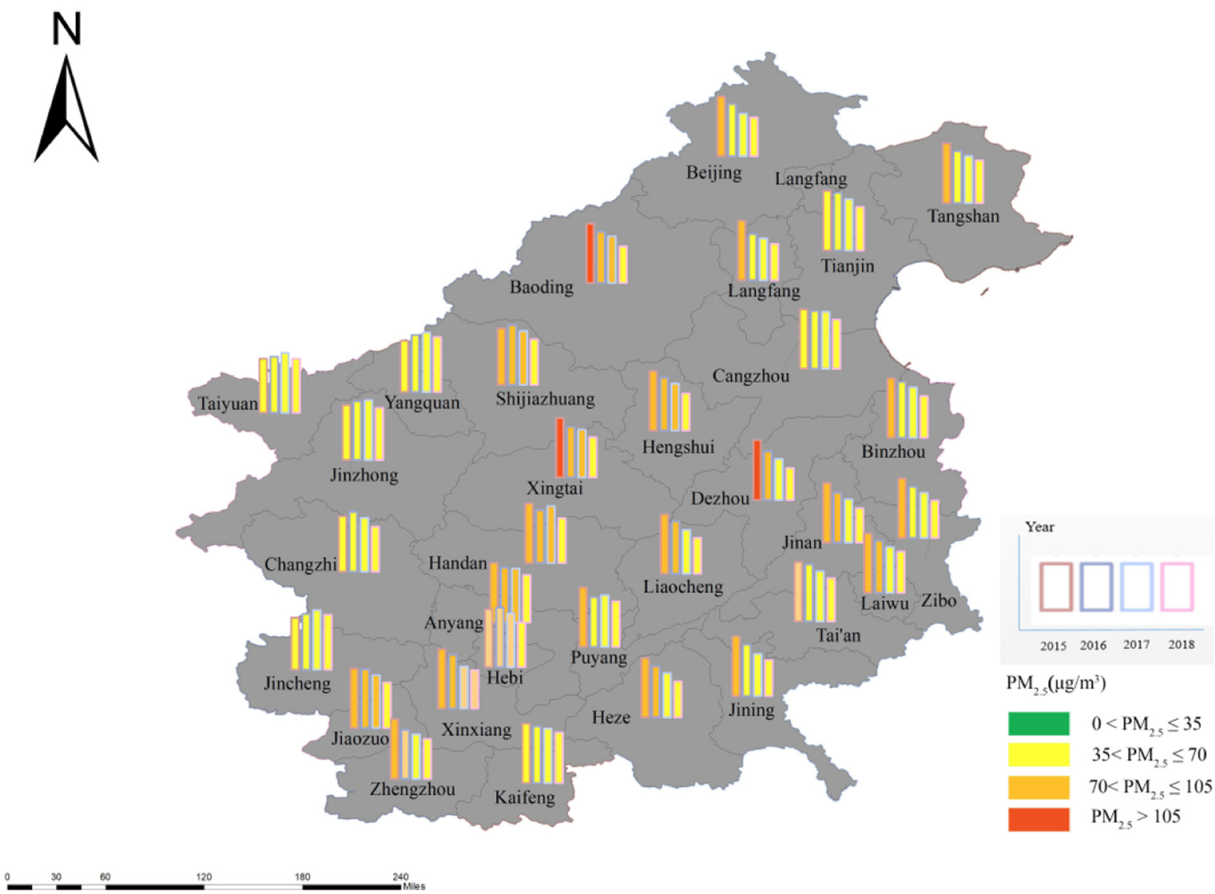

Fig. 3 – Spatial and temporal distribution of $PM_{2.5}$ of BTH and surrounding cities in 2015–2018.

1. Materials and methods

1.1. Study areas

The "Air Pollution Prevention and Control Work Plan of Beijing–Tianjin–Hebei and Surrounding Area in 2017" (Ministry of Ecology and Environment, 2017) defines the scope of the Beijing–Tianjin–Hebei air pollution transport channel cities (APTCC), including 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 (hereinafter referred to as "2 + 26" cities). In order to make the Beijing–Tianjin–Hebei air pollution transmission channel more complete, this study has added 3 cities, Shanxi Jinzhong, Shandong Laiwu and Tai'an, with a research scope of 31 cities (Fig. 1).

1.2. Data source and description

The air quality data (including $PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3 and CO) in 31 cities were collected from the National Urban Air Quality Real-time Publishing Platform of the Ministry of Ecology and Environment (http://106.37.208.233:20035/). The air pollution source data were collected from the continuous monitoring data of pollutants (SO_2, nitrogen oxides (NO_x) and particulate matter) emitted by air polluting enterprises in 31 cities.

In this study, the air quality indices were measured by the daily average, 8-hr moving average, monthly average, and annual average as defined in the China Ambient Air Quality Standard (GB 3095-2012). Among them, the 8-hr moving average refers to the arithmetic mean of the average concentration for 8 consecutive hours. The 24-hr average refers to the arithmetic mean of the 24-hr average concentration, which is also known as the daily average. The monthly average refers to the arithmetic mean of the average daily concentration for a calendar month. The annual average refers to the arithmetic mean of the average daily concentration for a calendar year. The annual O_3 values were based on the 90th percentile of the maximum 8-hr moving average of the day in a calendar year.

The procedure for calculation of the 90th percentile of the O_3 concentration sequence is as follows:

(1) Sort the O_3 concentrations from small to large, and sort the concentration sequence as {$Ozone_i$, i = 1, 2, …… n};

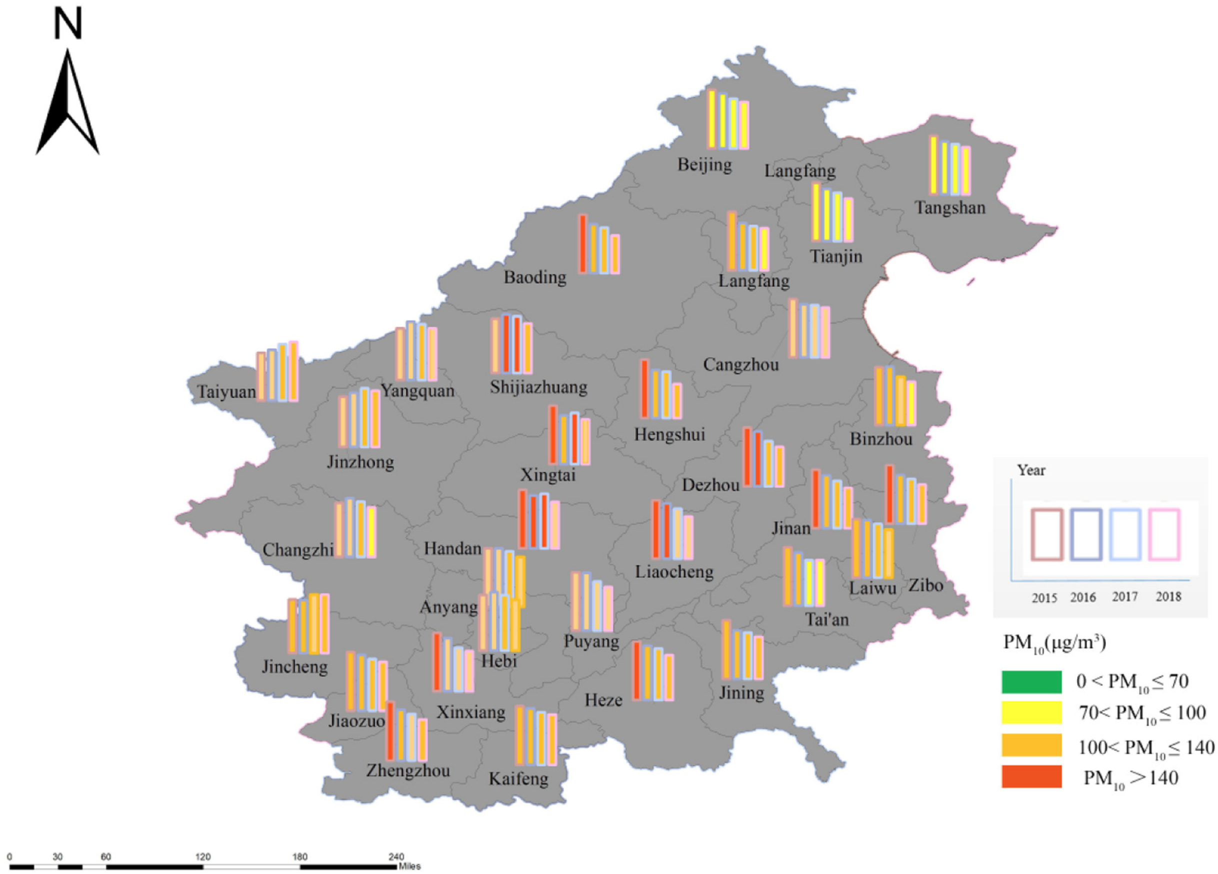

Fig. 4 – Spatial and temporal distribution of PM_{10} of BTH and surrounding cities in 2015–2018.

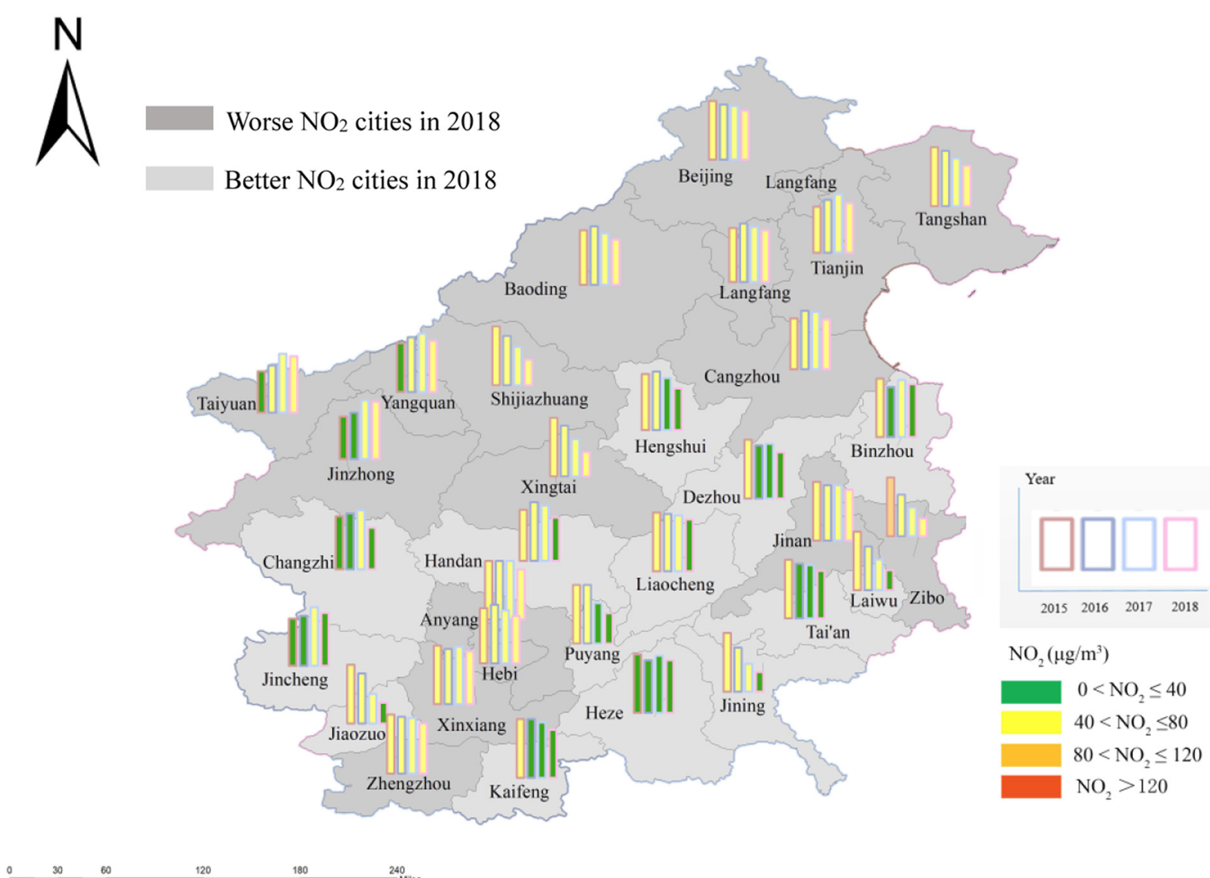

Fig. 5 – Spatial and temporal distribution of NO_2 of BTH and surrounding cities in 2015–2018.

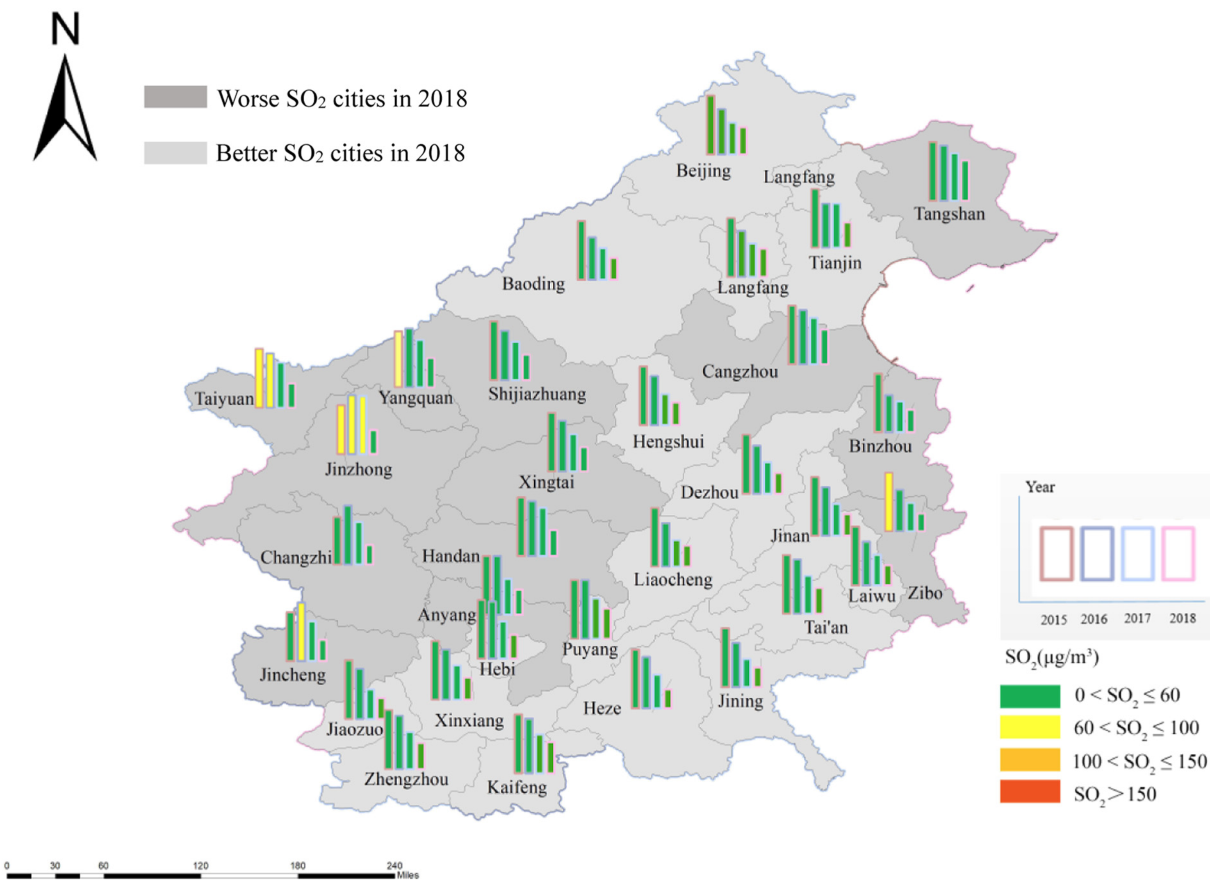

Fig. 6 – Spatial and temporal distribution of SO_2 of BTH and surrounding cities in 2015–2018.

(2) Calculate the ordinal number, k, of the 90th percentile (m_{90}):

$$k = 1 + (n-1) \times 90\% \tag{1}$$

(3) Calculate the 90th percentile:

$$m_{90} = \mathrm{Ozone}_s + (\mathrm{Ozone}_{(s+1)} - \mathrm{Ozone}_s) \times (k-s) \tag{2}$$

where, n is the number of concentration values in the ozone concentration sequence, s is the integer part of k, and s and k are equal when k is an integer.

1.3. Methods and models

1.3.1. Seasonal index

Seasonal indices are generally used for forecasting commodity sales, market yields, and crop growth in economic, social or agricultural activities (Liu et al., 2008; Ci et al., 2015). If there is no seasonal change in development of the phenomenon, the seasonal index of each period should be equal to 100%; however, if there is a significant seasonal change in a certain month or quarter, the seasonal index of each period should be greater or less than 100%. In this study, we used seasonal index indicators to reflect seasonal variations in air quality. The degree of seasonal variation was determined by the degree of deviation of each seasonal index from its average (100%). The seasonal index (C) was calculated by Eq. (3):

$$C = \overline{x}_{ij} / \overline{\overline{x_j}} \tag{3}$$

where, $\overline{x}_{ij}$ represents the average air quality observations of the same month or the same season in the j-th city and $\overline{\overline{x_j}}$ represents the average of all months or quarters of the j-th city in recent years.

1.3.2. Pearson correlation coefficient

The Pearson correlation coefficient is a nonparametric indicator that measures the dependence of two variables (He, 2015). We used the Pearson correlation index to measure the correlation between the daily average emission concentrations of different pollutants in APTCC cities, such as that between the $PM_{2.5}$ and PM_{10} in Beijing. The Pearson correlation coefficient (ρ) was calculated by Eq. (4):

$$\rho_{(X,Y)} = \frac{\sum_{ij}(X_{ij}-\overline{X}_j)(Y_{ij}-\overline{Y}_j)}{\sqrt{\sum_{ij}(X_{ij}-\overline{X}_j)^2 \sum_i (Y_{ij}-\overline{Y}_j)^2}} \tag{4}$$

where, X_{ij}, Y_{ij} represent the daily average air quality concentrations of different pollutants in city j.

1.3.3. Population exposure

Air quality has an important impact on population health (WHO, 2014; Omidvarborna et al., 2018). We proposed the indicator of air quality population exposure (AQPE) to

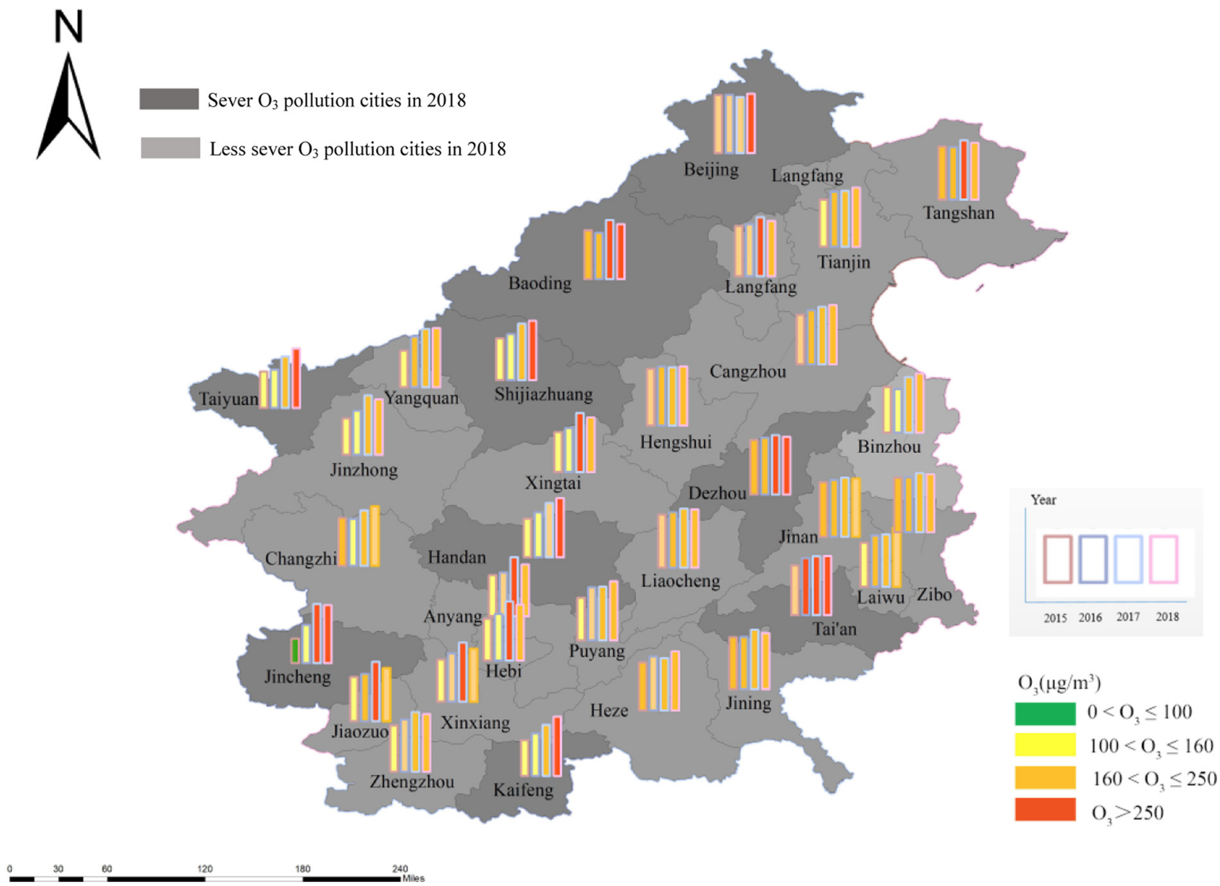

Fig. 7 – Spatial and temporal distribution of O_3 of BTH and surrounding cities in 2015–2018.

characterize the amount of population are affected by air pollution. The AQPE is defined as follows:

$$\mathrm{AQPE}_{mj} = \mathrm{Airpollution}_{mj} \times \mathrm{Population}_j / \mathrm{Area}_j \quad (5)$$

where, $\mathrm{Airpollution}_{mj}$ represents the annual average concentration of the m-th pollutant in j-th city (O_3 is the 90-percentile of the daily maximum 8-hr sliding average in a calendar year), $\mathrm{Population}_j$ indicates the total urban population of the j-th city and Area_j indicates the urban area of the j-th city.

1.3.4. *Multiple linear regression model*

We used air quality continuous monitoring data (including $PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3) and pollution source emission monitoring data (including SO_2, NO_x, soot) while considering the influence of meteorological factors to establish a multivariate linear regression model to identify the effects of industrial atmospheric emissions on air quality in BTH and surrounding cities. The average daily concentration of air pollutants was taken as the dependent variable, the average concentration of exhaust pollutants discharged by industrial enterprises was considered the independent variable, and factors such as meteorology (e.g., temperature, wind level, precipitation) were used as controls. The temperature data were the daily average temperatures (i.e., the mean daily maximum and minimum temperatures), and the rainfall (snowfall) was set as a dummy variable to indicate the influence of meteorological factors on air quality.

$$\mathrm{Airquality}_{mj} = \lambda_{mj} + \beta_{mj}\mathrm{IP}_{mj} + \delta_{mj}\mathrm{Rain} + \gamma_{mj}\mathrm{Tem} + \alpha_{mj}\mathrm{Wind} + \varepsilon \quad (6)$$

where, $\mathrm{Airquality}_{mj}$ represents the concentration of air pollutants including $PM_{2.5}$, PM_{10}, SO_2 and NO_2 in the j-th city, IP_{mj} represents the concentration of industrial pollutants in the j-th city, and Rain, Tem and Wind represent rainfall (snowfall), daily average temperature, and wind level, respectively. λ_{mj}, β_{mj}, δ_{mj}, γ_{mj}, and α_{mj} are the influence parameters of the regression model, ε is the error term or disturbance term. The statistical characteristics of the main variables in the multiple regression model are shown in Appendix A Table S1.

2. Results and discussion

2.1. *Air quality analysis*

2.1.1. *Annual change and regional distribution*

The air quality index (AQI) in BTH and the surrounding cities improved significantly from 2015 to 2018, especially in Hengshui, Baoding, Liaocheng, Dezhou and Jinan (Fig. 2). From the perspective of spatial distribution, air quality in Kaifeng, Jiaozuo, Handan, Shijiazhuang, Anyang is generally poor compared with other BTH cities in 2018. In Fig. 2, the AQI

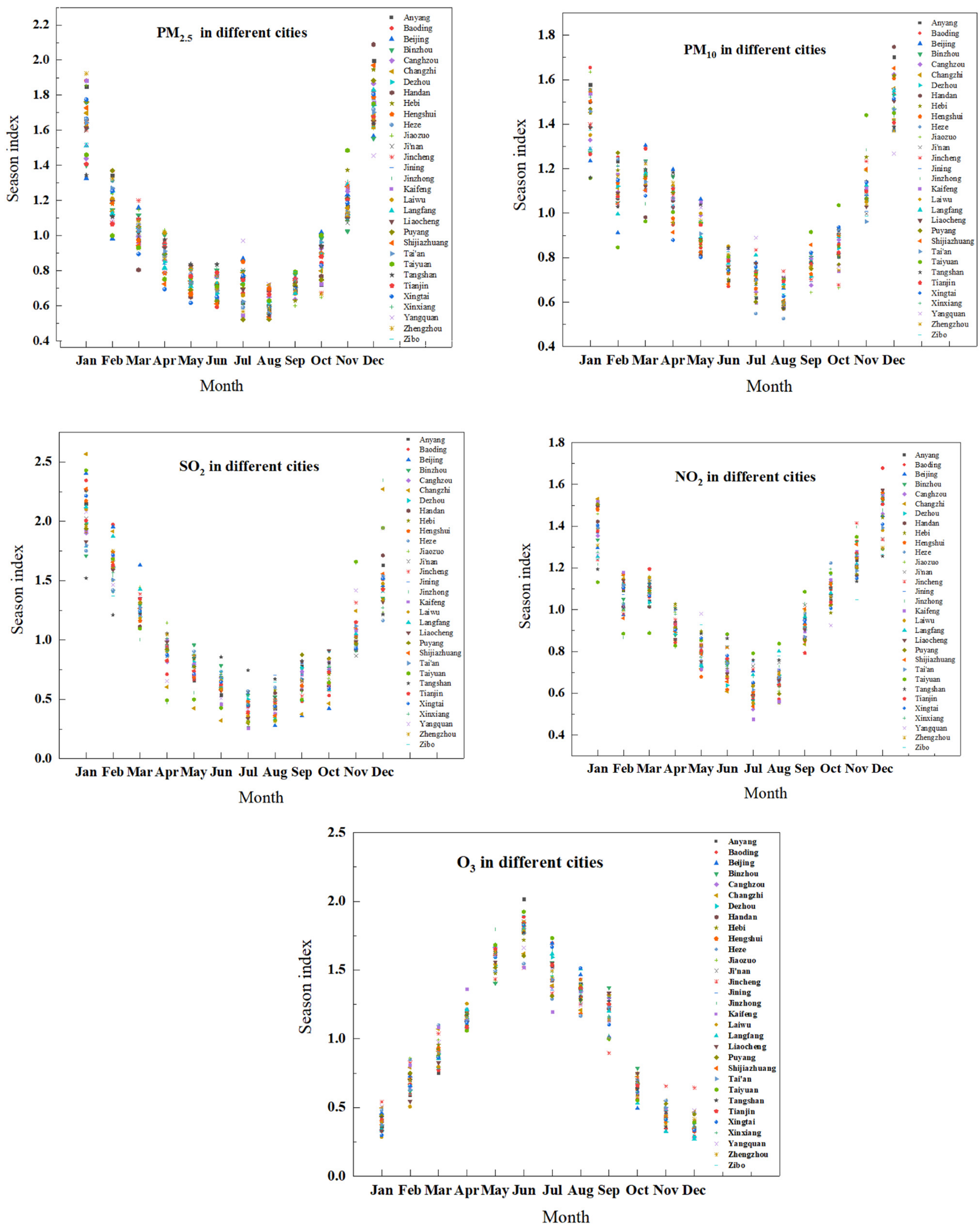

Fig. 8 – Analysis of seasonal indices of different pollutants in BTH and surrounding cities in 2015–2018.

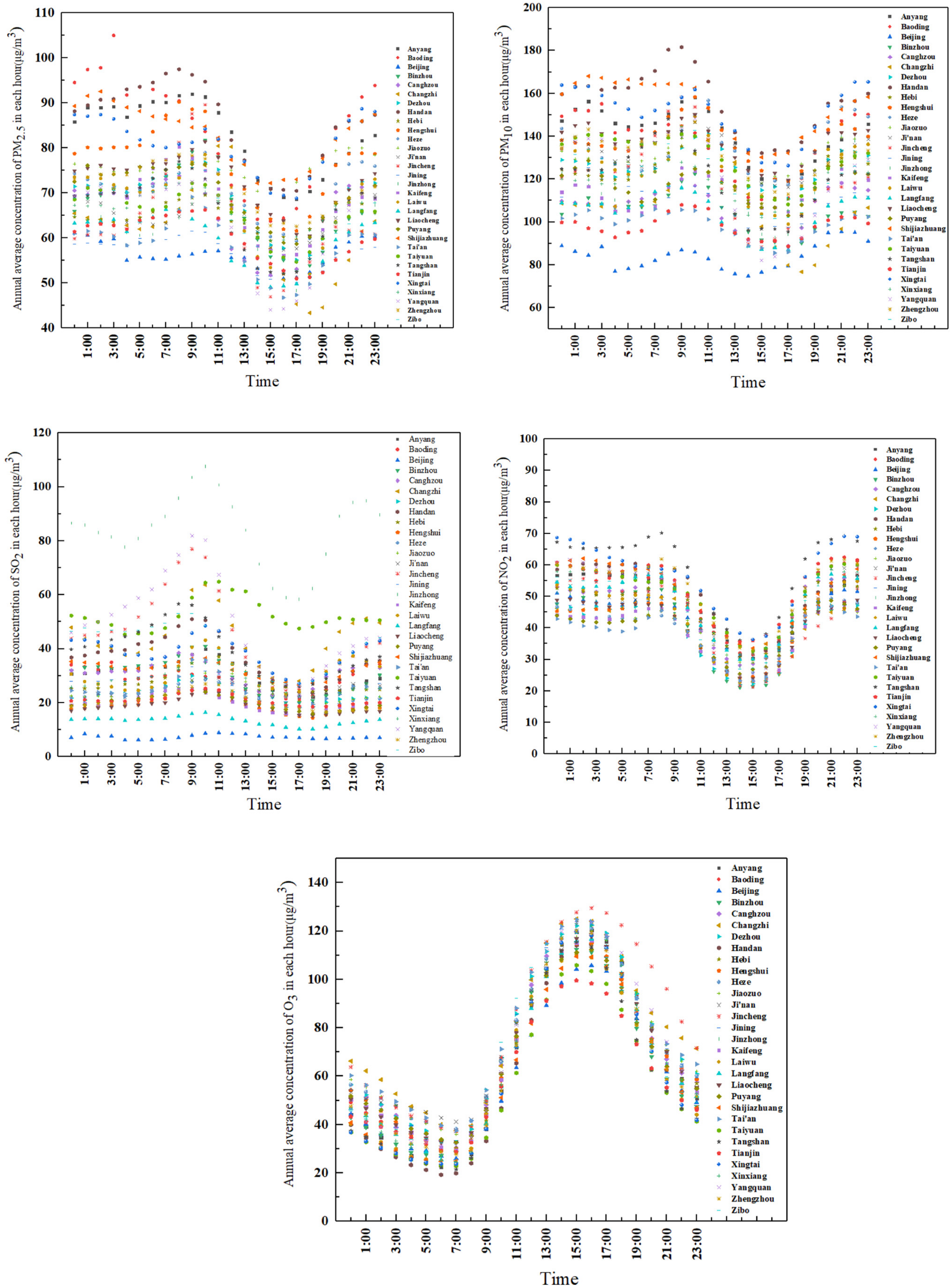

Fig. 9 – Trends in hourly concentration of different pollutants in BTH and surrounding cities.

of Shijiazhuang, Xingtai, Handan, Anyang still exceeded the national standard in 2018.

Specifically, the $PM_{2.5}$ concentrations of most of the 31 cities decreased significantly, especially in Beijing, Tangshan, Xingtai, Baoding, Zhengzhou, Langfang, Hengshui, Jinan, Zibo, Tai'an, and Laiwu (Fig. 3). Additionally, the average annual concentration of $PM_{2.5}$ in 31 cities in 2018 was 58.5 μg/m^3, which was 39.5% lower than that of 81.6 μg/m^3 in 2017, but still exceeded the national standard of 35 μg/m^3 in 2018. BTH and surrounding cities are concentrated in the power, steel, chemical raw material and manufacturing, nonmetallic mineral products, petroleum processing, and coking industries (Institute of Public and Environmental Affairs, 2018). Industrial boilers, building materials, as well as steel and coking industries are the dominant emitters of $PM_{2.5}$ (Hao and Yin, 2016).

The average annual concentration of PM_{10} in 2018 was 110.5 μg/m^3, which was 26.1% lower than 139 μg/m^3 in 2015. However, the average annual concentrations of $PM_{2.5}$ and PM_{10} of 31 cities in 2018 still had not reached the national standard, and the $PM_{2.5}$ concentration was generally higher than 48 μg/m^3, while the PM_{10} was generally higher than 77 μg/m^3. The average annual concentration of PM_{10} in all 31 cities exceeded the standard (Fig. 4).

The average annual concentration of NO_2 in 2018 was lower than in 2015 in most of the 31 cities. In 2018, the annual average concentration of NO_2 in cities such as Tangshan, Taiyuan, Zhengzhou, Xingtai, Xinxiang, Shijiazhuang, Langfang, Tianjin, Jinan, Baoding, Jinzhong, Yangquan, Hebi and Anyang exceeded the standard, indicating that NO_2 pollution control needs further improvement (Fig. 5).

However, the annual average concentration of SO_2 in the 31 cities was 19.5 μg/m^3 in 2018, which was 139% lower than that in 2015, and levels in all cities reached the national standards (Fig. 6). This is related to the desulfurization and denitrification projects in key industries in recent years, such as the installation of desulfurization facilities in coal-fired power plants (State Council, 2013).

When compared with 2015, the maximum 8-hr 90th quantitation concentration of ozone in 2018 was increased in Tianjin, Shijiazhuang, Tangshan, Handan, Xingtai, Baoding, Zhengzhou, Langfang, Taiyuan, Yangquan, Jincheng, Jinan, and Zibo (Fig. 7). In 2018, the maximum 8-hr 90th quantile concentration in the 31 cities exceeded 160 μg/m^3, with the highest levels being observed at 211 μg/m^3. From 2015 to 2018, the maximum 8-hr 90th quantitation concentration of ozone in cities such as Beijing, Tai'an, Zibo, Dezhou, Handan and Kaifeng showed a deteriorating trend. These findings indicate that great improvements are still needed in the air quality control of Beijing–Tianjin–Hebei and the surrounding areas.

2.1.2. *Seasonal index analysis*

This study analyzed the seasonal coefficients of $PM_{2.5}$, PM_{10}, SO_2, NO_2 and O_3 during 2015–2018. The results showed that the seasonal trends of $PM_{2.5}$, PM_{10}, SO_2 and NO_2 in Beijing–Tianjin–Hebei and the surrounding areas are consistent. The seasonal trends of PM_{10}, SO_2 and NO_2 showed a "U" type distribution from January to December (Fig. 8). The seasonal variability of PM_{10}, SO_2 and NO_2 was more obvious in January, July, August and December, with lower values being observed in July and August, and higher values in January and December. The concentrations of $PM_{2.5}$, PM_{10}, SO_2 and NO_2 were high in winter and low in summer (Lv et al., 2016; Wang et al., 2014).

The seasonal variation of O_3 was opposite to that of $PM_{2.5}$, PM_{10}, SO_2 and NO_2. Ozone pollution showed an "inverted U" distribution trend from January to December (Fig. 8). The seasonal variation of O_3 in January, February, June, July, November, and December was more obvious, being highest in June and July and lowest in January, November, and December. Ozone pollution tended to be high in summer and low in winter, which is consistent with existing research (Li et al., 2018b; Wu et al., 2018).

2.1.3. *Hourly change analysis*

We analyzed the hourly variations in $PM_{2.5}$, PM_{10}, SO_2, NO_2 and O_3. The results showed that $PM_{2.5}$ and PM_{10} in BTH and the surrounding areas had similar hourly trends. From 0:00 to 7:00,

Table 2 – Air quality population exposure (AQPE) in BTH and surrounding cities (μg/m^3 per 10,000 people/km^2).

City name	AQPE of $PM_{2.5}$	AQPE of PM_{10}	AQPE of SO_2	AQPE of NO_2	AQPE of O_3_8 hr
Six district average in Beijing	80.9	107.8	8.4	68.9	295.5
Beijing	4.2	6.4	0.5	3.3	15.8
Tianjin	4.5	7.5	1.0	3.9	17.5
Shijiazhuang	13.3	25.0	4.0	8.7	38.4
Tangshan	4.4	8.3	2.4	3.9	14.2
Handan	9.4	18.5	2.9	5.5	27.8
Xingtai	14.2	27.7	5.2	9.8	42.5
Baoding	7.2	12.6	2.2	4.9	23.4
Canghzou	17.2	30.6	6.8	12.1	59.5
Langfang	15.1	29.1	3.1	13.1	56.0
Hengshui	3.0	5.0	0.7	1.6	9.5
Taiyuan	11.2	25.6	5.3	9.3	36.0
Yangquan	6.3	12.1	3.2	4.5	19.9
Changzhi	11.5	21.3	4.5	6.5	41.4
Jincheng	15.8	31.9	6.4	10.1	55.5
Jinzhong	2.5	5.3	1.7	2.0	8.5
Ji'nan	4.9	10.5	1.6	4.1	19.7
Zibo	5.3	10.3	2.4	3.9	19.2
Jining	5.5	11.2	2.2	3.9	21.4
Tai'an	3.9	7.7	1.3	2.6	14.4
Laiwu	3.4	6.4	1.1	2.3	11.3
Dezhou	2.9	5.8	0.8	1.8	11.1
Liaocheng	4.2	8.2	1.0	2.6	14.9
Binzhou	3.5	5.9	1.4	2.4	13.1
Heze	4.0	8.3	0.9	2.5	13.8
Zhengzhou	9.7	17.8	2.2	7.3	27.5
Kaifeng	10.6	18.5	2.7	5.6	31.6
Anyang	15.8	27.8	4.6	9.1	42.3
Hebi	5.1	10.5	1.7	3.9	18.8
Xinxiang	14.7	26.8	4.5	11.4	49.2
Jiaozuo	11.3	21.0	2.8	6.5	32.9
Puyang	16.6	28.0	4.2	9.0	50.8

O_3_8 hr is the O_3 values which based on the 90th percentile of the maximum 8-hr moving average of the day in a calendar year, so the AQPE of O_3_8 hr is the air quality population exposure (AQPE) of O_3_8hr.

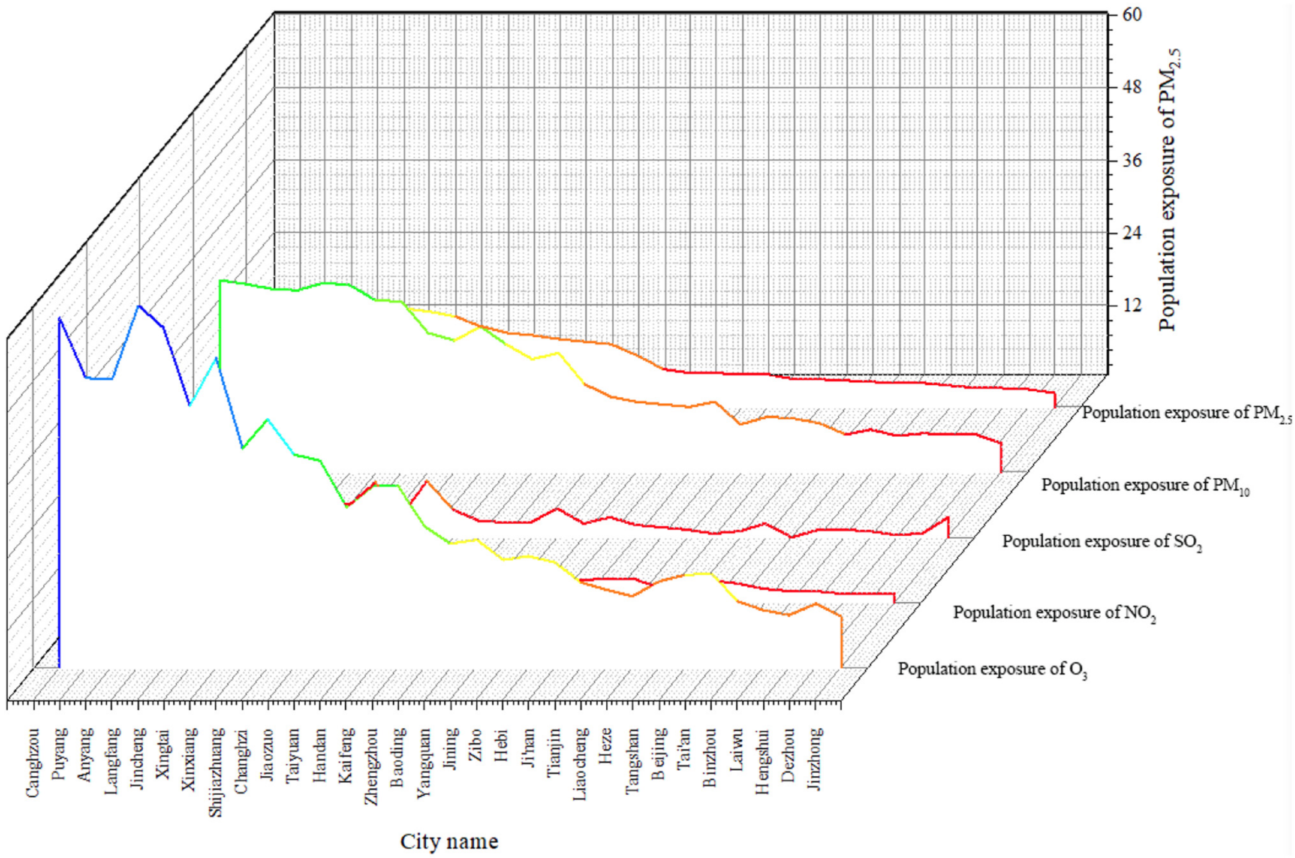

Fig. 10 – Comparison of AQPE of different pollutants in BTH and the 31 surrounding cities in 2018.

the $PM_{2.5}$ and PM_{10} levels showed an upward trend, after which they decreased until 16:00, at which time they rose again (Fig. 9). The peak $PM_{2.5}$ and PM_{10} levels were observed around 7:00 and 9:00, which may have been related to mobile source emissions. Specifically, the driving of heavy-duty diesel vehicles at night likely caused more $PM_{2.5}$ and PM_{10} pollution (http://www.wenming.cn/xj_pd/ssrd/201409/t20140905_2163692.shtml), while traffic congestion in the morning and evening peaks caused increases in $PM_{2.5}$, PM_{10} and NO_2 concentrations (Liu et al., 2017; Xiao et al., 2019).

When compared with $PM_{2.5}$ and PM_{10}, the SO_2 hourly trend was relatively flat, and the peak SO_2 pollution occurred from 10:00 to 12:00 in individual cities. The lowest concentration of NO_2 pollution occurred between 13:00 and 15:00 in the afternoon (Fig. 9). NO_2 pollution is affected by many factors, including meteorological events and traffic. The pollution diffusion conditions between 13:00 and 15:00 are better and traffic is less congested in this period (Beijing Institute of Transportation Development, 2018). The hourly variations in O_3 pollution were very obvious, and the trend was opposite to that of NO_2. The peak O_3 pollution occurred between 14:00 and 17:00, and there was a negative correlation between NO_2 and O_3 (Tiwari et al., 2015).

2.2. Air quality population exposure

This study established indicators of air quality population exposure. Because of the lack of data pertaining to population and area, the study used the population and regional area indicators in the China Urban Statistical Yearbook (2017). The air quality data used were from 2018, and it was assumed that the inter-annual changes in the population densities of the 31 cities were relatively stable. Beijing is a large-scale city in China that has an extremely dense population (Beijing Municipal Bureau of Statistics, 2018) that is mainly concentrated in six districts of Beijing (Dongcheng District, Xicheng District, Haidian District, Chaoyang District, Fengtai District, and Shijingshan District). This study analyzed the air quality population exposure of these six districts in Beijing. The results showed that the population density of these 6 districts was highest among the 31 investigated cities and 10 times that of the average density. Therefore, the population exposure of each pollutant was highest for these districts. Specifically, the $PM_{2.5}$ exposure in the six Districts of Beijing was about 9.6 times the average of the 31 cities, while that of PM_{10} was about 7.1 times the average (Table 2). In addition, the air quality population exposures to $PM_{2.5}$ and PM_{10} in Zhengzhou, Puyang, Anyang, Jincheng, Xingtai, Xinxiang, Shijiazhuang and Changzhi were also higher than the average.

Exposure of the population to SO_2 in Jincheng, Taiyuan, Changzhi, Zhengzhou, Xingtai and other cities was found to be higher than the average level for the 31 cities (2.75 $\mu g/m^3$ per 10,000 people/km^2) and the national average (4.09 $\mu g/m^3$ per 10,000 people/km^2). The exposure to NO_2 and O_3 in

Table 3 – Correlation analysis of different air pollutants in BTH and surrounding cities.

City	$PM_{2.5}$			PM_{10}		SO_2
	PM_{10}	SO_2	NO_2	SO_2	NO_2	NO_2
Beijing	0.873	0.559	0.723	0.485	0.605	0.565
Tianjin	0.829	0.575	0.724	0.480	0.564	0.728
Shijiazhuang	0.924	0.663	0.741	0.570	0.732	0.607
Tangshan	0.883	0.525	0.781	0.490	0.692	0.676*
Handan	0.913	0.552	0.735	0.628	0.755	0.691*
Xingtai	0.939	0.610	0.767	0.603	0.794	0.710*
Baoding	0.922	0.771	0.763	0.675	0.724	0.667
Cangzhou	0.894	0.606	0.678	0.503	0.565	0.641
Langfang	0.902	0.657	0.722	0.546	0.618	0.684
Hengshnui	0.852	0.586	0.702	0.587	0.615	0.622
Taiyuan	0.889	0.800	0.720	0.613	0.711	0.650
Yangquan	0.861	0.583	0.701	0.487	0.632	0.759
Changzhi	0.905	0.651	0.683	0.590	0.690	0.811
Jincheng	0.884	0.577	0.554	0.551	0.580	0.689
Jinzhong	0.854	0.748	0.652	0.586	0.643	0.612
Jinan	0.912	0.590	0.629	0.552	0.610	0.569
Zibo	0.900	0.591	0.728	0.533	0.643	0.736
Jining	0.893	0.511	0.629	0.406	0.518	0.610
Taian	0.905	0.649	0.717	0.546	0.622	0.696
Laiwu	0.894	0.690	0.686	0.602	0.575	0.628
Dezhou	0.873	0.577	0.618	0.514	0.502	0.600
Liaocheng	0.939	0.507	0.632	0.458	0.563	0.728
Binzhou	0.913	0.616	0.635	0.599	0.594	0.758
Heze	0.876	0.422	0.662	0.434	0.627	0.475
Zhengzhou	0.882	0.526	0.587	0.549	0.548	0.584
Kaifeng	0.825	0.582	0.656	0.464	0.497	0.728
Anyang	0.908	0.700	0.736	0.651	0.693	0.747
Hebi	0.901	0.666	0.647	0.643	0.640	0.524
Xinxiang	0.909	0.514	0.621	0.539	0.630	0.572
Jiaozuo	0.941	0.486	0.706	0.537	0.699	0.640
Puyang	0.873	0.613	0.706	0.567	0.636	0.779

Significance: 1% level.

Langfang, Zhengzhou, Xinxiang, Xingtai, Jincheng, Puyang, Anyang and Xingtai was higher than the average level for the 31 cities and the national average (Fig. 10).

Beijing is the economic, political and cultural center of China, and the population density of six districts in Beijing is much higher than that of the BTH region and other cities. The results of the present study showed that the AQPE of the six districts in Beijing was highest. The AQPE in Yangquan, Xingtai, Zhengzhou, Changzhi, Shijiazhuang, Jiaozuo, Anyang, Xinxiang, Baoding, Kaifeng, Jinzhong, Handan, Taiyuan and other cities was also higher than the average level (we use different colors to represent the exposure level of different pollutants). Accordingly, attention should be paid to these higher air quality population exposure cities.

2.3. Correlation analysis of various pollutants

Pearson correlation analysis was used to measure the correlation of different air pollutants in each 31 cities (here we use the air quality data of 2017). The significance level was defined as p, the correlation coefficient was difined as r. The results showed that there were positive synergistic effects of $PM_{2.5}$, PM_{10}, SO_2 and NO_2 in BTH and the 31 surrounding cities, especially the correlation between $PM_{2.5}$ and PM_{10} in Shijiazhuang ($p = 0.000$, $r = 0.924$), Handan ($p = 0.000$, $r = 0.913$), Xingtai ($p = 0.000$, $r = 0.939$), Langfang ($p = 0.000$, $r = 0.902$), Ji'nan ($p = 0.000$, $r = 0.912$), Tai'an ($p = 0.000$, $r = 0.905$) and Binzhou ($p = 0.000$, $r = 0.913$) (Table 3), Beijing ($p = 0.000$, $r = 0.873$) (Fig. 11). Therefore, it is recommended that the coordinated management of air pollution prevention and control in cities with air pollution transmission channels be strengthened, and that the synergistic effects of different pollutant emission reduction strategies be considered.

2.4. Correlation analysis of the effects of industrial air pollution source emissions and meteorological factors on air quality

Industrial pollution sources have huge emissions and are important human factors affecting air quality (Wang et al., 2018; Qiao et al., 2017). Meteorological conditions have a great impact on air quality (Hu et al., 2014; Tai et al., 2010; Zhang et al., 2018); therefore, their effects should be considered when analyzing the impact of industrial pollution emissions. Accordingly, the present study used meteorological factors as control variables and established a regression model of the impact of industrial air pollution sources on air quality in BTH and surrounding cities.

From the perspective of big data statistics, we used massive amounts of air quality continuous monitoring data (including $PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3), pollution source emission monitoring data (including SO_2, NO_x, soot), meteorological data (including temperature, wind level, precipitation) of 31 cities in 2017, took meteorological factors (e.g., temperature, wind level, precipitation) and industrial waste gas emission concentrations (SO_2, NO_x, soot) as the influencing variables, and established a multivariate regression model to find the influence of meteorological factors and industrial pollution emissions on air quality.

The results revealed a negative correlation between meteorological factors such as wind speed, daily average temperature and precipitation and air quality (Appendix A Table S2). Specifically, greater wind levels were associated with lower air quality pollutant concentrations. Moreover, the concentrations of air quality pollutants under precipitation conditions were lower than under non-precipitation conditions, the average temperature in winter was much lower than that during summer, and the concentration of air quality pollutants in winter was generally higher than that in summer.

Specifically, temperature factors in most cities, including Anyang, Baoding, Beijing, Binzhou, Zhengzhou, Changzhi, Dezhou, Handan, Hengshui, Jinan, Jining, Kaifeng, Langfang, Laiwu, Puyang, Taiyuan, Tangshan, Xingtai, Yangquan and Zhengzhou, were negatively correlated with $PM_{2.5}$, PM_{10}, SO_2 and NO_2. Additionally, wind factors in Baoding, Beijing, Changzhi, Dezhou, Jiaozuo, Kaifeng, Langfang, Shijiazhuang, Taiyuan, Tangshan, Tianjin, Yangquan and Zhengzhou were negatively correlated with $PM_{2.5}$, SO_2 and NO_2.

Industrial smoke and SO_2 emission concentrations in Anyang, Beijing, Binzhou, Dezhou, Jiaozuo, Jining, Kaifeng, and Puyang were found to be positively correlated with $PM_{2.5}$, PM_{10} and SO_2, indicating that industrial air pollution sources have an important impact on the air quality of these cities.

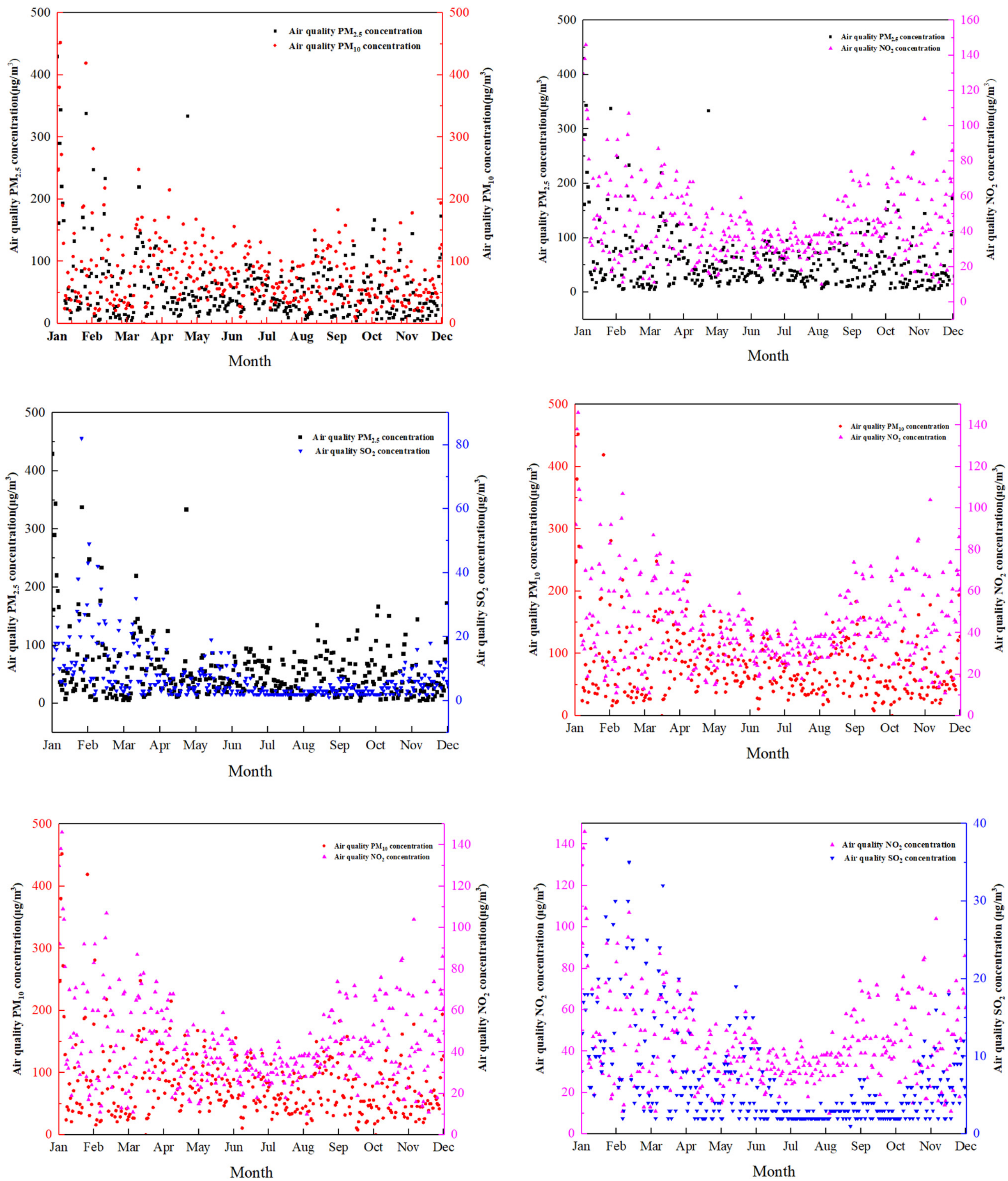

Fig. 11 – Correlation analysis of air pollutants in Beijing in 2017.

However, there were no obvious correlations between the concentrations of various pollutants emitted by industries in urban areas such as Baoding, Cangzhou, Changzhi, Hengshui, and Langfang and other air pollutants. Overall, air quality may be related to other types of pollution sources or other influencing factors, such as mobile sources and non-point sources (Ministry of Ecology and Environment, 2018b).

3. Conclusions

This study established an indicator system for urban air quality portraits to analyze the characteristics of air quality changes in BTH and surrounding cities of China. In addition, we established a multivariate regression model to analyze the impact of meteorological and industrial air pollution emissions on air quality that provides a decision-making basis for further improving the ambient air quality in BTH and the surrounding areas.

The results showed that significant overall improvement of $PM_{2.5}$ and PM_{10} pollution occurred in BTH and the surrounding areas from 2015 to 2018, but that $PM_{2.5}$ and PM_{10} still exceeded the air quality standard, and deterioration in ozone quality was obvious. The air quality indicators showed marked seasonal and hourly characteristics, with winter influencing $PM_{2.5}$, PM_{10}, SO_2, and NO_2 and summer influencing O_3.

The population density of 6 districts in Beijing was highest among the 31 investigated cities and had the greatest population exposure to air pollution. Therefore, it is important to further reduce the population of urban Beijing and effectively improve its air quality. In addition, the AQPE in Zhengzhou, Puyang, Anyang, Jincheng, Xingtai, Xinxiang, and Langfang was found to be higher than the average value for the 31 investigated cities and the national average.

The urban air quality of BTH and air pollution transmission channels is greatly affected by meteorological factors. Additionally, industrial pollution emissions and air quality in Anyang, Beijing, Binzhou, Dezhou, Jiaozuo, Jining, Kaifeng and Puyang are positively correlated, indicating that industrial air pollution sources have an important impact on the air quality of these cities.

The results of this study suggest that air quality should be concerned with the amount of population exposed, so air pollution control should take into account factors such as population exposure and industrial pollution emissions. The study also suggests consideration of joint prevention and control of inter-regional and urban areas to improve urban air quality in the APTCC cities.

This study focused on the distribution characteristics of air quality and analyzed the correlation between meteorological factors and industrial air pollution source emissions and air quality. Future research should take into account the impact of pollution emissions from key industries on air quality, and focus on analysis at the industry level.

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Appendix A. Supplementary data

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