RESEARCH PAPER

THE TEMPORAL AND SPATIAL CHANGES OF BEIJING'S $PM_{2.5}$ CONCENTRATION AND ITS RELATIONSHIP WITH METEOROLOGICAL FACTORS FROM 2015 TO 2020

Guo Peng[1*], Umarova A.B.[1], Bykova G.S.[1], Luan Yunqi[1]
[1]Department of Soil, Moscow State University, Moscow, Russian Federation
*Corresponding author: 956095891@qq.com
Received: February 20th, 2020 / Accepted: August 2nd, 2021 / Published: October 1st, 2021
https://DOI-10.24057/2071-9388-2020-42

ABSTRACT. Currently, Beijing is facing increasing serious air quality problems. Atmospheric pollutants in Beijing are mainly composed of particulate matter, which is a key factor leading to adverse effects on human health. This paper uses hourly data from 36 environmental monitoring stations in Beijing from 2015 to 2020 to obtain the temporal and spatial distribution of the mass concentration of particulate matter with a diameter smaller than 2.5 μm ($PM_{2.5}$). The 36 stations established by the Ministry of Ecology and Environment and the Beijing Environmental Protection Monitoring Center and obtain continuous real-time monitoring of particulate matter. And the 36 stations are divided into 13 main urban environmental assessment points, 11 suburban assessment points, 1 control point, 6 district assessment points, and 5 traffic pollution monitoring points. The annual average concentration of $PM_{2.5}$ in Beijing was 60 μg/m^3 with a negative trend of approximately 14% year^{-1}. In urban areas the annual average concentration of $PM_{2.5}$ was 59 μg/m^3, in suburbs 56 μg/m^3, in traffic areas 63 μg/m^3, and in district areas 62 μg/m^3. From 2015 to 2020, in urban areas PM2.5 decreased by 14% year-1, in suburbs by 15% year^{-1}, in traffic areas by 15% year^{-1}, and in district areas by 12% year-1. The quarterly average concentrations of PM2.5 in winter and spring are higher than those in summer and autumn (64 μg/m^3, 59 μg/m^3, 45 μg/m^3, 55 μg/m^3, respectively). The influence of meteorological factors on the daily average value of $PM_{2.5}$ in each season was analysed. The daily average $PM_{2.5}$ in spring, summer, autumn and winter is significantly negatively correlated with daily average wind speed, sunshine hours, and air pressure, and significantly positively correlated with daily average rainfall and relative humidity. Except for autumn, the daily average $PM_{2.5}$ is positively correlated with temperature. Although Beijing's $PM_{2.5}$ has been declining since the adoption of the 'Air Pollution Prevention and Control Action Plan', it is still far from the first level of the new 'Ambient Air Quality Standard' (GB309S-2012) formulated by China in 2012.

KEYWORDS: $PM_{2.5}$, Beijing, temporal and spatial changes, meteorological factors

CITATION: Guo Peng, Umarova A.B., Bykova G.S., Luan Yunqi (2021). The Temporal And Spatial Changes Of Beijing's Pm2.5 Concentration And Its Relationship With Meteorological Factors From 2015 To 2020. Geography, Environment, Sustainability, Vol.14, No 3, p. 73-81 https://DOI-10.24057/2071-9388-2020-42

Conflict of interests: The authors reported no potential conflict of interest.

INTRODUCTION

When the particle size is less than 2.5 μm, it can both enter and reach the end of the bronchus, thereby interfering with gas exchange in the lungs. When the particle size is less than 1 μm, it can even penetrate the alveoli and enter the blood circulation of the human body, passing through and affecting other organs. Therefore, fine particles are more harmful to human health than larger ones. Concern about the hazards of particulate matter only started in the 1970s (Lave et al. 1973). According to statistics, the number of deaths caused by particulate pollution in the United States before 2000 was approximately 22,000 to 52,000. In European countries, the death toll is as high as 200,000. A long-term study of 500,000 people in large cities was conducted in the United States (Pope et al. 2002) and showed that for every 10 μg/m^3 increase in the concentration of fine particles, the mortality rate of all diseases, cardiovascular diseases and lung cancer increased by 4%, 6% and 8%, respectively. The hazards of particulate matter mainly depend on the toxic substances that it adsorbs. For example, adsorbed carcinogens, organic pollutants, and heavy metals will have toxic effects on the human reproductive system. Studies have also shown (Pope et al. 2009) that for every 10 μg/m^3 decrease in particle concentration, the average life span of the human body will increase by 0.61 years. In addition, a large number of studies have shown that particulate matter can affect the integrity of vegetation and natural ecosystems (Whitby et al. 1978), visibility (Chestnut et al. 1997), and man-made materials (Baedecker et al. 1997), while climate change (Warren et al. 2006) has direct and indirect effects.

In the past few decades, Beijing has conducted many studies on $PM_{2.5}$. The mass concentration of $PM_{2.5}$ in Beijing is highest in winter and lowest in summer (Yang et al. 2009). In 2000 and 2001, the main sources of $PM_{2.5}$ in Beijing were coal burning and dust, motor vehicle emissions, construction dust, biomass combustion, secondary nitrate, sulfate and organic matter. Compared with 1989–1990, pollution sources underwent certain changes (Zhu et al. 2005). Using the continuous observation data of $PM_{2.5}$ in Beijing from 2003 to 2004 and using the source analysis method of positive matrix decomposition, the pollution sources of fine particulate matter in Beijing were analysed as soil dust, coal, transportation, ocean, aerosol and the steel industry (Xu et al. 2007). We collected and analysed the $PM_{2.5}$ samples in different seasons in Beijing from 2009 to 2010 and discussed the main sources. The 6 main categories were soil dust, coal, biomass combustion, automobile exhaust, industrial pollution and secondary inorganic aerosols. Average contributions to PM2.5 were 15%, 18%, 12%, 4%, 25%, and 26%, respectively (Zhang et al. 2013). Research on Beijing's $PM_{2.5}$ in 2007 and 2008 found that the concentration of $PM_{2.5}$ in urban areas was higher than that in suburbs, and the concentration of $PM_{2.5}$ in urban areas increased significantly under foggy weather. During the Olympics, $PM_{2.5}$ pollution was significantly lower than that before the Olympics (Zhang et al. 2010). Using the two monitoring stations of the Beijing Urban Ecosystem Research Station to study $PM_{2.5}$, the results showed that the $PM_{2.5}$ of the two monitoring stations during the Olympics dropped by 26% and 27% compared to before the Olympics. During the Olympics, human control factors impacted $PM_{2.5}$ (Zhang et al. 2013). A similar study was also performed, and a similar conclusion was reached (Zeng et al. 2010). An analysis of particulate matter samples in Beijing and surrounding areas in August 2007 found that atmospheric particulate matter in Beijing gradually decreased from south to north (Zhao et al. 2009). From 2013 to 2014, the factors that caused changes in the concentration of particulate matter included high winds and biological particles in spring, humidity and rainfall in summer, temperature inversion and snowfall in autumn and winter, and other meteorological factors (Liu et al. 2016). In the 2014 Asia-Pacific Economic Cooperation (APEC) meeting and in the 2015 China Victory Day parade, to reduce man-made emissions, Beijing and its surrounding areas temporarily closed factories, construction sites and gas stations, banned the passage of vehicles on the road, and a 6-day statutory holiday was provided for state-owned enterprises and local government agencies. $PM_{2.5}$ decreased significantly (Xu et al. 2017; Wang et al. 2017; Xue et al. 2018; Li et al. 2016; Sun et al. 2016; Wang et al. 2016; Li et al. 2017; Huang et al. 2015). Since then, 'APEC Blue' and 'Parade Blue' have referred to good air quality. In Beijing, the daily concentration of $PM_{2.5}$ during the 'APEC Blue' period was 47.53 μg/m^3, and during the 'March Blue' period, it was 17.07 μg/m^3 (Lin et al. 2017). Regarding gas and particulate pollutants in Beijing and other regions, there are also many reports of temporal and spatial changes (Zhou et al. 2015; Guo et al. 2017; Chen et al. 2016; Wang et al. 2017). There is also the use of the community multiscale air quality modelling system (CMAQ) to calculate the reduction in the 'Air Pollution Prevention and Control Action Plan' (the Action Plan). It is estimated that from 2013 to 2017, the national population-weighted average $PM_{2.5}$ will drop from 61.8 μg/m^3 to 42.0 μg/m^3. Regionally, the largest decline in $PM_{2.5}$ will be in Beijing-Tianjin-Hebei with a simulated value of 38% (Zhang et al. 2019). Other authors have conducted similar studies in other regions (Cai et al. 2017; Jiang et al. 2015; Zheng et al. 2017; Xue et al. 2019). Recent reports using the CMAQ V5.0.1 model, concluded that the reduction of human activities during the COVID-19 outbreak still leads to serious air pollution incidents that cannot be avoided in Beijing because of meteorological factors (Wang et al. 2020).

To strengthen pollution control in Beijing, reduce the harm of air pollutants to human health and the environment, and improve people's living environment, research and work on monitoring, managing and improving environmental air quality has become the primary task of urban environmental protection. For this reason, in China, a series of national standards and governance measures have also been formulated, revised and promulgated. For example, the Ministry of Ecology and Environment promulgated the 'Ambient Air Quality Standards' (GB309S-2012) and 'Ambient Air Quality Index Technical Rules 2012' (HJ633-2012) on February 29, 2012. In the implementation of the 'Ambient Air Quality Standards', the Ministry of Ecology and Environment proposed that areas with good economic and technological foundations but prominent air pollution in the Beijing-Tianjin-Hebei region, the Yangtze River Delta and the Pearl River Delta must take the lead in implementing the new standards. On 10 September 2013, the Action Plan issued by the State Council further proposed that the overall air quality of the country should be improved within 5 years, requiring that by 2017, fine particulate matter PM2.5 in Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta would be reduced by approximately 25%, 20% and 15%, respectively. The specific measures of the Action Plan can be divided into six main parts: strengthening industrial emission standards, upgrading industrial boilers, eliminating outdated industrial capabilities, promoting clean fuels in the residential sector, eliminating small polluting factories, and strengthening vehicle emission standards (State Council of the People's Republic of China 2013; Zhang et al. 2019). With the promulgation of the Action Plan, the Ministry of Ecology and Environment (MEE) has established a relatively complete network of comprehensive environmental monitoring stations covering the whole country. By 2015, a comprehensive monitoring network covering more than 1,600 sites in 366 cities was established. Each monitoring station records the mass concentration of atmospheric particulate matter $PM_{2.5}$ and other data once an hour. There are 36 monitoring stations in Beijing. Before 2012, it was difficult to obtain air quality data from ground monitoring stations. As a nationwide network of environmental monitoring stations has just been established, these local data are rarely used to study the impact of the Action Plan on Beijing's $PM_{2.5}$ and the temporal and spatial changes in Beijing's $PM_{2.5}$. This article uses hourly $PM_{2.5}$ data from 36 stations to study the temporal and spatial changes in atmospheric particulate matter $PM_{2.5}$ in Beijing from 2015 to 2020. With the gradual improvement of environmental monitoring stations, in recent years, some researchers have used them to study the temporal and spatial changes in pollutants. For example, according to data from 1,689 sites from 2015 to 2017, China's $PM_{2.5}$ and SO_2 showed a downward trend, O_3 showed an upward trend, and NO_2 showed little change (Silver et al. 2018). The temporal and spatial characteristics of air pollutants in China from 2015 to 2019 were studied, and except for O3, the mass concentration of $PM_{2.5}$ and other pollutants decreased (Guo et al. 2020). Other authors have performed similar studies (Guo et al. 2019; Fan et al. 2020). However, most of them take the whole country as the research object and there are relatively few specific studies on $PM_{2.5}$ in Beijing using the new monitoring stations. In addition, Beijing issued the 'Beijing Clean Air Action Plan 2013–2017' (Beijing Clean Air Action Plan, 2013), which requires the annual average concentration of $PM_{2.5}$ in Beijing to be reduced by more than 30% and controlled to approximately 60 μg/m^3. It also proposes 84 quantitative tasks and indicators based on pollution concerning automobile, industrial, coal and dust sources. The promotion of air pollution research is thus a current high priority. By studying the characteristics of Beijing's air pollution, analysing the level of pollutants and their temporal and spatial changes, air pollution research has important scientific significance for understanding Beijing's ambient air and controlling air pollution. Results can also provide references for decision makers to correctly formulate environmental policies.

MATERIALS AND METHODS

This article uses the data of 36 stations established by the Ministry of Ecology and Environment in Beijing. Each station records the mass concentration of $PM_{2.5}$ once an hour. The names and locations of these stations are given in Table 1 and Fig. 1. The data used in this article can be downloaded from http://beijingair.sinaapp.com/. Other researchers who used these data (Guo et al. 2020; Silver et al.2018; Guo et al. 2019; Fan et al.2020; Rohde and Muller 2015; Liang et al.2016; Leung et al. 2018).

From the time perspective, we statistically analysed the mass concentration of $PM_{2.5}$ per hour, month, quarter, and year in Beijing from 2015 to 2020. To understand and evaluate the air quality in Beijing, by the beginning of 2013, the Beijing Environmental Protection Monitoring Center had established a real-time monitoring network covering the city. The system includes a total of 36 automatic monitoring stations, which obtain continuous real-time monitoring of particulate matter $PM_{2.5}$ and are divided into the following categories according to their functions: 13 main urban environmental assessment points, 11 suburban assessment points, 1 control point, 6 district assessment points, and 5 traffic pollution monitoring points. The distribution of automatic monitoring sites, site names, site functions, and administrative area locations are shown in table 1 and figure 1. The monitoring site data are continuously sampled 24 hours per day with monitoring results reported as 1 h average values. The 36 monitoring points are located in Beijing's six areas of the main city and ten suburban counties, and their coverage can basically reflect the air quality of the entire Beijing area. The data in this article come from the Ministry of Ecology and Environment of China and the Beijing Ecological Environment Monitoring Center. The data of the Ministry of Ecology and Environment used in this article can be downloaded from http://beijingair.sinaapp.com/.

From a spatial perspective, we performed kriging interpolation on 36 stations in Beijing from 2015 to 2020 to obtain the spatial distribution of the Beijing $PM_{2.5}$ mass concentration. The kriging spatial interpolation method is based on the theoretical analysis of semivariograms and the method for unbiased optimal estimation of variable values within a region (Wang et al. 2015). Some scholars who study the spatial distribution of O_3 and PM have used this method for related research (Chih-Da Wu et al. 2018; James P. et al.1995).

To examine changes over time, we conducted a statistical analysis on the mass concentration of $PM_{2.5}$ in Beijing from 2015 to 2020 and calculated the relative changes in the mass concentration of $PM_{2.5}$ in months, seasons and years. Here, spring is from March to May, summer is from June to August, autumn is from September to November, and winter is from December to February.

The locations of the weather stations and their meteorological data come from the China Meteorological Science Data Sharing Service Network http://cdc.nmic.cn/home.do (China's ground climate data daily value dataset (V3.0) SURF_CLI_CHN_MUL_DAY_V3.0). This study uses data from three basic standard weather stations in Beijing, namely, Beijing, Yanqing and Miyun, and collects and organizes data for daily precipitation and daily averaged air pressure, temperature, wind speed, relative humidity, and sunshine hours. This study is based on monitoring data of the daily average $PM_{2.5}$ concentration in Beijing from 2015 to 2020 and comprehensively analyses the relationship between particulate matter and meteorological factors in terms of temporal resolution. The nonparametric correlation analysis method (Spearman rank correlation coefficient), which is more adaptable than traditional parameter analysis methods and has a wider application range, is used to study the correlation between the concentration of $PM_{2.5}$ and various meteorological factors in different seasons.

RESULTS AND DISCUSSION

Spatial distribution

We performed kriging interpolation on the annual average concentration of $PM_{2.5}$ at 36 sites in Beijing to obtain the spatial distribution of annual $PM_{2.5}$ from 2015 to 2020. From a geographical point of view, Beijing's $PM_{2.5}$ concentration is obviously high in the south and low in the north, with the highest concentration in the southeast. The concentration of $PM_{2.5}$ in the southwest is followed by the urban area and the northeast area, and the lowest concentration is in the northwest (Figure 1). In 2015, the difference between the regions with the highest and lowest concentrations of $PM_{2.5}$ reached 59 μg/m^3. This difference was reduced to 23 μg/m^3 by 2020. This spatial distribution

Table 1. Automatic monitoring site number, distribution, site name, site function and administrative area

Number	Longhude	Latitude	Place name	Function	Number	Longitude	Latitude	Place name	Function
1	116.43	39.95	Dongsi	Urban area	19	116.23	40.20	Changping Town	Suburbs
2	116.43	39.87	Temple ofHeaven	Urban area	20	116.11	39.94	Menlougou LongquanTown	Suburbs
3	116.36	39.94	Guanyuan	Urban area	21	117.10	40.14	PingguTown	Suburbs
4	116.37	39.87	Wanshou West Palace	Urban area	22	116.64	40.39	Huairou Town	Suburbs
5	116.41	40.00	Olympic Sports Center	Urban area	23	116.83	40.37	Miyun Town	Suburbs
6	116.47	39.97	Agricultural Exhibition HaD	Urban area	24	115.97	40.45	YanqingTown	Suburbs
7	116.32	39.99	Haidian Wanliu	Urban area	25	116.17	40.29	Dingling	Control poinl
8	116.17	40.09	Haidian North New District	Urban area	26	115.99	40.37	Badaling, Northwest Beijing	Distriet
9	116.21	40.00	Haidian Beijing Botanical Garden	Urban area	27	116.91	40.50	Miyun Reservoir in Northeast Beijing	District

10	116.28	39.86	Fengtai Garden	Urban area	28	117.12	40.10	Jingdong Donggao Village	Distriet
11	116.15	39.82	Fengtai Yungang	Urban area	29	116.78	39.71	Jingdongnan Yongle Store	District
12	116.47	39.96	U.S. Embassy	Urban area	30	116.30	39.52	Jingnan Yufa	District
13	116.23	39.93	Gucheng	Urban area	31	116.00	39.58	Soulhwestem Beijing Liuli River	District
14	116.14	39.74	Fangshan Liangxiang	Suburbs	32	116.40	39.90	Qianmen East Street	Traffic poinl
15	116.40	39.72	Daxing Huangcun Town	Suburbs	33	116.39	39.88	Yongdingmen Inner Street	Traffic poinl
16	116.51	39.80	Yrdiuang Development Zone	Suburbs	34	116.35	39.95	Xiühimen North Street	Traffic point
17	116.66	39.89	Tongzhou New City	Suburbs	35	116.37	39.86	South Third Ring Road West	Traffic point
18	116.72	40.14	Shunyi New City	Suburbs	36	116.48	39.94	East Fourth Ring Road	Traffic point

is related to Beijing's geomorphology and human activities. The northern part of Beijing is mostly mountainous areas, nature reserves and reservoirs, with few human activities, which is not conducive to the production of PM$_{2.5}$. The population and traffic in southern Beijing are both too high, which is conducive to the production of PM$_{2.5}$, especially under southerly winds. Particulates migrating from the south have the greatest impact on the southern part of Beijing and are more likely to form severe haze weather (Ma et al. 2017). Minor substances (NH^{4+}, SO_4^{2-} and NO^{3-}) are the main chemical components of aerosols; the trace material carried by the southerly wind is greater than that carried by the westerly wind, which, in turn, is larger than that carried by the northerly wind (Sun et al. 2006). Beijing's PM$_{2.5}$ has a good correlation with CO, NO_2 and SO_2 emissions in southern Hebei Province, and pollutant gas emissions in southern provinces have increased the burden of Beijing's PM$_{2.5}$ (Jiang et al. 2015). Long-distance transportation can even affect the aerosol boundary layer 1000 km away (Huang et al. 2020).

From the perspective of administrative regions, the mass concentration of PM$_{2.5}$ in urban areas is higher than that in suburbs, which is related to higher vehicle exhaust emissions in urban areas. Compared with previous studies on the source of PM$_{2.5}$, transportation is becoming increasingly important as a source of PM$_{2.5}$. In addition, there are other disadvantages caused by urbanization (Naděžda Zíková et al. 2016). The annual PM$_{2.5}$ concentration in traffic points and districts is higher than that in urban areas and suburbs. The higher PM$_{2.5}$ in the districts is related to the migration of particulate matter in the provinces and cities around Beijing. Except for individual months, the overall concentration in urban areas is higher than that in the suburbs, as shown in figure 2 and figure 4.

Changes over time

From 2015 to 2020, Beijing's PM2.5 concentration dropped with a linear trend of 13.98% year^{-1}. Although PM2.5 is declining year by year, the annual average mass

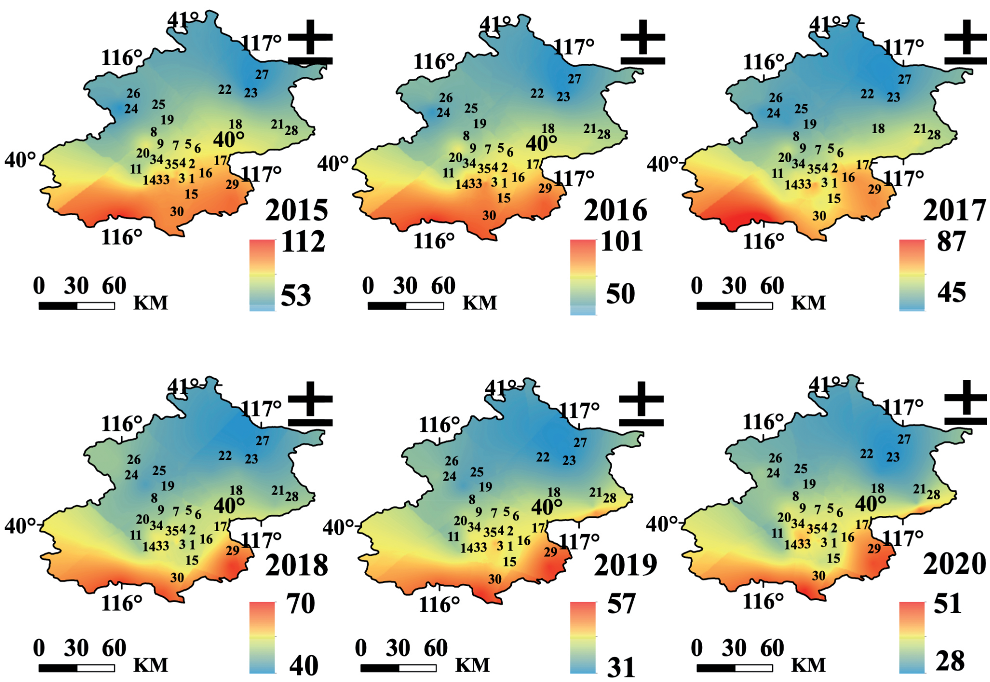

Fig. 1. The spatial distribution of PM2.5 (unit: μg/m³) in Beijing from 2015 to 2020 (1-36: site number)

concentration of $PM_{2.5}$ in 2020 is 37.99 μg/m^3, which is still above the first level (35 μg/m^3) of the latest 'ambient air quality standard' and some distance away from the World Health Organization's Air Quality Guidelines (10 μg/m^3). From 2015 to 2020, the higher mass concentration of $PM_{2.5}$ in Beijing usually occurs in winter and spring and is related to local coal burning. According to the survey and research in the Beijing-Tianjin-Hebei region, residents' coal accounts for 46% of the monthly average $PM_{2.5}$, and Beijing, Tianjin and Hebei account for 3%, 3% and 40%, respectively. Since the Action Plan, Beijing has switched to natural gas and electricity instead of coal, but Hebei Province has had a significant impact on air pollution in Tianjin and Beijing (Zhang et al. 2017). In winter, more attention should be given to the prevention and control of $PM_{2.5}$. Lower $PM_{2.5}$ occurs in summer and autumn, which is related to increased precipitation or photochemical degradation in summer and autumn (Zhou et al. 2015). There are occasional low $PM_{2.5}$ mass concentrations in winter and spring, which may be related to snowfall in winter and spring, since snow plays an important role in the purification of $PM_{2.5}$ (Liu et al. 2016).

From 2015 to 2020, the $PM_{2.5}$ decreased the most in the fall of 2015, with a linear trend of 14.54% year^{-1}, followed by winter with a decrease of 12.70% year^{-1} and spring with a decrease of 11.88% year^{-1}. This is related to the Action Plan's emission reduction policy (Zhang et al. 2019). During summer, the decrease is approximately 8.59% year^{-1} due to the low $PM_{2.5}$ concentration. In terms of months, December and October had the largest decreases in $PM_{2.5}$, with decreases of 23.92% year^{-1} and 14.07% year^{-1}, respectively. From 2015 to 2020, only in February and January did the annual average relative change (year^{-1}) show a nonsignificant upward trend (0.04% year^{-1} in February, 6.48% year^{-1} in January). The increase in $PM_{2.5}$ in January and February is related not only to coal burning but also to higher relative humidity in January and February, which will increase the man-made secondary inorganic matter and liquid water content in $PM_{2.5}$, and condensed water promotes the conversion of gaseous pollutants into particles and accelerates the formation of dense fog (Wu et al. 2018). The high air pressure in winter is also for a contributor to the high concentration of $PM_{2.5}$. The daily average air pressure in winter from 2015 to 2020 in Beijing was 1028.86 hPa, which was higher than that in other seasons. High pressure easily forms stable meteorological conditions, which reduce the diffusion of particulate matter. The greater drop in $PM_{2.5}$ concentration in June is related to the concentrated rainfall in summer. The daily average precipitation in summer from 2015 to 2020 in Beijing is 3.81 mm, which is much higher than that in other seasons. From the perspective of regional functions, the $PM_{2.5}$ of Beijing's main urban area has dropped by 13.62% year^{-1}, suburban areas have dropped by 14.99% year^{-1}, traffic points have dropped by 14.91% year-1, and districts have dropped by 12.25% year^{-1} from 2015 to 2020. The annual average relative changes in $PM_{2.5}$ at 36 stations in the main city, suburbs, traffic areas, and districts all showed a downward trend. Fengtai Yungang in the main city, Fangshan Liangxiang in the suburbs, East Fourth Ring

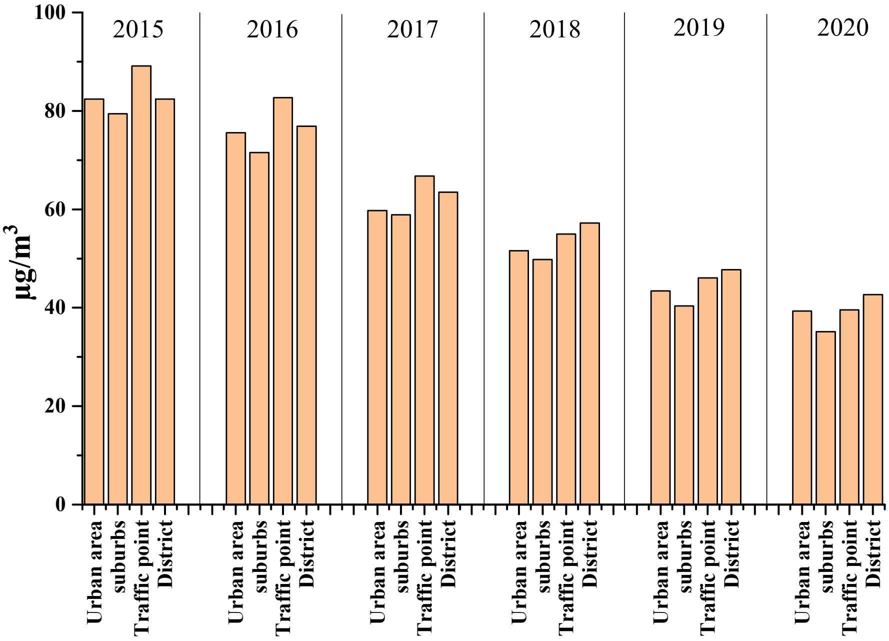

Fig. 2. The annual average mass concentration of $PM_{2.5}$ in each functional area from 2015 to 2020

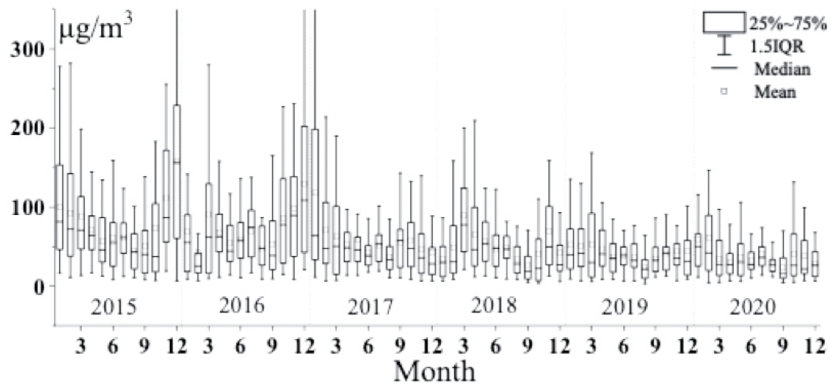

Fig. 3. Monthly change in $PM_{2.5}$ concentration in Beijing from 2015 to 2020

Road in the traffic areas, and Liuli River in the districts have the most decline, with a decrease of 15.59% year^{-1}, 16.50% year^{-1}, 16.12% year^{-1}, 15.64% year^{-1}, respectively. Haidian Botanical Garden in the main urban area, Yanqing Town in the suburbs, the Badaling Great Wall in the districts, the Xizhimen North Street in the traffic areas have the least decline with a decrease of 12.12% year^{-1}, 11.38% year^{-1}, 12.69% year^{-1}, 8.16% year^{-1}. The drop of the Great Wall's $PM_{2.5}$ is less due to its low concentration.

The hourly average concentration of $PM_{2.5}$ in different seasons from 2015 to 2020 did not show regularity. For example, the high concentration of $PM_{2.5}$ in the winter of 2015 appeared at 8 am, while in the winter of 2016 to 2020 at 8 am the average concentration is high or low, and the low concentration in the winter of 2020 appears at 8 am, which is the opposite of 2015, as shown in figure 5. As another example, the lowest average concentration of $PM_{2.5}$ in the winter of 2015 was at 1 am. The highest $PM_{2.5}$ concentration in the winter of 2018 was also at 1 am. Other seasons also showed similar phenomena, which are related to the variability of hourly meteorological factors.

As shown in Table 2, the daily mean $PM_{2.5}$ concentration in spring in Beijing has a significant negative correlation with wind speed and sunshine hours, while its relationship with relative humidity shows a significant positive correlation. With the increase in sunshine hours, the vertical diffusion capacity of the atmosphere is strengthened, which is conducive to the migration and diffusion of pollutants in the atmosphere and reduces the concentration of particulate matter at ground level (Li et al. 2009). The daily average value of $PM_{2.5}$ concentration in summer is significantly positively correlated with relative humidity. When the summer air humidity increases and the water vapour pressure increases, the particulate matter does

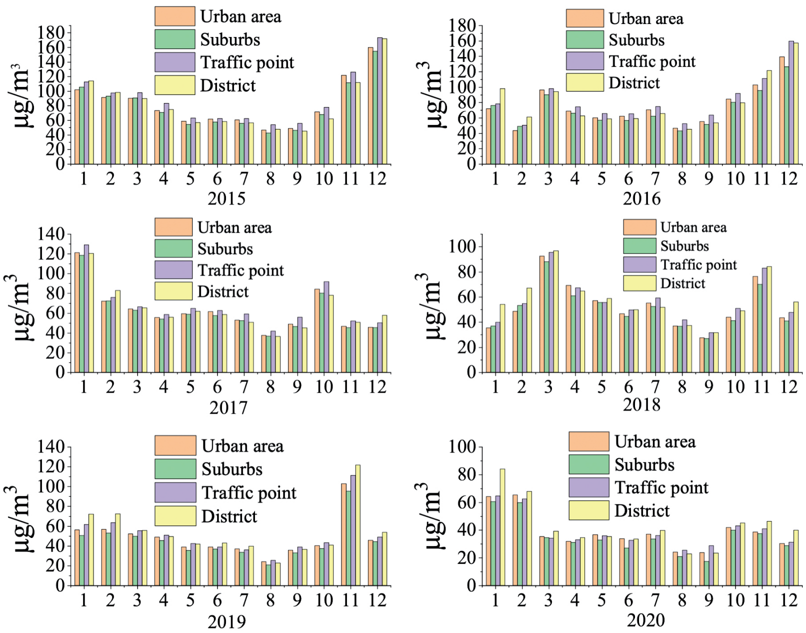

Fig. 4. Monthly mean $PM_{2.5}$ concentration in urban, suburbs traffic area, and district from 2015 to 2020

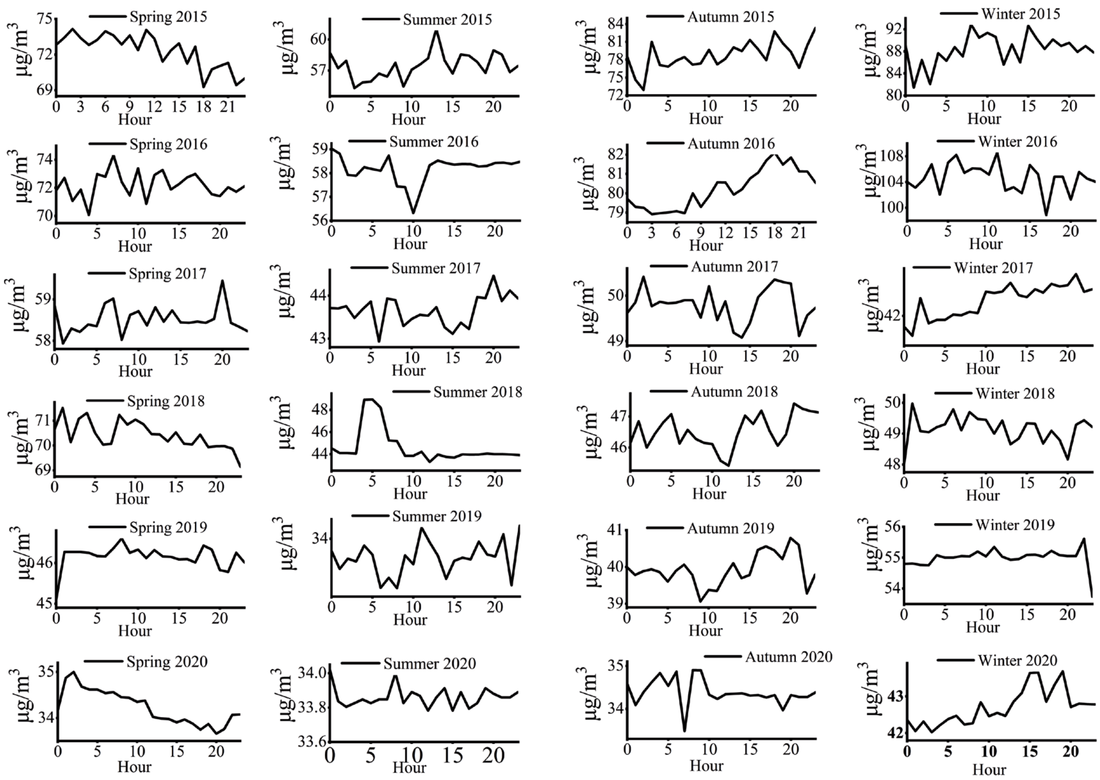

Fig. 5. Hourly average concentration of $PM_{2.5}$ in different seasons from 2015 to 2020

Table 2. The relationship between daily average $PM_{2.5}$ and daily average temperature, wind speed, humidity, precipitation, sunshine duration, and air pressure from 2015 to 2020. Yellow is the more significant correlation coefficient

		$PM_{2.5}$			
		Spring	Summer	Autumn	Winter
Temperature	Spearman	0.05	0.17	-0.08	0.13
	P value	0.20253	3.68E-05	0.06698	0.00563
Wind speed	Spearman	-0.21	-0.08	-0.22	-0.24
	P value	8.51E-07	0.06917	1.58E-07	6.30E-08
Humidity	Spearman	0.53	0.32	0.56	0.48
	P value	3.43E-41	1.53E-14	8.54E-46	3.03E-29
Precipitation	Spearman	0.04	0.01	0.08	0.08
	P value	0.36875	0.80717	0.08056	6.65E-02
Sunshine duration	Spearman	-0.42	-0.29	-0.47	-0.35
	P value	1.59E-25	4.23E-12	1.09E-31	6.64E-15
Air pressure	Spearman	-0.21	-0.07	-0.06	-0.18
	P value	5.90E-07	1.00E-01	0.14649	6.85E-05

not easily migrate and diffuse, and its concentration value increases. Precipitation factors have a significant effect on the deposition of atmospheric particulate matter (Hu et al. 2006). Summer is hot and rainy in Beijing, and the daily average precipitation in summer from 2015 to 2020 reaches 3.81 mm, which is twice the rainfall in other seasons. Although the correlation between the concentration of particulate matter and precipitation is not significant, it can be concluded from the daily average value of $PM_{2.5}$ concentration that its concentration is basically at a low level. Summer rainfall can effectively remove particulate matter in the atmosphere. Precipitation directly affects the value of water vapour pressure and relative humidity, which can better diffuse and settle atmospheric particulate matter in summer and achieve the least pollution. The daily average value of $PM_{2.5}$ in autumn in Beijing has a statistically significant negative correlation with average sunshine hours and wind speed and a positive correlation with relative humidity. In the autumn from 2015 to 2020, the wind speed in Beijing was the lowest in the four seasons, the daily average wind speed in autumn from 2015 to 2020 was only 1.76 m/s, the daily average relative humidity was high, the temperature inversion was prone to persist for many days, the weather system was stable, which was not conducive to the diffusion of $PM_{2.5}$, and pollutants easily continued to accumulate. The daily average value of $PM_{2.5}$ in winter is directly proportional to the daily average relative humidity and inversely proportional to the daily average sunshine duration and wind speed from 2015 to 2020.

CONCLUSION

Based on the $PM_{2.5}$ and meteorological data of various stations in Beijing, we studied the spatial distribution and temporal changes of $PM_{2.5}$ in Beijing from 2015 to 2020 and the correlation between $PM_{2.5}$ and temperature, air pressure, rainfall, relative humidity, and sunshine in different seasons. The concentration of $PM_{2.5}$ varies in different seasons. This is related to both human and meteorological factors. Until 2020, the annual average $PM_{2.5}$ in Beijing was 37.99 μg/m^3, which was 53.10% lower than the $PM_{2.5}$ in 2015, reflecting the effectiveness of the Action Plan. The annual PM2.5 concentration value is still higher than the World Health Organization 10 μg/m^3 standard value. Winter is the season of high incidence of $PM_{2.5}$. More attention should be given to the problem of $PM_{2.5}$ pollution in winter. The traffic area still has a high $PM_{2.5}$ concentration. To reduce $PM_{2.5}$ at traffic points, Beijing should continue to strengthen motor vehicle emission standards.

REFERENCES

Silver B., Reddington C.L., Arnold S.R. and Spracklen D.V. (2018). Substantial changes in air pollution across China during 2015–2017. Environmental Research Letters. 13, 11.

Baedecker P.A., Reddy M.M., Reimann K.J., et al. (1992). Effects of acidic deposition on the erosion of carbonate stone-experimental results from the US National Acid Precipitation Assessment Program (NAPAP). Atmospheric Environment. Part B. 26(2), 147-158.

Li C.C., Mao J.T., Liu Q.H. et al. (2005). Application of MODIS satellite remote sensing aerosol products in Beijing air pollution research. Science in China. (S1), 177-186. (in Chinese).

Chen T., He J., Lu X., She J. & Guan Z. (2016). Spatial and Temporal Variations of PM2.5 and Its Relation to Meteorological Factors in the Urban Area of Nanjing, China. International journal of environmental research and public health. 13.

Cheng N. et al. (2018). Ground-Level NO2 in Urban Beijing: Trends, Distribution, and Effects of Emission Reduction Measures. Aerosol and Air Quality Research. 18, 343-356.

Chestnut L.G, Dennis R.L. (1997). Economic benefits of improvements in visibility: Acid rain provisions of the 1990 Clean Air Act Amendments. Journal of the Air&Waste Management Association. 47(3), 395-402.

Franke R. (1982). Smooth Interpolation of Scattered Data by Local Thin Plate Splines.Computer and Mathematics with Applications, 8(4), 273-281.

Yang M., He K.B., Ma Y.L., et al. (2002). The variation characteristics of Beijing PM2.5 concentration and its relationship with PM10, TSP. China Environmental Science. 22(6), 27-31. (in Chinese).

Wang G., Cheng S., Wei W., Yang X., Wang X., Jia J., Lang J., Lv Z. (2017). Characteristics and emission-reduction measures evaluation of PM2.5 during the two major events: APEC and Parade. Sci. Total Environ, 595, 81-92.

Chih-DaWuab Yu-Ting Zengab Shih-Chun Candice Lung. A hybrid kriging/land-use regression model to assess PM2.5 spatial-temporal variability Science of The Total Environment, 645(15) December 2018, 1456-1464, DOI: 10.1016/j.scitotenv.2018.07.073.

Guo H. et al. (2017). Assessment of PM2.5 concentrations and exposure throughout China using ground observations. The Science of the total environment. 601-602, 1024-1030.

Guo P., Umarova A.B., Luan Y. (2020). The spatiotemporal characteristics of the air pollutants in China from 2015 to 2019. PLOS ONE 15(8): e0227469, DOI: 10.1371/journal.pone.0227469.

Li H., Zhang Q., Duan F., Zheng B., He K. (2016). The «Parade Blue»: effects of short-term emission control on aerosol chemistry. Faraday Discuss, 189, 317-335.

Lin H., Liu T., Fang F., Xiao J., Zeng W., Li X., Guo L., Tian L., Schootman M., Stamatakis K.A., Qian Z., Ma W.. (2017). Mortality benefits of vigorous air quality improvement interventions during the periods of APEC Blue and Parade Blue in Beijing, China. Environ. Pollut., 220, 222-227.

Hu Min, Liu Shang, Wu Zhijun, etc. The influence of high temperature, high humidity and precipitation process in summer in Beijing on the distribution of atmospheric particulate matter is close. Science, 2006, 27(11), 2293-2298. (in Chinese).

Wang H., Zhao L., Xie Y., Hu Q.. (2016). 'APEC blue'-The effects and implications of joint pollution prevention and control program. Sci. Total Environ., 553, 429-438.

Hao Fan, Chuanfeng Zhao, Yikun Yang. (2020). A comprehensive analysis of the spatio-temporal variation of urban air pollution in China during 2014-2018. Atmospheric Environment. 220, 117066, DOI: 10.1016/j.atmosenv.2019.117066.

Hong Guo, Xingfa Gu, Guoxia Ma, Shuaiyi Shi, Wannan Wang, Xin Zuo & Xiaochuan Zhang. (2019). Spatial and temporal variations of air quality and six air pollutants in China during 2015–2017. Scientific Reports, 9, 15201.

James P. Bennett, Mousumi Banerjee,Air pollution vulnerability of 22 midwestern parks,Journal of Environmental Management, Volume 44, 5, 339-360, DOI: 10.1016/S0301-4797(95)90356-9.

World Health Organization. (2005). https://apps.who.int/iris/bitstream/handle/10665/69477/WHO_SDE_PHE_OEH_06.02_chi.pdf;jsessionid=ACB2C9CFB2DFBF6A1384B4978DD527AC?sequence=3

Ambient air quality standards. (2012). https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/dqhjbh/dqhjzlbz/201203/W020120410330232398521.pdf. (in Chinese).

Technical Regulation on Ambient Air Quality Index (on trial). (HJ 633-2012). (2012). https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/jcffbz/201203/t20120302_224166.shtml.

Huang X., Ding A., Wang Z. et al. (2020). Amplified transboundary transport of haze by aerosol–boundary layer interaction in China. Nat. Geosci. 13, 428-434, DOI: 10.1038/s41561-020-0583-4. (in Chinese).

Beijing Clean Air Action Plan for 2013–2017. (2013). http://sthjj.beijing.gov.cn/bjhrb/index/xxgk69/sthjlyzwg/wrygl/603133/index.html. (in Chinese).

Wang J., Yang F.M., Wang D.Y. et al. (2010). Characteristics and correlation of MODIS aerosol optical thickness and PM2.5 mass concentration in Beijing. 27(l), 10-16. (in Chinese).

Zeng J., Liao X.L., Ren Y.F. et al. (2010). Dynamic characteristics and influencing factors of Beijing PM2.5, $N0_2$, CO during the Olympics. Acta Ecologica Sinica. 30 (22), 6227-6233. (in Chinese).

Jiang J., Zhou W., Cheng Z., Wang S., He K. and Hao J. (2015). Particulate Matter Distributions in China during a Winter Period with Frequent Pollution Episodes. Aerosol Air Qual. Res. 15: 494-503, DOI: 10.4209/aaqr.2014.04.0070.

Huang K., Zhang X., Lin Y. (2015). The «APEC Blue» phenomenon: Regional emission control effects observed from space. Atmos. Res. 164-165, 65-75.

Krotkov N.A, et al. (2016). Aura OMI observations of regional SO_2 and NO_2 pollution changes from 2005 to 2015 Atmos. Chem. Phys. 16, 4605-29.

Li Jun, Sun Chunbao, Liu Xiande, et al. Subparametric analysis of the influence of meteorological factors on the concentration of atmospheric particulate matter in Beijing. Environmental Science Research, 2009, 22(6), 663-669. (in Chinese).

Zhang L., Zaho X.J., Pu W.W., et al. (2010). Comparative analysis of element characteristics of atmospheric fine particulate PM2.5 in Beijing urban and suburban areas. China Powder Technology, 16(1), 2834. (in Chinese).

Lave L.B., Seskin E.P. (1973). An Analysis of the Association Between U.S. Mortality and Air Pollution. Statistical Association, 68 (342), 342.

Ma Z., Hu X., Sayer A.M., Levy R., Zhang Q., Xue Y., Tong S., Bi J., Huang L. and Liu Y. (2016). Satellite-based spatiotemporal trends in PM2.5 concentrations: China, 2004–2013 Environ. Health Perspect, 124, 184-92.

Mokdad A.H., James S.M., Stroup D.F., et al. Actual Causes of Death in the United States, (2000). The Journal of the American Mdeical Association, 2004, 291 (10), 1238-1245.

Mitas L., and Mitasova H. (1988). General Variational Approach to the Interpolation Problem.Computer and Mathematics with Applications, 16(12), 983-992.

Naděžda Zíková et al. (2016). On the source contribution to Beijing PM2.5 concentrations. Atmospheric Environment, 134, 84-95.

Peng J., Chen S., Lv H., Liu Y. and Wu J. (2016). Spatiotemporal patterns of remotely sensed PM2.5 concentration in China from 1999 to 2011. Remote Sens. Environ. 174, 109-21.

Pengfei Wang et al. (2020). Severe air pollution events not avoided by reduced anthropogenic activities during COVID-19 outbreak. Resources, Conservation and Recycling. 158, 104814, DOI: 10.1016/j.resconrec.2020.104814.

Pope C.A., Bumett R.T. (2002). Lung cancer, cardiopulmonary mortality and long term exposure to fine particulate air pollution. American Medical Association, 287(9), 1132-1141.

Pope C.A., Ezzati M., Dockery D.W., et al. (2009). Fine-particulate air pollution and life expectancy in the United States. The New England Journal of Medicine, 360(4), 376-386.

Qiangxia Ma et al. (2017). Roles of regional transport and heterogeneous reactions in the PM2.5 increase during winter haze episodes in Beijing. Science of The Total Environment, 599-600, 246-253.

Qing Zhao, He K.B., Ma Y.L., et al. (2009). Regional pollution characteristics of atmospheric particulate matter in summer in Beijing and surrounding areas. Environmental science, 30(7), 1873-1880. (in Chinese).

Siyi Cai, et al. (2017). The impact of the «Air Pollution Prevention and Control Action Plan» on PM2.5 concentrations in Jing-Jin-Ji region during 2012–2020. Sci. Total Environ, 580, 197-209.

State Council of the People's Republic of China. Notice of the general office of the state council on issuing the air pollution prevention and control action plan. http://www.gov.cn/zwgk/2013-09/12/content_2486773.htm.

Sulaman Muhammad, Xingle Long, Muhammad Salman. (2020). COVID-19 pandemic and environmental pollution: A blessing in disguise? Science of The Total Environment. 728, 138820, DOI: 10.1016/j.scitotenv.2020.138820.

Xue T., et al. (2019). Rapid improvement of PM2.5 pollution and associated health benefits in China during 2013–2017. Sci. China Earth Sci. 62, 1847-1856.

Van D.A., Martin R.V., Brauer M., et al. (2010). Global estimates of ambient fine particulate matter concentrations from satellite-based aerosol optical depth: development and application. Environmental health perspectives, 8(6), 847.

Xu W., Song W., Zhang Y., Liu X., Zhang L., Zhao Y., Liu D., Tang A., Yang D., Wang D., Wen Z., Pan Y., Fowler D., Collett J.L., Erisman J.W., Goulding K., Li Y., Zhang F.. (2017). Air quality improvement in a megacity: implications from 2015 Beijing Parade Blue pollution control actions. Atmos. Chem. Phys, 17 (1), 31-46.

Wang W.N., et al. (2017). Assessing Spatial and Temporal Patterns of Observed Ground-level Ozone in China. Scientific reports, 7, 3651.

Warren R., Arnell N., Nicholls R., et al. (2006). Understanding the regional impacts of climate change. UK: University of east anglia.

Whitby K.T. (1978). The physical characteristics of sulfur aerosols. Atmospheric Environment, 12(1-3), 135-159.

Wang Zhanshan, Li Yunting, Chen Tian, et al. (2015). The temporal and spatial distribution of PM2.5 in Beijing in 2013. Acta Geographica Sinica, 70(l), 110-120. (in Chinese).

Jiang X., Chaopeng Hong, Yixuan Zheng, Bo Zheng, Dabo Guan, Andy Gouldson et al. (2015). To what extent can China's near-term air pollution control policy protect air quality and human health? A case study of the Pearl River Delta region. Environ. Res. Lett, DOI: 10: 104006.

Zhu X.L., Zhang Y.H., Zeng L.M., et al. (2005). Research on the source of atmospheric fine particulate matter PM2.5 in Beijing. Environmental Science Research, 18(5), 1-5. (in Chinese).

Li X., Qiao Y., Zhu J., Shi L., Wang Y.. (2017). The «APEC blue» endeavor: causal effects of air pollution regulation on air quality in China. Cleaner Prod, 168, 1381-1388.

Xu G., Ding A., Yan P. (2007). The composition characteristics and source analysis of PM2.5 in Beijing. Journal of Applied Meteorology, 18(5), 645-654. (in Chinese).

Sun Y., Wang Z., Wild O., Xu W., Chen C., Fu P., Du W., Zhou L., Zhang Q., Han T., Wang Q., Pan X., Zheng H., Li J., Guo X., Liu J., Worsnop D.R. (2016). «APEC Blue»: secondary aerosol reductions from emission controls in Beijing. Sci. Rep. 6, 20668.

Xue Y., Wang Y., Li X., Tian H., Nie L., Wu X., Zhou J., Zhou Z.. (2018). Multi-dimension apportionment of clean air «parade blue» phenomenon in Beijing. Environ Sci (China), 65, 29-42.

Zheng Y., Tao Xue, Qiang Zhang, Guannan Geng, Dan Tong, Xin Li, et al. (2017). Air quality improvements and health benefits from China's clean air action since 2013. Environ. Res. Lett, 12, 114020.

Yele Sun, Guoshun Zhuang, Aohan Tang, Ying Wang, and Zhisheng An. (2006). Environmental Science & Technology, 40(10), 3148-3155, DOI: 10.1021/es051533g.

Zhang R., Jing J., Tao J., et al. (2013). Chemical characterization apportionment and source atmospheric of PM2.5 in Beijing: seasonal perspective. Chemistry and Physics, 13(14), 7053-7074.

Zhang R., Jing J., Tao J., et al. (2013). Chemical characterization and source apportionment of PM2.5 in Beijing: seasonal perspective. Atmospheric Chemistry and Physics, 13(14), 7053-7074.

Zhang Y.L. & Cao F. (2015). Fine particulate matter (PM2.5) in China at a city level. Scientific reports, 5, 14884.

Zhang Q., Yixuan Zheng, Dan Tong, Min Shao, Shuxiao Wang, Yuanhang Zhang et al. (2019). Drivers of improved PM2.5 air quality in China from 2013 to 2017. PNAS. 116(49), 24463-24469.

Zhang J., Ouyang Z.Y., Miao H., et al. (2013). Comparison and analysis of the characteristics of atmospheric fine particulate matter in Beijing during the early and during the Olympic. Environmental science, 34 (7), 2512-2518. (in Chinese).

Zhijun Wu, Yu Wang, Tianyi Tan, Yishu Zhu, Mengren Li, Dongjie Shang, Haichao Wang, Keding Lu, Song Guo, Limin Zeng, and Yuanhang Zhang. (2018). Aerosol Liquid Water Driven by Anthropogenic Inorganic Salts: Implying Its Key Role in Haze Formation over the North China Plain. Environmental Science & Technology Letters, 5(3), 160-166, DOI: 10.1021/acs.estlett.8b00021.

Zhongzhi Zhang et al. (2017). The contribution of residential coal combustion to PM2.5 pollution over China's Beijing-Tianjin-Hebei region in winter. Atmospheric Environment, 159, 147-161.

Zhou Y., Shuiyuan Cheng, Dongsheng Chen, Jianlei Lang, GangWang, Tingting Xu et al. (2015). Temporal and Spatial Characteristics of Ambient Air Quality in Beijing, China. Aerosol and Air Quality Research, 15, 1868-1880.