Study on Spatial-temporal Variation of Atmospheric Pollution in China between 2014 and 2019

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Abstract: The study in this paper reveals that the atmospheric contaminants in mainland China is of concentricity in spatial distribution, persistence in temporal distribution and correlation between different parameters. This spatial-temporal variation law plays an important role in improving and addressing the problem with atmospheric environment of given cities and regions by employing focused and pointed measures. In this paper, seven kinds of atmospheric pollution parameters including PM2.5, PM10, AQI, CO, NO2, O3 and SO2 in 370 Chinese cities from 2014 to 2019 are analyzed based on their hourly mass concentration. The spatial-temporal variations of each parameter in each separated year are obtained by using interpolation calculation towards the annual atmospheric pollution parameters. The results show that higher mass concentration (including the highest mass concentration) of PM2.5,AQI, PM10, CO, NO2, SO2 mainly concentrated in Beijing-Tianjin-Hebei region in the northeast of mainland China and its neighboring regions and Xinjiang region in the northwest of mainland China. The spatial variation of PM2.5, AQI, PM10, CO, NO2, SO2 experienced similar trend. Higher mass concentration (including the highest mass concentration) of O3 mainly concentrated in Qinghai and Inner Mongolia in the central

north of mainland China and Shandong on the right side of Beijing-Tianjin-Hebei region. The spatial variation of O₃ experienced different trend from that of other parameters. PM_{2.5}, AQI, PM₁₀ indicated increase and decrease, followed by increase and decrease again with time, which was a S-shaped change. Almost the same temporal variation happened to PM_{2.5}, AQI, PM₁₀ and to CO, NO₂, SO₂, which was opposite to O₃. The analysis from the perspective of the annual highest mass concentration of PM_{2.5}, AQI, PM₁₀, NO₂ and O₃ indicates the atmospheric environment of mainland China had not been authentically improved by 2019. The analysis from the perspective of the annual highest mass concentration of CO and SO₂ indicates the atmospheric environment of mainland China had been authentically improved by 2019. What should we do immediately is to strengthen environmental governance and address the source of contamination in Beijing-Tianjin-Hebei region in the northeast of China, Xinjiang region in the northwest of China, Qinghai and Inner Mongolia regions in the central north of China.

Keywords: atmospheric particulates, contaminated gas, spatial-temporal variation, Beijing-Tianjin-Hebei region, Xinjiang region

Introduction: At present, a great number of cities in China confront severe situation associated with air pollution, which has become an environmental and social problem drawing much concerns of the general public ^[1-2]. In general, the relative humidity of

fog is higher than 90%, but the haze would come into being with this index less than 80% and atmospheric particulates increasing. In people's daily life, the concentration of atmospheric particulates could witness an upward trend due to many industrial, agricultural and architectural practices, such as the emission of contaminants from power plants, the combustion of such biomass as straw ^[19], the development of real state and the construction of various infrastructures. Among these, PM_{2.5}, a chief culprit, is a kind of so fine atmospheric particulate (aerodynamic diameter is no more than 2.5 μm) that it could easily pass through the nasal cavity and respiratory tract and directly enter bronchi and pulmonary alveoli. Also, it is of great difficulty for our bodies to release them by depending on metabolic process ^[6]. Meanwhile, the large superficial area and strong adsorption capacity of PM_{2.5} make itself become a mighty carrier to diffuse microorganisms like bacteria and virus ^[19], organic cyanides, dioxins^[3], heavy metals^[3,14,17] and other kinds of carcinogenic substances. Long-term exposure to such substances could increase the risk of getting cancer to a large extent^[4]. Also, regional pollution^[8,9] induced by CO, NO₂, SO₂, O₃ ^[10,11] is increasingly remarkable. In some pivotal cities located in the Beijing-Tianjin-Hebei region and its surrounding areas, Xinjiang, Qinghai, Inner Mongolia, developed Yangtze River Delta region and Pearl River Delta region, haze pollution is frequent and continuous and leads to visibility reduction in a long period^[12-13]. The air quality of these cities is not only far worse than that of developed countries in Europe and America, but also worse than that of other regions in China.

1 Sample collection and analysis approach

According to the data derived from the Ministry of Ecology and Environment of the People's Republic of China^[24], Beijing Municipal Environmental Monitoring Center^[23], Beijing Bureau of Statistics^[21], the hourly atmospheric pollution parameters related to PM_{2.5}, PM₁₀, AQI, CO, NO₂, O₃, SO₂ in 370 Chinese cities from the year 2014 to 2019 were collected in this paper. The analysis approach employed here is to implement Radial Basis Functions (RBF)-based interpolation calculation towards the annual atmospheric pollution parameters of each category through Arcgis. As a consequence, atmospheric pollution parameters in mainland China could be shown in the form of spatial-temporal distribution diagrams. By further statistics, the top ten cities with higher mass concentration of each air pollution parameter per year between 2014 and 2019 were selected out of the 370 cities, and the frequency of their occurrences was also evaluated and analyzed.

2. Discussion and analysis

2.1 The spatial-temporal variation of PM_{2.5} in mainland China from 2014 to 2019

From Figure 1, it can be seen that the Beijing-Tianjin-Hebei region in the northeast of mainland China and Xinjiang region in the northwest of mainland China showed higher mass concentration (including the highest mass concentration) of pm_{2.5}

from the year 2014 to 2019. There was a similar trend between the spatial variation of PM_{2.5} and it of AQI, PM₁₀, CO, NO₂, SO₂ analyzed in the following content, but that of O₃ would indicate a different trend compared with PM_{2.5}. The highest annual mass concentration of PM_{2.5} was 161 $\mu\text{g}\cdot\text{m}^{-3}$, 201 $\mu\text{g}\cdot\text{m}^{-3}$, 204 $\mu\text{g}\cdot\text{m}^{-3}$, 187 $\mu\text{g}\cdot\text{m}^{-3}$, 217 $\mu\text{g}\cdot\text{m}^{-3}$, 183 $\mu\text{g}\cdot\text{m}^{-3}$ respectively in every separated year between 2014 and 2019. The highest mass concentration of PM_{2.5} in the year 2018 and 2014 were the highest and lowest among the six years, reaching 217 $\mu\text{g}\cdot\text{m}^{-3}$ and 161 $\mu\text{g}\cdot\text{m}^{-3}$ respectively. In addition, this index represented increase and then decrease, followed by an increase and decrease again, a kind of S-shaped change with time. The temporal variation of PM_{2.5} had a similar trend to that of AQI, PM₁₀. On the other hand, from the perspective of the annual highest mass concentration of PM_{2.5}, it can be analyzed that the atmospheric condition of mainland China had not been authentically improved until the year 2019.

Figure 1. The spatial-temporal variation of the mass concentration of PM2.5 in mainland China from 2014 to 2019.

Table 1 indicates the ten cities with higher mass concentration of PM2.5 among 370 cities over the six-year period from 2014 to 2019, from which it can be seen that the proportions represented by some cities located in Beijing-Tianjin-Hebei region and Xinjiang region were about 5/6 and 1/6 respectively, with a lower proportion made up by some cities bordering Beijing-Tianjin-Hebei region. Among these records, Baoding and Xingtai, two cities situated in Beijing-Tianjin-Hebei region, combined with Kashi and Hetian, two areas situated in Xinjiang region, ranked the top of the list five to six times in the six years.

Table 1. Ten cities with higher mass concentration of PM2.5 among 370 cities from 2014 to 2019.

2014 PM2.5			2015 PM2.5			2016 PM2.5		
City	Belongs to area	Concentration/ ($\mu\text{g}\cdot\text{m}^{-3}$)	City	Belongs to area	Concentration ($\mu\text{g}\cdot\text{m}^{-3}$)	City	Belongs to area	Concentration/ ($\mu\text{g}\cdot\text{m}^{-3}$)
Baoding ⁽⁵⁾	Jingjinji	117	Kashi area ⁽⁵⁾	Xinjiang	118	Kashi area ⁽⁵⁾	Xinjiang	157
Xingtai ⁽⁶⁾	Jingjinji	105	Baoding ⁽⁵⁾	Jingjinji	106	Hetian area ⁽⁵⁾	Xinjiang	107
Handan ⁽⁴⁾	Jingjinji	100	Dezhou ⁽²⁾	Shandong (border jingjinji)	101	Shijiazhuang ⁽⁴⁾	Jingjinji	94
Shijiazhuang ⁽⁴⁾	Jingjinji	99	Xingtai ⁽⁶⁾	Jingjinji	101	Baoding ⁽⁵⁾	Jingjinji	92
Dezhou ⁽²⁾	Shandong (border jingjinji)	97	Hengshui ⁽⁴⁾	Jingjinji	98	Akesu area ⁽²⁾	Xinjiang	91
Hengshui ⁽⁴⁾	jingjinji	96	Hetian area ⁽⁵⁾	Xinjiang	98	Hengshui ⁽⁴⁾	Jingjinji	87
Liaocheng ⁽³⁾	Shandong (border jingjinji)	94	Liaocheng ⁽³⁾	Shandong (border jingjinji)	98	Xingtai ⁽⁶⁾	Jingjinji	87
Laiwu ⁽²⁾	Shandong (border jingjinji)	90	Zhengzhou ⁽¹⁾	Henan (border jingjinji)	95	Liaocheng ⁽³⁾	Shandong (border jingjinji)	86
Tangshan ⁽¹⁾	Jingjinji	90	Heze ⁽¹⁾	Shandong (border jingjinji)	94	Jiazuo ⁽¹⁾	Henan (border jingjinji)	85
Langfang ⁽¹⁾	Jingjinji	89	Xinxiang ⁽¹⁾	Henan (border jingjinji)	93	Anyang ⁽⁴⁾	Henan (border jingjinji)	85

2017 PM2.5			2018 PM2.5			2019 PM2.5		
City	Belongs to area	Concentration/ ($\mu\text{g}\cdot\text{m}^{-3}$)	City	Belongs to area	Concentration ($\mu\text{g}\cdot\text{m}^{-3}$)	City	Belongs to area	Concentration ($\mu\text{g}\cdot\text{m}^{-3}$)
Kashi area ⁽⁵⁾	Xinjiang	100	Hetian area ⁽⁵⁾	Xinjiang	117	Hetian area ⁽⁵⁾	Xinjiang	108
Hetian area ⁽⁵⁾	Xinjiang	92	Kashi area ⁽⁵⁾	Xinjiang	94	Laiwu ⁽²⁾	Shandong (border jingjinji)	106
Handan ⁽⁴⁾	Jingjinji	86	Akesu area ⁽²⁾	Xinjiang	74	Shangqiu ⁽¹⁾	Henan (border jingjinji)	94
Baoding ⁽⁵⁾	Jingjinji	84	Anyang ⁽⁴⁾	Henan (border jingjinji)	69	Kashi area ⁽⁵⁾	Xinjiang	85
Linfen ⁽³⁾	shanxi (border Jingjinji)	82	Shijiazhuang ⁽⁴⁾	Jingjinji	68	Anyang ⁽⁴⁾	Henan (border jingjinji)	67
Anyang ⁽⁴⁾	Henan (border jingjinji)	82	Linfen ⁽³⁾	shanxi (border Jingjinji)	67	Handan ⁽⁴⁾	Jingjinji	63
Shijiazhuang ⁽⁴⁾	Jingjinji	82	Xingtai ⁽⁶⁾	Jingjinji	66	Xingtai ⁽⁶⁾	Jingjinji	62
Xingtai ⁽⁶⁾	Jingjinji	81	Handan ⁽⁴⁾	Jingjinji	65	Luoyang ⁽¹⁾	Henan (border jingjinji)	60
Xianyang ⁽¹⁾	shanxi (border Jingjinji)	79	Baoding ⁽⁵⁾	Jingjinji	65	Linfen ⁽³⁾	shanxi (border Jingjinji)	59
Hengshui ⁽⁴⁾	Jingjinji	77	Xuzhou ⁽¹⁾	Jiangsu	62	Puyang ⁽¹⁾	Henan (border jingjinji)	59

***(1),(2),(3),(4),(5),(6): the frequency of these cities ranking the top ten from 2014 to 2019**

From Figure 2, it can be seen that the Beijing-Tianjin-Hebei region and its surrounding region in the northeast of mainland China and Xinjiang region in the northwest of mainland China showed higher mass concentration (including the highest mass concentration) of AQI from the year 2014 to 2019. There was a similar trend between the spatial variation of AQI and it of the above PM2.5 and the following PM10, CO, NO2, SO2, but it of O3 would indicate a different trend compared with AQI. The highest mass concentration of AQI was 161, 201, 204,187, 217,183 respectively in every separated year between 2014 and 2019. The highest AQI in the

year 2018 and 2014 were the highest and lowest among the six years, reaching 217 $\mu\text{g}\cdot\text{m}^{-3}$ and 161 $\mu\text{g}\cdot\text{m}^{-3}$ respectively. In addition, this index represented increase and then decrease, followed by an increase and decrease again, a kind of S-shaped change with time. The temporal variation of AQI had a similar trend to that of the above PM_{2.5} and the following PM₁₀. On the other hand, from the perspective of the annual highest AQI, it can be analyzed that the atmospheric condition of mainland China had not been authentically improved until the year 2019.

Figure 2. The spatial-temporal variation of the annual average AQI in mainland China from 2014 to 2019

According to Table 2 which indicates the ten cities with higher mass concentration of AQI among 370 cities over the six-year period from 2014 to 2019, it can be seen that the proportions represented by some cities located in Beijing-Tianjin-Hebei region and Xinjiang region were almost the same, at about 1/2, with a lower proportion made up by some cities bordering Beijing-Tianjin-Hebei region. Among these records, Baoding, Xingtai and Handan, three cities situated in Beijing-Tianjin-Hebei region, combined with Kashi, Hetian, Aksu and Kezhou, four areas situated in Xinjiang region, ranked the top of the list four to five times in the six years.

Table 2. Ten cities with higher annual average AQI and their affiliated regions from 2014 to 2019.

2014 AQI			2015 AQI			2016 AQI		
City	Belongs to area	AQI	City	Belongs to area	AQI	City	Belongs to area	AQI
Baoding ⁽⁴⁾	Jingjinji	162	Hetian area ⁽⁵⁾	Xinjiang	201	Kashi area ⁽⁵⁾	Xinjiang	205
Xingtai ⁽⁵⁾	Jingjinji	146	Kashi area ⁽⁵⁾	Xinjiang	198	Hetian area ⁽⁵⁾	Xinjiang	184
Hengshui ⁽³⁾	Jingjinji	143	Akesu area ⁽⁵⁾	Xinjiang	148	Akesu area ⁽⁵⁾	Xinjiang	155
Handan ⁽⁴⁾	Jingjinji	140	Baoding ⁽⁴⁾	Jingjinji	144	Kezhou area ⁽⁵⁾	Xinjiang	147
Shijiazhuang ⁽⁴⁾	Jingjinji	138	Hengshui ⁽³⁾	Jingjinji	141	Kuerle ⁽³⁾	Xinjiang	133
Dezhou ⁽³⁾	Shandong (border Jingjinji)	131	Dezhou ⁽³⁾	Shandong (border Jingjinji)	139	Shijiazhuang ⁽³⁾	Jingjinji	131
Liaozheng ⁽²⁾	Shandong (border Jingjinji)	130	Xingtai ⁽⁵⁾	Jingjinji	138	Baoding ⁽⁴⁾	Jingjinji	128
Langfang ⁽¹⁾	Jingjinji	127	Kezhou area ⁽⁵⁾	Xinjiang	137	Tulufan area ⁽⁴⁾	Xinjiang	127
Tangshan ⁽¹⁾	Jingjinji	126	Zhengzhou ⁽¹⁾	Henan (border jingjinji)	135	Hengshui ⁽³⁾	Jingjinji	126
Heze ⁽¹⁾	Shandong (border Jingjinji)	125	Liaozheng ⁽²⁾	Shandong (border Jingjinji)	134	Dezhou ⁽³⁾	Shandong (border Jingjinji)	123
2017 AQI			2018 AQI			2019 AQI		
City	Belongs to area	AQI	City	Belongs to area	AQI	City	Belongs to area	AQI
Hetian area ⁽⁵⁾	Xinjiang	187	Hetian area ⁽⁵⁾	Xinjiang	217	Hetian area ⁽⁵⁾	Xinjiang	184
Kashi area ⁽⁵⁾	Xinjiang	162	Kashi area ⁽⁵⁾	Xinjiang	180	Kashi area ⁽⁵⁾	Xinjiang	152
Akesu area ⁽⁵⁾	Xinjiang	135	Kezhou area ⁽⁵⁾	Xinjiang	155	Laiwu ⁽¹⁾	Shandong (border Jingjinji)	142
Handan ⁽⁴⁾	Jingjinji	126	Akesu area ⁽⁵⁾	Xinjiang	153	Shangqiu ⁽¹⁾	Henan (border jingjinji)	134
Anyang ⁽³⁾	Henan (border jingjinji)	123	Tulufan area ⁽⁴⁾	Xinjiang	122	Akesu area ⁽⁵⁾	Xinjiang	120
Xingtai ⁽⁵⁾	Jingjinji	122	Kuerle ⁽³⁾	Xinjiang	121	Kezhou area ⁽⁵⁾	Xinjiang	118
Baoding ⁽⁴⁾	Jingjinji	122	Anyang ⁽³⁾	Henan (border jingjinji)	115	Kuerle ⁽³⁾	Xinjiang	116
Shijiazhuang ⁽³⁾	Jingjinji	122	Xingtai ⁽⁵⁾	Jingjinji	114	Tulufan area ⁽⁴⁾	Xinjiang	112
Xianyang ⁽²⁾	shanxi (border Jingjinji)	121	Handan ⁽⁴⁾	Jingjinji	114	Anyang ⁽³⁾	Henan (border jingjinji)	106
Kezhou area ⁽⁵⁾	Xinjiang	120	Wujiaqu ⁽¹⁾	Xinjiang	113	Handan ⁽⁴⁾	Jingjinji	102
Tulufan area ⁽⁴⁾	Xinjiang	120	Xianyang ⁽²⁾	Shanxi (border Jingjinji)	112	Xingtai ⁽⁵⁾	Jingjinji	100

***(1),(2),(3),(4),(5),(6): the frequency of these cities ranking the top ten from 2014 to 2019**

From Figure 3, it can be seen that the Beijing-Tianjin-Hebei region and its

surrounding region in the northeast of mainland China and Xinjiang region in the

northwest of mainland China showed higher mass concentration (including the highest mass concentration) of PM10 from the year 2014 to 2019. There was a similar trend between the spatial variation of PM10 and it of the above PM2.5 and AQI and the following CO, NO2 and SO2, but it of the following O3 would indicate a different trend compared with PM10. The highest mass concentration of PM10 was 196 $\mu\text{g}\cdot\text{m}^{-3}$, 340 $\mu\text{g}\cdot\text{m}^{-3}$, 434 $\mu\text{g}\cdot\text{m}^{-3}$, 317 $\mu\text{g}\cdot\text{m}^{-3}$, 432 $\mu\text{g}\cdot\text{m}^{-3}$, 334 $\mu\text{g}\cdot\text{m}^{-3}$ respectively in every separated year between 2014 and 2019. The highest PM10 in the year 2016 and 2014 were the highest and lowest among the six years, reaching 434 $\mu\text{g}\cdot\text{m}^{-3}$ and 196 $\mu\text{g}\cdot\text{m}^{-3}$ respectively. In addition, this index represented increase and then decrease, followed by an increase and decrease again, a kind of S-shaped change with time. The temporal variation of PM10 had a similar trend to that of the above PM2.5 and AQI. On the other hand, from the perspective of the annual highest mass concentration of PM10, it can be analyzed that the atmospheric condition of mainland China had not been authentically improved until the year 2019.

Figure 3. The spatial-temporal variation of the annual average mass concentration of PM10 in mainland China from 2014 to 2019

According to Table 3 which indicates the ten cities with higher mass concentration of PM10 among 370 cities over the six-year period from 2014 to 2019, it can be seen that the proportions represented by Beijing-Tianjin-Hebei region and Xinjiang region were about 1/2, with a lower proportion made up by some areas bordering Beijing-Tianjin-Hebei region. Among these records, Handan, a city situated in Beijing-Tianjin-Hebei region, combined with Kashi, Hetian, Aksu and Kezhou, four areas situated in Xinjiang region, ranked the top of the list five to six times in the six years.

Table 3. Ten cities with higher annual average mass concentration of PM10 and their affiliated regions from 2014 to 2019

2014 PM10			2015 PM10			2016 PM10		
City	Belongs to area	Concentration /($\mu\text{g}\cdot\text{m}^{-3}$)	City	Belongs to area	Concentration /($\mu\text{g}\cdot\text{m}^{-3}$)	City	Belongs to area	Concentration /($\mu\text{g}\cdot\text{m}^{-3}$)
Baoding ⁽²⁾	Jingjinji	198	Hetian area ⁽⁵⁾	Xinjiang	341	Kasha area ⁽⁵⁾	Xinjiang	435
Xingtai	Jingjinji	187	Kasha area ⁽⁵⁾	Xinjiang	308	Hetian area ⁽⁵⁾	Xinjiang	283
Hengshui ⁽²⁾	Jingjinji	176	Akesu area ⁽⁵⁾	Xinjiang	217	Akesu area ⁽⁵⁾	Xinjiang	246
Handan ⁽⁶⁾	Jingjinji	174	Kezhou ⁽⁵⁾	Xinjiang	186	Kezhou ⁽⁵⁾	Xinjiang	217
Shijiazhuang ⁽³⁾	Jingjinji	172	Hengshui ⁽²⁾	Jingjinji	176	Kuerle ⁽⁵⁾	Xinjiang	210
Liaocheng ⁽²⁾	Shandong (border jingjinji)	165	Baoding ⁽²⁾	Jingjinji	175	Tulufan area ⁽⁴⁾	Xinjiang	170
Linyi ⁽¹⁾	Shandong (border jingjinji)	163	Xingtai ⁽¹⁾	Jingjinji	172	Shijiazhuang ⁽³⁾	Jingjinji	161
Zibo ⁽¹⁾	Shandong (border jingjinji)	161	Handan ⁽⁶⁾	Jingjinji	167	Dezhou ⁽²⁾	Shandong (border jingjinji)	152
Jinan ⁽¹⁾	Shandong (border jingjinji)	158	Zhengzhou ⁽¹⁾	Henan (border jingjinji)	166	Handan ⁽⁶⁾	Jingjinji	151
Kuerle ⁽⁵⁾	Xinjiang	152	Dezhou ⁽²⁾	Shandong (border jingjinji)	165	Liaocheng ⁽²⁾	Shandong (border jingjinji)	150

2017 PM10			2018 PM10			2019 PM10		
City	Belongs to area	Concentration /($\mu\text{g}\cdot\text{m}^{-3}$)	City	Belongs to area	Concentration /($\mu\text{g}\cdot\text{m}^{-3}$)	City	Belongs to area	Concentration /($\mu\text{g}\cdot\text{m}^{-3}$)
Hetian area ⁽⁵⁾	Xinjiang	318	Hetian area ⁽⁵⁾	Xinjiang	432	Hetian area ⁽⁵⁾	Xinjiang	335
Kasha area ⁽⁵⁾	Xinjiang	248	Kasha area ⁽⁵⁾	Xinjiang	331	Kasha area ⁽⁵⁾	Xinjiang	229
Akesu area ⁽⁵⁾	Xinjiang	198	Kezhou ⁽⁵⁾	Xinjiang	291	Kezhou ⁽⁵⁾	Xinjiang	182
Tulufan area ⁽⁴⁾	Xinjiang	158	Akesu area ⁽⁵⁾	Xinjiang	256	Akesu area ⁽⁵⁾	Xinjiang	181
Handan ⁽⁶⁾	Jingjinji	157	Tulufan area ⁽⁴⁾	Xinjiang	180	Kuerle ⁽⁵⁾	Xinjiang	171
Kezhou ⁽⁵⁾	Xinjiang	154	Kuerle ⁽⁵⁾	Xinjiang	171	Laiwu ⁽¹⁾	Shandong (border jingjinji)	168
Shijiazhuang ⁽³⁾	Jingjinji	153	Wujiaqu ⁽¹⁾	Xinjiang	136	Tulufan area ⁽⁴⁾	Xinjiang	164
Xingtai ⁽²⁾	Jingjinji	152	Handan ⁽⁶⁾	Jingjinji	136	Handan ⁽⁶⁾	Jingjinji	124
Pingdu ⁽¹⁾	Shandong (border jingjinji)	150	Xingtai ⁽²⁾	Jingjinji	136	Shangqiu ⁽¹⁾	Henan (border jingjinji)	124
Kuerle ⁽⁵⁾	Xinjiang	142	Weinan ⁽¹⁾	Shanxi (border jingjinji)	135	Zaozhuang ⁽¹⁾	Shandong (border jingjinji)	117

*(1),(2),(3),(4),(5),(6): the frequency of these cities ranking the top ten from 2014 to 2019

Similarly, it can be seen, from Figure 4, that the Beijing-Tianjin-Hebei region

and its surrounding region in the northeast of mainland China and Xinjiang region in the northwest of mainland China showed higher mass concentration (including the highest mass concentration) of CO from the year 2014 to 2019. There was a similar trend between the spatial variation of CO and it of PM_{2.5}, PM₁₀, AQI, NO₂ and SO₂ acquired in the above and following contents, but it of the following O₃ would indicate a different trend compared with CO. The highest mass concentration of CO was 2.2 $\mu\text{g}\cdot\text{m}^{-3}$, 2.5 $\mu\text{g}\cdot\text{m}^{-3}$, 2.4 $\mu\text{g}\cdot\text{m}^{-3}$, 2 $\mu\text{g}\cdot\text{m}^{-3}$, 1.7 $\mu\text{g}\cdot\text{m}^{-3}$, 1.1 $\mu\text{g}\cdot\text{m}^{-3}$ respectively in every separated year between 2014 and 2019. The highest mass concentration of CO in the year 2015 and 2019 were the highest (2.5 $\mu\text{g}\cdot\text{m}^{-3}$) and lowest (1.1 $\mu\text{g}\cdot\text{m}^{-3}$) among the six years. It also shows that this indicator had experienced a dramatic decline by the year 2019, which was less than the half of the figure in 2015. On the other hand, the temporal variation of CO witnessed a similar trend to that of the following NO₂ and SO₂. In addition, what is worth pointing is that extraordinarily high concentrations arose in Xinjiang region from 2018 to 2019. From the perspective of the annual highest mass concentration of CO, it can be analyzed that the atmospheric condition of mainland China had not been authentically improved until the year 2019.

Figure 4. The spatial-temporal variation of the mass concentration of CO in mainland China from 2014 to 2019

The top ten cities with higher annual mass concentration of CO from 2014 to 2019 and their affiliated regions are shown in Table 4. The results indicate that 1/3 of them were occupied by Shanxi, and Beijing-Tianjin-Hebei region and its neighboring

areas like Shandong and Henan represented 1/2. To be more specific, Linfen and Changzhi, two cities situated in Shanxi province, combined with Anyang, a city situated in Henan province, ranked on the list of cities with top ten mass concentration of CO consecutively in the six years.

Table 4. Ten cities with higher annual average mass concentration of CO and their affiliated regions from 2014 to 2019

2014 CO			2015 CO			2016 CO		
City	Belongs to area	Concentration $/(μg·m^{-3})$	City	Belongs to area	Concentration $/(μg·m^{-3})$	City	Belongs to area	Concentration $/(μg·m^{-3})$
Penglai(2)	Shandong (border Jingjinji)	2.25	Lvliang(1)	Shanxi (border Jingjinji)	2.75	Linfen(6)	Shanxi (border Jingjinji)	2.52
Linfen(6)	Shanxi (border Jingjinji)	2.20	Linfen(6)	Shanxi (border Jingjinji)	2.36	Tangshan(6)	Jingjinji	2.27
Binzhou(2)	Shandong (border Jingjinji)	2.13	Tangshan(6)	Jingjinji	2.13	Anyang(5)	Henan (border jingjinji)	2.17
Zibo(4)	Shandong (border Jingjinji)	2.11	Zibo(4)	Shandong (border Jingjinji)	2.11	Yuncheng(3)	Shanxi (border Jingjinji)	2.06
Benxi(1)	Liaoning (border Jingjinji)	2.09	Binzhou(2)	Shandong (border Jingjinji)	2.10	Jincheng(4)	Shanxi (border Jingjinji)	2.00
Tangshan(6)	Jingjinji	2.06	Naqu area(1)	Xinjiang	2.09	Luoyang(1)	Henan (border jingjinji)	2.00
Changzhi(5)	Shanxi (border Jingjinji)	2.05	Anyang(5)	Henan (border jingjinji)	2.06	Changzhi(5)	Shanxi (border Jingjinji)	2.00
Liaocheng(1)	Shandong (border Jingjinji)	2.00	Zhoukou(1)	Henan (border jingjinji)	2.02	Hebi(2)	Henan (border jingjinji)	1.96
Yanan(1)	Shanxi (border Jingjinji)	1.93	Yuncheng(3)	Shanxi (border Jingjinji)	1.96	Zibo(4)	Shandong (border Jingjinji)	1.90
Baoding(1)	Jingjinji	1.93	Changzhi(5)	Shanxi (border Jingjinji)	1.96	Yilihasake(1)	Xinjiang	1.85

2017 CO			2018 CO			2019 CO		
City	Belongs to area	Concentration $/(μg \cdot m^{-3})$	City	Belongs to area	Concentration $/(μg \cdot m^{-3})$	City	Belongs to area	Concentration $/(μg \cdot m^{-3})$
Linfen(6)	Shanxi (border Jingjinji)	2.07	Linfen(6)	Shanxi (border Jingjinji)	1.76	Laiwu(1)	Shandong (border Jingjinji)	1.53
Jincheng(4)	Shanxi (border Jingjinji)	1.98	Tangshan(6)	Jingjinji	1.69	Linfen(6)	Shanxi (border Jingjinji)	1.46
Tangshan(6)	Jingjinji	1.96	Panzhuhua(2)	Sichuan	1.53	Tangshan(6)	Jingjinji	1.37
Anyang(5)	Henan (border jingjinji)	1.85	Anyang(5)	Henan (border jingjinji)	1.53	Datong(2)	Shanxi (border Jingjinji)	1.35
Dekehasake(2)	Xinjiang	1.83	Dekehasake(2)	Xinjiang	1.46	Changzhi(5)	Shanxi (border Jingjinji)	1.25
Zibo(4)	Shandong (border Jingjinji)	1.76	Loudi(1)	Hunan	1.45	Ganzhou(2)	Jiangxi	1.24
Yuncheng(3)	Shanxi (border Jingjinji)	1.71	Datong(2)	Shanxi (border Jingjinji)	1.42	Jincheng(4)	Shanxi (border Jingjinji)	1.23
Hebi(2)	Henan (border jingjinji)	1.68	Ganzhou(2)	Jiangxi	1.42	Anyang(5)	Henan (border jingjinji)	1.21
Changzhi(5)	Shanxi (border Jingjinji)	1.67	Xining(1)	Qinghai	1.41	Panzhuhua(2)	Sichuan	1.20
Xingtai	Jingjinji	1.67	Jincheng(4)	Shanxi (border Jingjinji)	1.38	Penglai(2)	Shandong (border Jingjinji)	1.19

*(1),(2),(3),(4),(5),(6): the frequency of these cities ranking the top ten from 2014 to 2019

From Figure 5, it can be seen that northern cities or areas with higher concentration (including the highest mass concentration) of NO₂ are also mostly situated in the Beijing-Tianjin-Hebei region and Xinjiang region from the year 2014 to 2017. Simultaneously, the concentration of NO₂ took a high level position in Yangtze River Delta region, Pearl River Delta region and Sichuan Basin. It should be pointed that the distribution of NO₂ was more extensive than other parameters, especially in the region where local economy was more developed such as Yangtze River Delta region, Pearl River Delta region and Sichuan Basin. There was a similar trend between the spatial variation of NO₂ and it of the above PM_{2.5}, PM₁₀, AQI, CO and the

following SO₂, but it of the following O₃ would indicate an opposite trend compared with CO. The highest mass concentration of NO₂ was 56 $\mu\text{g}\cdot\text{m}^{-3}$, 59 $\mu\text{g}\cdot\text{m}^{-3}$, 60 $\mu\text{g}\cdot\text{m}^{-3}$, 58 $\mu\text{g}\cdot\text{m}^{-3}$, 54 $\mu\text{g}\cdot\text{m}^{-3}$, 50 $\mu\text{g}\cdot\text{m}^{-3}$ respectively in every separated year between 2014 and 2019. The highest mass concentration of NO₂ in the year 2016 and 2019 were the highest (60 $\mu\text{g}\cdot\text{m}^{-3}$) and lowest (50 $\mu\text{g}\cdot\text{m}^{-3}$) among the six years. On the other hand, the temporal variation of NO₂ witnessed a similar trend to that of the above CO and the following SO₂, but a different trend to that of the following O₃. From the perspective of the annual highest mass concentration of NO₂, it can be analyzed that the atmospheric condition of mainland China had not been authentically improved until the year 2019.

Figure 5. The spatial-temporal variation of the mass concentration of NO₂ in mainland China from 2014 to 2019

Table 5 indicates the cities whose annual average mass concentration of NO₂ ranked the top then from 2014 to 2019 and their affiliated regions. It can be seen that the number of these cities in Beijing-Tianjin-Hebei region and its neighboring areas accounted more than 2/3. Tangshan and Xingtai, two cities bordering Beijing-Tianjin-Hebei region, ranked on the list of cities with top ten mass concentration of NO₂ consecutively in the six years. Also, Zhengzhou, the provincial capital of Henan province bordering Beijing-Tianjin-Hebei region, similarly ranked on this list up to five times in these years.

Table 5. Ten cities with higher annual average mass concentration of NO₂ and

273

their affiliated regions from 2014 to 2019

2014 NO2			2015 NO2			2016 NO2		
City	Belongs to area	Concentration $/(\mu\text{g}\cdot\text{m}^{-3})$	City	Belongs to area	Concentration $/(\mu\text{g}\cdot\text{m}^{-3})$	City	Belongs to area	Concentration $/(\mu\text{g}\cdot\text{m}^{-3})$
Zibo(3)	Shandong (border jingjinji)	65	Zibo(3)	Shandong (border jingjinji)	61	Xingtai(6)	Jingjinji	61
Tangshan(6)	Jingjinji	58	Tangshan(6)	Jingjinji	60	Tangshan(6)	Jingjinji	58
Linyi(1)	Shandong (border jingjinji)	57	Xingtai(6)	Jingjinji	59	Baoding(3)	Jingjinji	57
Xingtai(6)	Jingjinji	56	Zhengzhou(5)	Henan (border jingjinji)	55	Handan(2)	Jingjinji	54
Jinan(3)	Shandong (border jingjinji)	53	Baoding(3)	Jingjinji	53	Huzhou(3)	Jiangsu	54
Baoding(3)	Jingjinji	52	Linxiashou(1)	Gansu	53	Shijiazhuang(2)	Jingjinji	54
Beijing(1)	Jingjinji	52	Suzhou(2)	Jiangsu	51	Zhengzhou(5)	Henan (border jingjinji)	53
Suzhou(2)	Jiangsu	51	Jinan(3)	Shandong (border jingjinji)	51	Zibo(3)	Shandong (border jingjinji)	52
Laiwu(2)	Shandong (border jingjinji)	51	Zhuji(1)	Zhejiang	51	Hebi(1)	Henan (border jingjinji)	52
Qinhuangdao(2)	Shandong (border jingjinji)	50	Xinxiang(2)	Henan (border jingjinji)	51	Wulumuqi(1)	Xinjiang	52

274

2017 NO2			2018 NO2			2019 NO2		
City	Belongs to area	Concentration $(\mu\text{g}\cdot\text{m}^{-3})$	City	Belongs to area	Concentration $(\mu\text{g}\cdot\text{m}^{-3})$	City	Belongs to area	Concentration $(\mu\text{g}\cdot\text{m}^{-3})$
Tangshan(6)	Jingjinji	58	Huzhou(3)	Jiangsu	54	Laiwu(2)	Shandong (border jingjinji)	51
Xian(3)	Shan Xi	58	Tangshan(6)	Jingjinji	54	Tangshan(6)	Jingjinji	49
Xingtai(6)	Jingjinji	56	Xian(3)	Shan Xi	53	Yunlin(1)	Henan (border jingjinji)	47
Huzhou(3)	Jiangsu	55	Changzhou(1)	Jiangsu	49	Xian(3)	Shan Xi	46
Xianyang(2)	Shan Xi	53	Tianjin(2)	Jingjinji	49	Taiyuan(2)	Shanxi (border jingjinji)	44
Tianjin(2)	Jingjinji	53	Xingtai(6)	Jingjinji	47	Lvliang	Shanxi (border jingjinji)	44
Zhengzhou(5)	Henan (border jingjinji)	52	Xinxiang(2)	Henan (border jingjinji)	47	Huzhou(2)	Jiangsu	44
Weinan(1)	Shan Xi	51	Xianyang(2)	Shan Xi	47	Jinan(3)	Shandong (border jingjinji)	43
Handan(2)	Jingjinji	51	Taiyuan(2)	Shanxi (border jingjinji)	46	Xingtai(6)	Jingjinji	42
Shijiazhuang(2)	Jingjinji	50	Zhengzhou(5)	Henan (border jingjinji)	46	Zhengzhou(5)	Henan (border jingjinji)	42

*(1),(2),(3),(4),(5),(6): the frequency of these cities ranking the top ten from 2014 to 2019

From Figure 6, it can be seen that higher concentration (including the highest mass concentration) of O₃ was mainly distributed in Qinghai, Inner Mongolia in the central north of mainland China and Shandong province bordering Beijing-Tianjin-Hebei region on the right side from the year 2014 to 2019. In fact, the spatial variation of O₃ experienced a different trend compared with other kinds of atmospheric pollution parameters on account that only O₃ showed a high concentration in both Qinghai and Inner Mongolia regions. The highest mass concentration of O₃ was 47 $\mu\text{g}\cdot\text{m}^{-3}$, 93 $\mu\text{g}\cdot\text{m}^{-3}$, 95 $\mu\text{g}\cdot\text{m}^{-3}$, 100 $\mu\text{g}\cdot\text{m}^{-3}$, 100 $\mu\text{g}\cdot\text{m}^{-3}$ respectively in every

separated year between 2014 and 2019. The highest mass concentration of O₃ in the year 2014 were the lowest (47 $\mu\text{g}\cdot\text{m}^{-3}$) among the six years and after 2015, the highest mass concentration of O₃ was slightly higher in each year. On the other hand, the temporal variation of O₃ had different trends compared with the above CO and NO₂ and the following SO₂. From the perspective of the annual highest mass concentration of O₃, it can be analyzed that the atmospheric condition of mainland China had become worse by the year 2019.

Figure 6. The spatial-temporal variation of the mass concentration of O₃ in mainland China from 2014 to 2019

Table 6 lists the cities with top ten annual mass concentration of O₃ and their affiliated regions from the year 2014 to 2019, which indicates that more than 1/3 of them were situated in Qinghai and Inner Mongolia regions and 1/6 of them were situated in Shandong province bordering Beijing-Tianjin-Hebei region, with the rest distributed the neighboring regions like Gansu, Liaoning provinces, etc. Especially, in four out of the total six years, Haibeizhou in Qinghai and Alxa in Inner Mongolia were selected into the cities whose annual mass concentration was top ten.

Based on the combination of Figure 6 and Table 6, it can be seen that the distribution of O₃ in mainland China was different from that of other atmospheric pollution parameters discussed in this paper. In fact, the concentration of O₃ distributed in Qinghai and Inner Mongolia in North China was higher.

Table 6. Ten cities with higher annual average mass concentration of O₃ and their affiliated regions from 2014 to 2019

2014 O ₃			2015 O ₃			2016 O ₃		
City	Belongs to area	Concentration/ ($\mu\text{g}\cdot\text{m}^{-3}$)	City	Belongs to area	Concentration/ ($\mu\text{g}\cdot\text{m}^{-3}$)	City	Belongs to area	Concentration/ ($\mu\text{g}\cdot\text{m}^{-3}$)
Rongcheng(3)	Shandong (border jingjinji)	93	Haixizhou(3)	Qinghai	97	Haibeizhou(4)	Qinghai	95
Weihai(4)	Shandong (border jingjinji)	92	Alashanmeng(4)	Neimenggu	94	Alashanmeng(4)	Neimenggu	95
Penglai(1)	Shandong (border jingjinji)	87	Hainanzhou(3)	Qinghai	94	Hainanzhou(3)	Qinghai	83
Linan(1)	Zhejiang	85	Haibeizhou(4)	Qinghai	90	Yixing(1)	Jiangsu	82
Jiaonan(2)	Shandong (border jingjinji)	82	Yanzheng(1)	Jiangsu	82	Guoluozhou(3)	Qinghai	81
Weifang(1)	Shandong (border jingjinji)	81	Jiayuguan(2)	Gansu	81	Yingkou(2)	Liaoning	81
Wendeng(1)	Shandong (border jingjinji)	81	Guoluozhou(3)	Qinghai	81	Jiayuguan(2)	Gansu	81
Dongying(1)	Shandong (border jingjinji)	80	Yingkou(2)	Liaoning	80	Eerduosi(2)	Neimenggu	80
Eerduosi(2)	Neimenggu	80	Lasa(1)	Xizang	80	Jiaonan(1)	Jiangsu	80
Qingdao(1)	Shandong (border jingjinji)	80	Weihai(4)	Shandong (border jingjinji)	79	Dalian(1)	Liaoning	79

2017 NO2			2018 NO2			2019 NO2		
City	Belongs to area	Concentration/ ($\mu\text{g}\cdot\text{m}^{-3}$)	City	Belongs to area	Concentration/ ($\mu\text{g}\cdot\text{m}^{-3}$)	City	Belongs to area	Concentration/ ($\mu\text{g}\cdot\text{m}^{-3}$)
Enshizhou(1)	Hubei	37	Alashanmeng(4)	Neimenggu	105	Haixizhou(3)	Qinghai	104
Xiangxi	Hunan	38	Guoluzhou(3)	Qinghai	90	Alashanmeng(4)	Neimenggu	102
Qiandongnanzhou(1)	Guizhou	38	Kezhou(1)	Xinjiang	89	Haibeizhou(4)	Qinghai	96
Xishuangbanna(1)	Yunnan	40	Weihai(4)	Shandong (border jingjinji)	89	Weihai(4)	Shandong (border jingjinji)	92
Qianxinanzhou(1)	Guizhou	40	Haixizhou(3)	Qinghai	88	Hainanzhou(3)	Qinghai	89
Nujiang(1)	Yunnan	41	Jiaozuo(2)	Henan (border jingjinji)	87	Jiaozuo(2)	Henan (border jingjinji)	89
Chongqing(1)	Chongqing	42	Haibeizhou(4)	Qinghai	87	Rongcheng(3)	Shandong (border jingjinji)	89
Wuzhou(1)	Guangxi	42	Rongcheng(3)	Shandong (border jingjinji)	85	Jinchang(1)	Gansu	86
Hechi(1)	Jiangsu	43	Qingyang(1)	Gansu	85	Changzhi(2)	Shanxi (border jingjinji)	85
Pingxiang(1)	Jiangxi	43	Changzhi(2)	Shanxi (border jingjinji)	84	Jincheng(1)	Shanxi (border jingjinji)	84

*(1),(2),(3),(4),(5),(6): the frequency of these cities ranking the top ten from 2014 to 2019

From Figure 7, it can be seen that the area with higher concentration (including the highest mass concentration) of SO₂ was mainly situated in Shanxi and Shandong provinces nearby Beijing-Tianjin-Hebei region and a small part of areas bordering such places (e.g. Liaoning province and Inner Mongolia region) from the year 2014 to 2019. There was a similar trend between the spatial variation of SO₂ and that of the above PM_{2.5}, PM₁₀, AQI, CO and NO₂, but a different trend between the spatial variation of SO₂ and that of the above O₃. The highest mass concentration of SO₂ was 83 $\mu\text{g}\cdot\text{m}^{-3}$, 76 $\mu\text{g}\cdot\text{m}^{-3}$, 87 $\mu\text{g}\cdot\text{m}^{-3}$, 82 $\mu\text{g}\cdot\text{m}^{-3}$, 48 $\mu\text{g}\cdot\text{m}^{-3}$, 37 $\mu\text{g}\cdot\text{m}^{-3}$ in each separated year from 2014 to 2019. Among these, the highest concentration of SO₂ was 87 $\mu\text{g}\cdot\text{m}^{-3}$ in 2016, which was higher than the other five years and more than two times as high as that in

2019, the lowest one with figure 37 $\mu\text{g}\cdot\text{m}^{-3}$. After the year 2018, the highest mass concentration of SO₂ in atmosphere experienced a significant decline. On the other hand, the temporal variations of SO₂ and the above CO and NO₂ indicated similar trend but that of O₃ was different. From the perspective of the annual highest mass concentration of SO₂, it can be analyzed that the atmospheric condition of mainland China had been remarkably improved by the year 2019.

**Figure 7. The spatial-temporal variation of the mass concentration of SO₂ in
mainland China from 2014 to 2019**

There are some cities with top ten annual mass concentration of SO₂ from the year 2014 to 2019 and their affiliated regions in Table 7, which indicates that more than 1/2 of these areas existed in Shanxi province on the left side of Beijing-Tianjin-Hebei region, with 1/6 in Shandong province on the right side of Beijing-Tianjin-Hebei region, 1/6 in Ningxia and the rest in the areas bordering the above places, like Inner Mongolia and Liaoning Province. In six consecutive years, Linfen, located in Shanxi province, ranked the top ten cities with higher annual mass concentration of SO₂, followed by Shijiazui in Ningxia, which was selected onto the list in five years.

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372 **Table 3. Ten cities with higher annual average mass concentration of SO₂ and**

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their affiliated regions from 2014 to 2019.

2014 SO2			2015 SO2			2016 SO2		
City	Belongs to area	Concentration /($\mu\text{g}\cdot\text{m}^{-3}$)	City	Belongs to area	Concentration /($\mu\text{g}\cdot\text{m}^{-3}$)	City	Belongs to area	Concentration /($\mu\text{g}\cdot\text{m}^{-3}$)
Zibo(2)	Shandong (border jingjinji)	108	Zibo(2)	Shandong (border jingjinji)	82	Jinzhong(4)	Shanxi (border jingjinji)	87
Yangquan(3)	Shanxi (border jingjinji)	85	Shuozhou(3)	Shanxi (border jingjinji)	76	Linfen(6)	Shanxi (border jingjinji)	82
Laiwu(2)	Shandong (border jingjinji)	81	Hetiandiqu(1)	Xinjiang	72	Shuozhou(3)	Shanxi (border jingjinji)	67
Taiyuan(4)	Shanxi (border jingjinji)	66	Jinzhong(4)	Shanxi (border jingjinji)	72	Shijiazui(5)	Ningxia	67
Jining	Shandong (border jingjinji)	64	Shijiazui(5)	Ningxia	71	Jincheng(1)	Shanxi (border jingjinji)	66
Shandong	Shandong (border jingjinji)	64	Taiyuan(4)	Shanxi (border jingjinji)	68	Yuncheng(2)	Shanxi (border jingjinji)	66
Zaozhuang	Shandong (border jingjinji)	63	Lvliang(5)	Shanxi (border jingjinji)	68	Taiyuan(4)	Shanxi (border jingjinji)	65
Linfen(6)	Shanxi (border jingjinji)	63	Zhangqiu(1)	Shandong (border jingjinji)	64	Lvliang(5)	Shanxi (border jingjinji)	62
Shijiazui(5)	Ningxia	59	Linfen(6)	Shanxi (border jingjinji)	63	Yangquan(3)	Shanxi (border jingjinji)	61
Shenyang(1)	Liaoning (border jingjinji)	57	Wuhai(4)	Neimenggu	62	Changzhi(1)	Shanxi (border jingjinji)	61

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2017 SO ₂			2018 SO ₂			2019 SO ₂		
City	Belongs to area	Concentration /($\mu\text{g}\cdot\text{m}^{-3}$)	City	Belongs to area	Concentration /($\mu\text{g}\cdot\text{m}^{-3}$)	City	Belongs to area	Concentration /($\mu\text{g}\cdot\text{m}^{-3}$)
Jinzhong(4)	Shanxi (border jingjinji)	83	Linfen(6)	Shanxi (border jingjinji)	48	Baiyin(2)	Ningxia	39
Linfen(6)	Shanxi (border jingjinji)	79	Baiyin(2)	Ningxia	42	Wuhai(4)	Neimenggu	33
Lvliang(5)	Shanxi (border jingjinji)	68	Lvliang(5)	Shanxi (border jingjinji)	39	Laiwu(2)	Shandong (border jingjinji)	32
Shijiazui(5)	Ningxia	51	Panzhihua(2)	Sichuan	38	Shuozhou(3)	Shanxi (border jingjinji)	29
Taiyuan(4)	Shanxi (border jingjinji)	51	Jinzhou(2)	Liaoning (border jingjinji)	37	Panzhihua(2)	Sichuan	29
Yinchuang(2)	Ningxia	51	Shijiazui(5)	Ningxia	37	Xinzhou(2)	Shanxi (border jingjinji)	29
Yuncheng(2)	Shanxi (border jingjinji)	51	Jinzhong(4)	Shanxi (border jingjinji)	36	Lvliang(5)	Shanxi (border jingjinji)	29
Wuhai(4)	Neimenggu	51	Yinchuang(2)	Ningxia	36	Datong(1)	Shanxi (border jingjinji)	28
Yangquan(3)	Shanxi (border jingjinji)	49	Huludao(1)	Liaoning (border jingjinji)	36	Linfen(6)	Shanxi (border jingjinji)	27
Xinzhou(2)	Shanxi (border jingjinji)	48	Wuhai(4)	Neimenggu	34	Jinzhou(2)	Liaoning (border jingjinji)	27

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376 *(1),(2),(3),(4),(5),(6): the frequency of these cities ranking the top ten from 2014 to 2019

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378 3 Conclusion

379 The spatial-temporal distribution law of atmospheric pollution in China is of
380 persistence, concentricity and correlation between different atmospheric pollution
381 parameters. From the year 2014 to 2019, such atmospheric pollution parameters as
382 PM_{2.5}, AQI, PM₁₀, CO, NO₂ and SO₂ were mainly concentrated in Beijing-Tianjin-
383 Hebei region in the northeast of mainland China and its neighboring Shandong, Shanxi,

Henan provinces and Xinjiang areas in the west of mainland China. In addition, the concentration of NO₂ was also higher in such economically developed regions as Yangtze River Delta, Pearl River Delta and Sichuan Basin, which indicates the distribution of NO₂ was of universality, a different characteristic compared with the concentricity occupied by the other parameters. By contrast, O₃, one of the atmospheric pollution parameters, was mainly distributed in Qinghai and Inner Mongolia in the central north of mainland China. PM_{2.5}, AQI and PM₁₀ experienced almost the same variation trend with time, which also happened to CO, NO₂ and SO₂. Whereas, O₃ witnessed an opposite variation trend to CO, NO₂ and SO₂ with time. These cities including Baoding, Xingtai, Handan, Tangshan in Beijing-Tianjin-Hebei region, Langfang in Shandong province, Linfen in Shanxi province, haibeizhou in Qinghai, Kashi, Hetian, Aksu and Kezhou in Xinjiang should be emphatically improved. Except for the decline of the highest concentration of CO and SO₂ from 2014 to 2019, this indicator of other parameters was not improved. In general, the atmospheric environment of mainland China had not been obviously improved over the six years. As a consequence, the study in this paper urges us to pay attention to the problem with the atmospheric environment of northern region of China, and also indicates cities and regions with severer atmospheric contamination, for which authentic actions should be implemented to address the corresponding problems.

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Figure 1. The spatial-temporal variation of the mass concentration of PM2.5 in mainland China from 2014 to 2019.

Figure 2. The spatial-temporal variation of the annual average AQI in mainland China from 2014 to 2019

Figure 3. The spatial-temporal variation of the annual average mass

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concentration of PM10 in mainland China from 2014 to 2019

Figure 4. The spatial-temporal variation of the mass concentration of CO in

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Figure 5. The spatial-temporal variation of the mass concentration of NO₂ in mainland China from 2014 to 2019

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Figure 6. The spatial-temporal variation of the mass concentration of O₃ in mainland China from 2014 to 2019

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