Research Article

Spatiotemporal Patterns and Cause Analysis of PM$_{2.5}$ Concentrations in Beijing, China

Guangjin Tian ![ORCID],[1] Xiaojuan Liu,[2] and Lingqiang Kong[2]

[1] School of Government, Beijing Normal University, Xinjie Kouwai Street, Beijing 100875, China
[2] State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University,
 Xinjie Kouwai Street, Beijing 100875, China

Correspondence should be addressed to Guangjin Tian; tianguangjin@bnu.edu.cn

According to the monthly comprehensive air index ranking in China in 2016, Beijing ranked in the bottom tenth three times, indicating that the air pollution situation is very serious compared to other cities in China. In this study, we chose 23 urban environmental assessment points, which covered all districts and counties in Beijing. We used ArcGIS software to analyze atmospheric concentrations of particulate matter with a diameter $< 2.5\,\mu$m (PM$_{2.5}$) for each month of 2016 in each district/county of Beijing. Our results showed that PM$_{2.5}$ concentrations in winter and spring were generally higher than those in summer and autumn. The higher monthly average PM$_{2.5}$ concentrations were primarily in the southwest and southeast areas. The higher annual average values were distributed in Fangshan, Daxing, and Tongzhou, which were closely related to the high terrain in the northwest and the low-lying terrain in the southeast, the "Beijing Bay" terrain, and local climatic conditions. The temporal and spatial distributions of PM$_{2.5}$ constitute a warning signal for human life and production during different seasons and regions.

1. Introduction

In recent years, the frequent occurrence of haze events has gradually influenced human health and living. The composition of haze is very complex, including hundreds of atmospheric particles [1]. Aerosol particles $10\,\mu$m in diameter are the most harmful particles for human health: floating dust, aerosols, and inhalable particles can directly enter the human body and adhere to the upper and lower respiratory tract and lungs, causing rhinitis, bronchitis, and other diseases. These particles will induce lung cancer if they exist in this environment for a long time. Particles $> 10\,\mu$m do not easily enter the respiratory tract. Most 5–10 μm particles are deposited in the upper respiratory tract, whereas most 2.5–5 μm particles are deposited in the bronchioles and alveoli. However, about 75% of particles $< 2.5\,\mu$m (PM$_{2.5}$) in diameter are deposited in alveoli. Because the alveolar area has a large surface area and the alveolar wall has an abundant capillary network, the soluble fraction (including some heavy metals) is easily absorbed into the blood and has effects in the human body, while the insoluble fraction,

as a foreign body, is phagocytized by macrophages, causing an inflammatory reaction. In addition, PM$_{2.5}$ also damage the cardiovascular and nervous systems. Although PM$_{2.5}$ particles are small, a large number of toxic and harmful substances readily attach to them. Particles attached to toxic substances have the characteristics of long duration and long-distance transportation in the atmosphere, causing a greater impact on human health and the atmosphere.

In February 2012, the State Council of China revised and issued an Ambient Air Quality Standard (GB3095-2012), in which PM$_{2.5}$ was added as a new monitoring indicator. PM$_{2.5}$ is equivalent to 1/20 the diameter of a human hair, and particles of this size directly enter the lungs. Although PM$_{2.5}$ content is very small compared to other components of the Earth's atmosphere, they have important implications for air quality and visibility. In 2013, PM$_{2.5}$ was identified as a primary carcinogen by the International Cancer Research Institute. The composition of PM$_{2.5}$ is very complex and mainly depends on the source, which can be natural (soil dust, volcanic eruption, and forest fires) or anthropogenic (burning of fossil fuels, emission of motor vehicles, and

burning and dust of straw waste), which are the most harmful to human health [2]. Secondhand smoke is a major source of $PM_{2.5}$, followed by cooking fumes. The frequent hazy weather in Beijing is caused by several factors, including industrial development, coal-based energy consumption, and increases in motor vehicle ownership and urban construction projects.

The objective of the present study was to investigate the temporal and spatial patterns of $PM_{2.5}$ in Beijing in 2016 and to analyze the causes of their formation. The findings provided by this study will support environmental policymakers who should make informed decisions pertaining to urban planning to mitigate atmospheric pollution events in Beijing.

2. Data and Methods

2.1. Data Sources. In this study, we selected 23 urban environmental assessment points, covering all districts and counties in Beijing, and collected data on the average $PM_{2.5}$ concentrations in each month of 2016. The data were in the fo0rm of monthly air quality data for Beijing, released by the Beijing Environmental Protection Bureau (http://www.bjepb.gov.cn/bjhrb/xxgk/ywdt/hjzlzk/dqhjzl/index.html), the National Environmental Monitoring Station (http://www.tianqihoubao.com/aqi/beijing-201610.html), and the Zhenqi network (https://www.zq12369.com/environment.php?tab=city&city=%E5%8C%97%E4%BA%AC&order=desc#envtab).

2.2. Analytical Methods. The data were preprocessed by Excel, ArcGIS, and other software. We obtained the temporal and spatial patterns of $PM_{2.5}$ in Beijing in 2016. Based on the distribution characteristics and the present situation in Beijing, we mainly focused on the spatial patterns, which have particular significance for constructing a ventilation corridor in Beijing.

3. Results and Discussion

3.1. Temporal Patterns of $PM_{2.5}$ in Beijing in 2016

3.1.1. Current Situation. The Beijing-Tianjin-Hebei region and surrounding areas (including Shanxi, Shandong, Inner Mongolia, and Henan) suffer from severe pollution, which in 2016 in Beijing persisted for more than 40 days. For nearly half of the year, Beijing experiences a minimum of light pollution, while March and October–December are the major pollution seasons. Heavy pollution has occurred many times in Beijing in December, and 35.5% of days were considered a heavy pollution, which was significantly higher than that in other months. The annual average $PM_{2.5}$ concentration in Beijing in 2016 was 73 $\mu g/cm^3$, which was reduced by 9.9% from the year earlier, and the annual average concentrations in 2016 of three other major atmospheric pollutants, PM_{10}, sulfur dioxide, and nitrogen dioxide, were 92, 10, and 48 $\mu g/cm^3$, respectively, which were reduced by 9.8%, 28.6%, and 4.0%, respectively, compared with that in the year earlier. It is undeniable that Beijing still experiences severe air quality issues, as shown by the hazy weather conditions highlighted by the monitoring data.
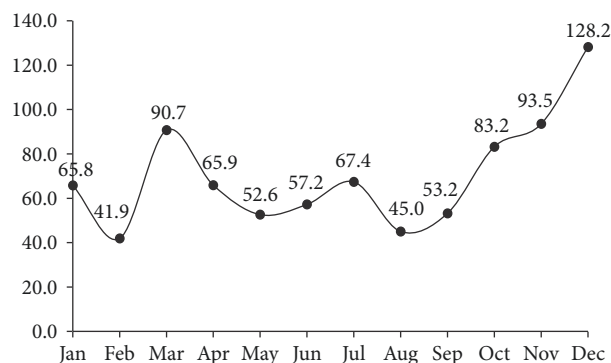

FIGURE 1: Monthly average particulate matter with a diameter < 2.5 μm ($PM_{2.5}$) concentrations in Beijing in 2016.

3.1.2. Monthly Mean $PM_{2.5}$ Concentration Distribution in Beijing. Figure 1 shows the monthly average $PM_{2.5}$ concentrations in Beijing in 2016. It is clear that the average $PM_{2.5}$ concentration was highest in December (mean = ~133 $\mu g/cm^3$, SD = 21 $\mu g/cm^3$ versus ~100 $\mu g/cm^3$, SD = 13 $\mu g/cm^3$ for November). The average $PM_{2.5}$ concentration in March 2016 was ~92.8 $\mu g/cm^3$ (SD = 8 $\mu g/cm^3$). Significant increases in $PM_{2.5}$ concentrations were detected from August to December. $PM_{2.5}$-induced pollution in March and October–December was more serious than in other months, in which the average concentrations ranged from 45 to 70 $\mu g/cm^3$. Fluctuations in summer and autumn were small. The lowest concentration, ~43.5 $\mu g/cm^3$, occurred in February. Figure 1 shows that $PM_{2.5}$ concentration declined in March, increased in August, and reached its maximum in December. The mean $PM_{2.5}$ concentrations in summer and autumn were lower than those in winter and spring, indicating better air quality during summer and autumn in Beijing.

3.1.3. Monthly Mean $PM_{2.5}$ Concentrations in Beijing: District and County Data. Figure 2 shows the monthly average $PM_{2.5}$ concentration distributions in the 16 districts and counties of Beijing. We found that the $PM_{2.5}$ concentration of each county was lowest in February and around August. Statistical analysis showed that the concentrations in February and August were significantly lower than those in the other months ($P < 0.05$). Monthly average concentrations from April to August in each county were all low, but the differences among these months were significant for each county ($P < 0.05$). The $PM_{2.5}$ concentrations in districts and counties rose rapidly beginning in September and attained their highest levels in December. Statistical analysis showed significant differences in monthly average concentrations among all months ($P < 0.05$), except between May and September ($P > 0.05$). Overall, the concentrations at the district and county levels were consistent with the regionally averaged concentrations in Beijing. Moreover, the monthly changes in regional PM2.5 concentrations were significantly correlated among the 16 regions in Beijing ($P < 0.05$).

Figure 2 shows that the highest monthly average $PM_{2.5}$ concentration occurred in Fangshan district (161 $\mu g/cm^3$) and

Dongcheng County

Xicheng County

Chaoyang County

Haidian County

Fengtai County

Daxing County

Mentougou County

Shijingshan County

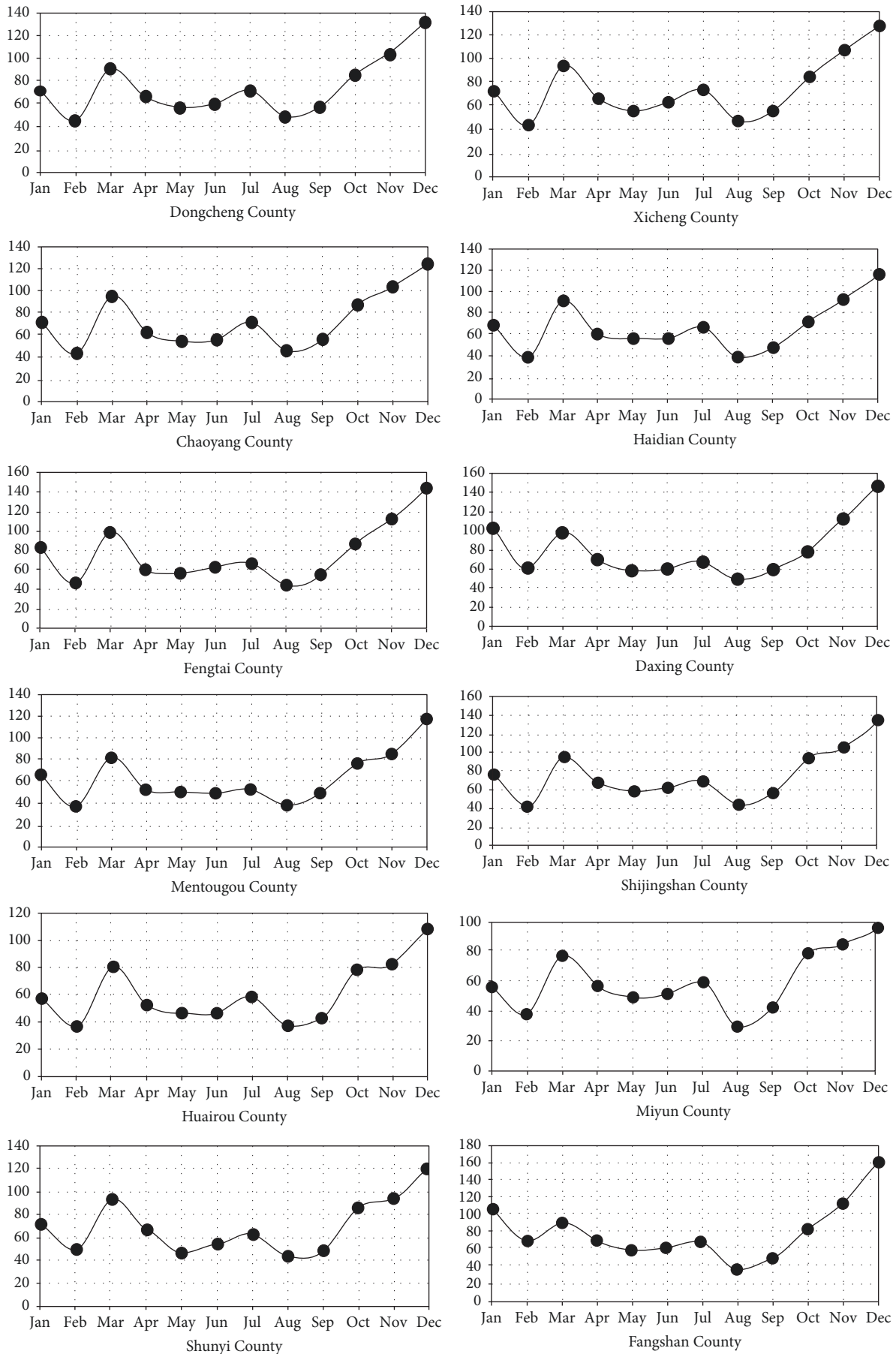Huairou County

Miyun County

Shunyi County

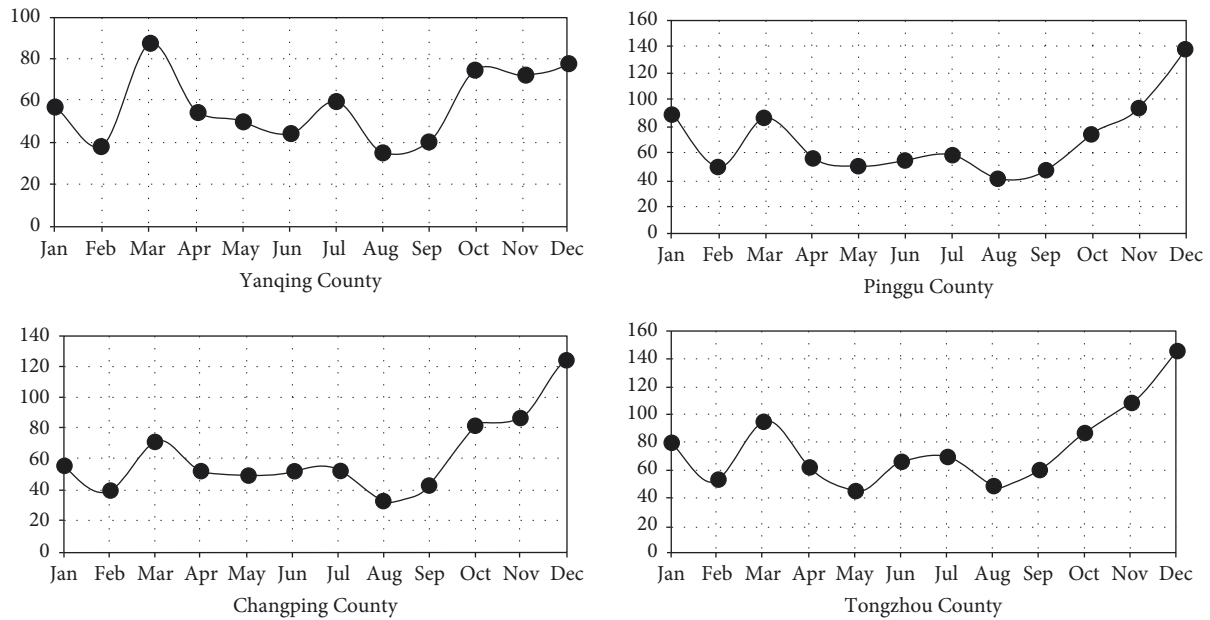Fangshan County

Figure 2: Continued.

FIGURE 2: Monthly average PM$_{2.5}$ concentrations in the 16 districts of Beijing in 2016.

the lowest concentration was in Miyun district (37 μg/cm^3). The yearly average PM$_{2.5}$ concentrations in Daxing and Fangshan districts were the highest among all districts, (80.6 ± 28.8 and 80.5 ± 34.0 μg/cm^3, respectively), ranging from 49 to 146 μg/cm^3 and 36 to 161 μg/cm^3, respectively. The mean concentrations in Yanqing and Miyun districts were the lowest among all regions (57.8 ± 17.1 and 59.7 ± 20.0 μg/cm^3, respectively) ranging from 30 to 95 μg/cm^3 and 35 to 88 μg/cm^3, respectively. The highest monthly concentrations in Yanqing and Miyun districts were <100 μg/cm^3. Overall, our results show higher PM$_{2.5}$ concentrations in southern compared with the northern regions of Beijing.

3.2. Spatial Patterns of PM$_{2.5}$ in Beijing in 2016

3.2.1. Current Situation. The topography of Beijing is described as "Beijing Bay," being surrounded by mountains on three sides: the west, north, and northeast sides [3]. The southeast is a large plain gradually leaning to "Bohai Bay." Beijing has a typically temperate and semihumid continental monsoon climate: it is hot and rainy in summer and cold and dry in winter. There were spatial concentration differences in PM$_{2.5}$ in Beijing according to the data of monitoring stations located in each district and county. The highest PM$_{2.5}$ concentrations occurred southeast and southwest of Beijing, mainly in Daxing, Tongzhou, and urban areas in the southeast, whereas lower PM$_{2.5}$ concentrations occurred in the northern, northwestern, and northeastern suburbs. The most serious pollution caused by haze is always in the southeast and urban areas of Beijing, reflecting the more developed economy, and higher population density, in these regions [4]. More hazy weather confers more risks to human health.

FIGURE 3: The spatial distribution of annual average PM$_{2.5}$ concentrations in Beijing in 2016.

3.2.2. PM$_{2.5}$ Spatial Distribution Characteristics. Figure 3 shows the spatial distribution of the annual average PM$_{2.5}$ concentrations in Beijing in 2016. The annual average PM$_{2.5}$ concentrations in Fangshan and Daxing districts were the highest (~80 μg/cm^3) among all districts; the concentrations in Yanqing and Miyun districts were <60 μg/cm^3, those in Huairou, Changping, and Mentougou districts were in the range of 60–65 μg/cm^3, those in Haidian, Pinggu, and Shunyi districts were in the range of 65–70 μg/cm^3, and

those in other regions were in the range of 70–80 μg/cm^3. A decreasing trend in PM$_{2.5}$ concentrations was observed from south to north: there was more serious PM$_{2.5}$ pollution in the south and better air quality in northern regions.

3.3. Temporal and Spatial PM$_{2.5}$ Concentration Distributions

3.3.1. Monthly Average PM$_{2.5}$ Concentrations by District/County. Spatial and temporal variability was detected in the air quality in Beijing in 2016, shown by the concentration distributions of PM$_{2.5}$ between January and December in its 16 districts and by the monthly air quality report of the Beijing Environmental Protection Bureau. The average air quality was better in 2016 than in 2015.

Figure 4 shows the spatial patterns in monthly average PM$_{2.5}$ concentrations during 2016. In January, mean PM$_{2.5}$ concentrations in Changping, Miyun, Yanqing, and Huairou districts were low, whereas those in Daxing, Fangshan, and Pinggu districts were high. In February, the mean concentrations in Miyun, Changping, Yanqing, Huairou, Mentougou, and Haidian districts were low, whereas those in Fangshan and Daxing districts were high. In March, the concentrations in Changping, Miyun, and Huairou were low, and the concentrations in Daxing, Fengtai, Tongzhou, and Shijingshan were high. In April, the concentrations in Huairou, Changping, and Mentougou were low, whereas the concentrations in Daxing, Fangshan, and Shijingshan were high. In May, the average concentrations in Beijing were low compared to those of other months; the concentrations in Tongzhou, Shunyi, and Huairou were low, whereas those in Daxing and Shijingshan were high. Air quality in all districts improved somewhat in June, compared to that in the month earlier. The concentrations in Changping, Huairou, Miyun, Yanqing, and Mentougou were lower than those in other districts, whereas those in Tongzhou and Fangshan were higher. In July, the concentrations in Changping and Mentougou were lower versus other districts, whereas those in Dongcheng, Xicheng, Chaoyang, and Tongzhou were higher. In August, the concentrations in Miyun, Changping, and Yanqing were lower versus other districts, and those in Daxing, Daxing, and East-West districts were higher. The PM$_{2.5}$ concentrations in all districts in this month were lower than the averaged values of other months, and the air quality in Beijing in August was generally better than other months. In September, the PM$_{2.5}$ concentrations in Miyun, Yanqing, Changping, and Huairou were low versus other districts, whereas the concentrations in Tongzhou and Daxing districts were high. In October, the concentrations in Haidian, Yanqing, Pinggu, and Mentougou were low, while the concentration in Shijingshan was the highest among all districts. In November, the concentrations in Yanqing, Huairou, and Miyun were low, whereas the concentrations in Fangshan, Daxing, and Fengtai were high. In December, the concentrations of PM$_{2.5}$ in all districts were higher compared to all other months, and the concentrations in Miyun and Yanqing were lower than the average level in Beijing. Moreover, the concentration in Fangshan was the highest among all districts of Beijing during December.

3.3.2. Seasonal Average PM$_{2.5}$ Concentrations by District and County. Figure 5 shows the spatial distribution of quarterly average PM$_{2.5}$ concentrations in Beijing in 2016. Clear seasonal differences were observed in the spatial distributions of PM$_{2.5}$ concentrations. In spring, the mean PM$_{2.5}$ concentrations were 54.7–89.0 μg/cm^3 at the district/county level. The highest PM$_{2.5}$ concentrations and pollution levels were observed in the southwest and southern regions, followed by the eastern regions, primarily including Fangshan, Daxing, Fengtai, Tongzhou, and Pinggu districts. The mean PM$_{2.5}$ concentrations in northern Beijing, Changping, Miyun, and Huairou were lower than those in other regions. In summer, the PM$_{2.5}$ concentrations in all districts/counties were 49.3–63.5 μg/cm^3. The concentrations in the south and southwest of Beijing, including Daxing and Fangshan, and the main urban areas, including Shijingshan, Dongcheng, and Xicheng, were high. This finding may be related to the urban heat island effect. In general, the PM$_{2.5}$ concentration showed a decreasing trend from the south to north of Beijing; the concentration in the northern region was low, indicating better air quality in this region. In autumn, the mean PM$_{2.5}$ concentrations in all counties were 43.3–60.0 μg/cm^3. The mean concentrations in the southeast and southern regions, including Tongzhou, Daxing, and Xicheng, were high, whereas those in the west, southwest, and north were low. The mean concentrations in all counties were higher in winter than in other seasons. The average winter PM$_{2.5}$ concentrations in all districts were in the range of 74.7–119.7 μg/cm^3, and the average was >100 μg/cm^3 in most regions, indicating that air quality was lowest at this time of year. Statistical analysis showed that the winter values were significantly higher than those in other seasons (P < 0.01). In winter, pollution in the southwestern and southeastern regions, including Fangshan, Fengtai, and Tongzhou, was most serious, followed by that in Daxing and Shijingshan. The PM$_{2.5}$ concentrations in Yanqing, Miyun, Huairou, and Mentougou were lower compared to those in other regions. Spatial differences in PM$_{2.5}$ concentrations at the district/county level were primarily related to the local climate and topographical conditions and to the productivity levels and living habits of Beijing residents during winter [5, 6].

3.4. Causes Analysis of PM$_{2.5}$ Concentrations

3.4.1. Causes of PM$_{2.5}$ Temporal Distributions. The average PM$_{2.5}$ concentrations in winter and spring were significantly higher than those in summer and autumn in Beijing. The average PM$_{2.5}$ concentration was highest in December. The concentrations from April to September showed moderate fluctuations, and the levels in this period tended to be lower versus the rest of the year. The reasons for this were particulate emissions caused by coal consumption in the north in winter and the transportation of particulates by the frequent southwesterly winds, which led to a large number of polluted air masses and warm, humid air flows. Moreover, local emissions further increased pollution in Beijing during the winter [7]. In spring, the hazy weather decreased significantly, reducing the likelihood of particle retention
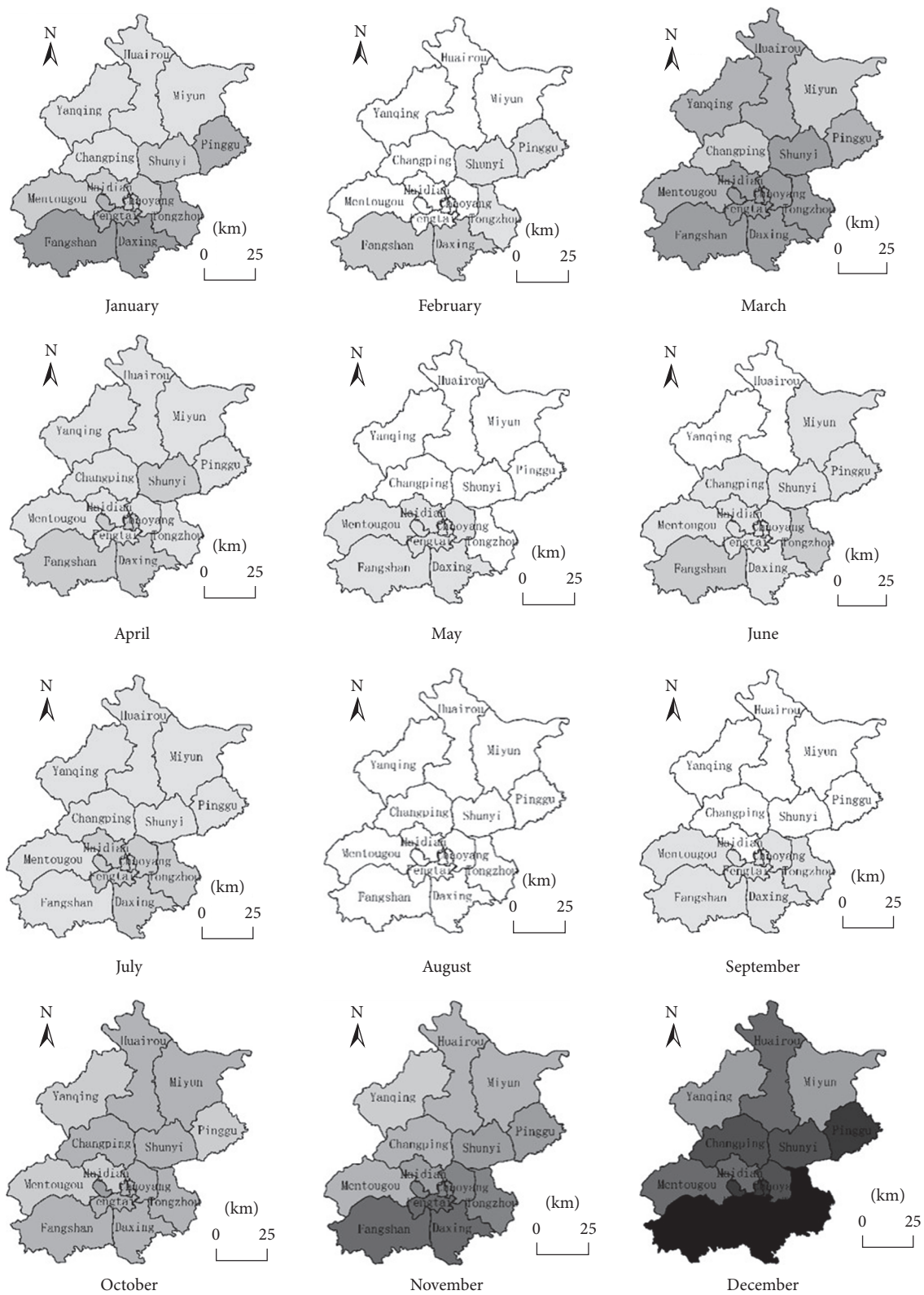
FIGURE 4: Monthly average PM$_{2.5}$ concentrations in the 12 months of 2016 in Beijing.
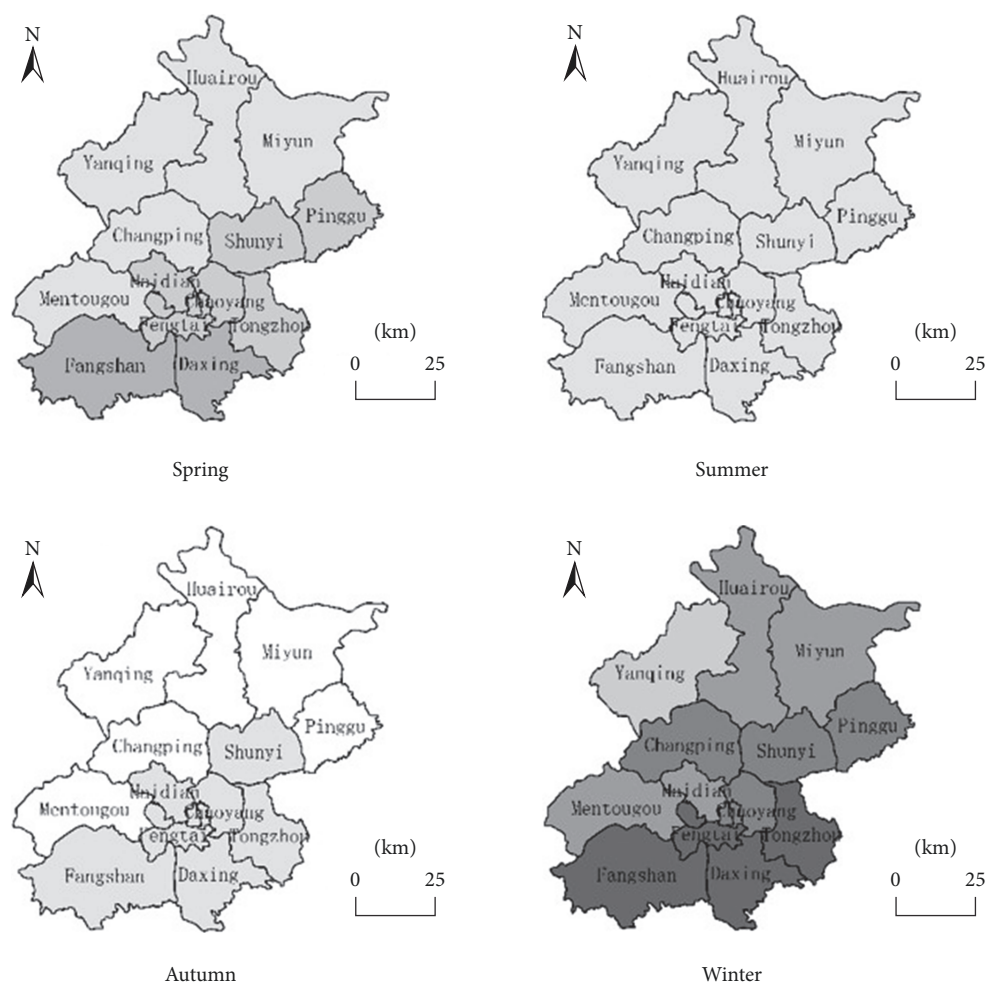
FIGURE 5: Spatial distribution of quarterly average PM$_{2.5}$ concentrations in Beijing in 2016.

and decreasing the concentrations of particles. In addition, wind speed was high in spring (generally 5 m/s), particularly in the northwest and the east, which was reflected in the lower mean PM$_{2.5}$ concentrations during spring in Beijing compared with winter. Summer and autumn are not heating seasons and there were adequate sunlight and moderate wind speed (<4 m/s). Internal emissions in Beijing have played a leading role in PM$_{2.5}$ concentrations over the years. These emissions include automobile exhaust emissions and dust arising from construction sites, which aggravate air pollution in Beijing [8, 9].

3.4.2. Causes of PM$_{2.5}$ Concentration Spatial Distribution Patterns. PM$_{2.5}$ concentrations in Beijing were high in the south and low in the north; the concentrations in the southeast and southwest border regions were the highest across the entire city. The eastern region had the second highest concentration, which also matched the overall mean for Beijing. The northern region generally had acceptable PM$_{2.5}$ concentrations. According to the Environmental Monitoring Center, Beijing Environmental Protection Bureau, PM$_{2.5}$ concentrations in Yanqing, Miyun, and Huairou were the lowest among all districts in Beijing, while those in Daxing,

Fangshan, Tongzhou, and Fengtai were the highest. The difference in PM$_{2.5}$ concentrations between the north and south was significant, and air quality in the north was better than that in the south due to natural and anthropogenic factors.

Beijing has a semi-basin terrain. The northern, western, and eastern regions of Beijing are surrounded by mountains, and only the eastern and southern regions are fully exposed. The main wind directions in Beijing are easterly, southerly, and northwesterly. Low wind speed mainly occurs in the southern and eastern directions, with high wind speed mainly occurring in easterly and northwesterly directions [10]. In general, the winter season has the most serious pollution; it is cold and dry with little rain and is significantly influenced by the dry cold air mass from Siberia, which forms northerly and northwesterly winds. Wind blowing from the north to the south leads to clean air in the northern region of Beijing, in which there are fewer people and less industrial development. Meanwhile, the polluted air in the southern region is due to the direction of the wind. In addition, the southeast region of Beijing is almost situated within the plains and includes populated areas, such as the large industrial areas in the Hebei and Tianjin regions. A large number

of power plants, cement plants, chemical plants, smelters, and other high-energy consumption enterprises are located in this area, leading to more serious industrial emissions. According to the influence of the mountains present on three sides of Beijing and to the particular atmospheric circulation background, a large number of pollutants in the south are transported to Beijing through medium- and long-distance transmission, causing pollution in the central urban area of Beijing [11]. The accumulation and increase in pollutants were accelerated by the warm and wet air flow in southern areas, under the influence of southwestern and southeastern air flow conditions. The haze in Beijing can be cleared by a "clean" sea breeze, that is, a strong easterly wind. However, when the east wind is weak, only water vapor, large amounts, is transported to Beijing and is sufficient only for second-generation pollutants, instead of conferring any cleaning effect [12].

4. Conclusions

(1) The spatial distribution of $PM_{2.5}$ concentrations in Beijing was reported at the district/county level. In the first half of the year, $PM_{2.5}$ concentrations in Fangshan and Daxing were higher than those in the other districts in spring. No significant regional differences were detected in summer. However, $PM_{2.5}$ concentrations in the eastern and southern districts were higher than those in other regions during the second half of the year. Southern regions, including Fangshan, Daxing, and Tongzhou, had higher particulate concentrations in winter. Overall, high $PM_{2.5}$ concentrations were usually found in the south, while low concentrations were found in the north; in addition, high concentrations occurred during winter and spring and low concentrations occurred during summer and autumn.

(2) We used 2016 data to analyze the temporal and spatial characteristics of $PM_{2.5}$ concentrations in Beijing; the use of these recent data ensured the precision of the research, which could inform the construction of ventilation corridors in Beijing. According to the annual average $PM_{2.5}$ concentration data, the pollution throughout the year in the south of Beijing was more serious than that in the north. It is proposed that more ventilation corridors based on wind direction should be established in the south of Beijing, to improve the ventilation conditions for the dense populace in that region.

(3) The $PM_{2.5}$-induced air pollution had different time durations, from a short period of 1 hour to a long period of 12 days. The differences in duration are attributable to differences in the intensity of the local source of $PM_{2.5}$, the concentration of the contaminant, the atmospheric diffusion conditions, and various meteorological factors. This study attempted to provide guidance for improving human living conditions: living in polluted air for a long period increases the health risks for humans.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] C. Zhao, Y. Q. Wang et al., "Spatial and temporal distribution of $PM_{2.5}$ and PM_{10} pollution levels in winter and spring in Beijing and its relationship with meteorological conditions," *Environmental Science*, vol. 35, pp. 418–427, 2014 (Chinese).

[2] X. N. Liao, X. L. Zhang et al., "Comparative analysis of environmental meteorological conditions of persistent haze in winter and summer in Beijing," *Environmental Science*, vol. 35, pp. 2031–2044, 2014.

[3] S. S. Li, J. L. Cheng et al., "The spatial distribution and source simulation of $PM_{2.5}$ concentration in the Beijing-Tianjin-Hebei region in 2014," *China Environmental Science*, vol. 35, no. 10, pp. 2908–2916, 2014.

[4] T. Zhou and X. T. Ru, "Research on the causes and governance of smog in Beijing," *Journal of Huabei Power University (social science edition)*, vol. 2, pp. 12–16, 2012.

[5] S. Batterman, L. Xu, F. Chen, F. Chen, and X. Zhong, "Characteristics of $PM_{2.5}$ concentrations across Beijing during 2013–2015," *Atmospheric Environment*, vol. 145, pp. 104–114, 2016.

[6] J. Wang, Y. Wang, H. Liu et al., "Diagnostic identification of the impact of meteorological conditions on $PM_{2.5}$ concentrations in Beijing," *Atmospheric Environment*, vol. 81, pp. 158–165, 2013.

[7] P. S. Zhao, F. Dong, D. He et al., "Characteristics of concentrations and chemical compositions for $PM_{2.5}$ in the region of Beijing, Tianjin, and Hebei, China," *Atmospheric Chemistry and Physics*, vol. 13, no. 9, pp. 4631–4644, 2013.

[8] X. Ni, H. Huang, and W. Du, "Relevance analysis and short-term prediction of $PM_{2.5}$ concentrations in Beijing based on multi-source data," *Atmospheric Environment*, vol. 150, pp. 146–161, 2017.

[9] L. Xue, J. Sun, Y. Lin et al., "Characteristics of air pollution on hazy days in shenzhen in winter," *Environmental SciencesResearch*, p. 5, 2011.

[10] S. Q. Yu and X. D. Xu, "Spatial and temporal characteristics of air pollution in urban areas of Beijing," *Journal of Applied Meteorology*, vol. 13, pp. 92–99, 2002.

[11] Y. Wang, "Beijing time and space change characteristics and the study of meteorological causes during heavy pollution period," *Nanjing University of Information Engineering*, p. 59, 2014.

[12] Y. Zhao, J. Pan, and H. Y. Zhang, "Analysis on the pollution status of particulate matter in the atmosphere in Beijing," *Environmental Science Research*, vol. 17, pp. 67–69, 2004.