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RESEARCH ARTICLE

Spatial and temporal characteristics of air quality and air pollutants in 2013 in Beijing

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Abstract Air pollution has become an ever more critical issue in Beijing in more recent years. In this study, we use the air quality index (AQI), corresponding primary pollutant types and meteorological data which are collected at 16 monitoring stations in Beijing between January 2013 and December, 2013 studying the spatial and temporal variations of air quality and air pollutants. The results show that $PM_{2.5}$ was the most serious pollutant, followed by O_3. The average $PM_{2.5}$ mass concentration was $119.5 \pm 13.8\ \mu g\ m^{-3}$ in Beijing. In addition, the air quality varies across different seasons. More specifically, winter season showed the worst air quality. Moreover, while particulate matter ($PM_{2.5}$ and PM_{10}) concentrations were relatively higher in the spring and winter seasons, gaseous pollutants (O_3 and NO_2) were more serious in the summer and autumn. In terms of spatial heterogeneity, the findings showed that AQI and $PM_{2.5}$ concentrations were higher in south and lower in the north of the city, and the O_3 showed exactly a pattern with the opposite direction—higher in the north and lower in the south. NO_2 was found to have a greater impact on the central region compared with that in other regions. Furthermore, $PM_{2.5}$ was found to be positively correlated with the relative humidity, but negatively correlated with wind speed and atmospheric pressure ($P < 0.01$). However, the dominant meteorological factors that influence the $PM_{2.5}$ concentrations varied in different seasons. The results in this paper provide additional information for the effective control of the air pollution in Beijing.

Keywords Air quality index (AQI) · $PM_{2.5}$ · Spatial-temporal variation · Meteorological factors · Beijing

Introduction

Air pollution has become a serious threat to people all over the world, especially in China (Shi et al. 2014; Tang et al. 2012). As urbanization, industrial development, vehicle usage, and other environmentally hazardous processes increase, more fossil fuels are burned, resulting in increased carbon dioxide (CO_2), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), and particulate matter (PM) concentrations in the troposphere (Liu et al. 2012; Tian et al. 2014). Among these pollution sources, $PM_{2.5}$ (aerodynamic diameter $\leq 2.5\ \mu m$) is considered to be the major reason for the deterioration of the air quality of Beijing (Xu et al. 2013). $PM_{2.5}$ has attracted worldwide attention due to their adverse impacts on visibility reduction (Gao et al. 2015), human health (Leiva et al. 2013; Pascal et al. 2014; Shankardass et al. 2015), and global climate (Yang et al. 2015).

Beijing, the capital city of China, is one of the most seriously air polluted cities in the country (Chan and Yao 2008; Sun et al. 2011). In recent years, many researches about air pollution levels of Beijing have been conducted (Guan et al. 2014; He et al. 2001). These previous studies have provided the characteristics of the mass concentrations of air pollutants

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in different temporal and meteo-climatic conditions, e.g., during the dust storm period (Xie et al. 2005), during hazy days, and non-hazy days (Sun et al. 2013; Zhang et al. 2015a), in a week (Shi et al. 2014), in a month (Yang et al. 2015), in a season (Quan et al. 2014; Takegawa et al. 2009). However, all of these works did not take the pollutants on the monthly and seasonal variations into account, especially the spatial heterogeneity. Beijing is a mega city with a population over 21 million, covering 14 districts and two counties, with a total area of approximately 16,410.54 km^2 (Beijing Statistics Bureau 2010). Due to the different population size and functions in each district of Beijing, air pollutants emissions and concentrations vary from district to district. Therefore, it is very necessary to discover the spatial characteristics of air quality and air pollutants in Beijing to come out effective strategies for pollution reduction.

A considerable number of studies have shown that meteorological conditions affect atmospheric pollution in numerous ways (Grundström et al. 2015; Pearce et al. 2011; Unal et al. 2011). Choi et al. (2008) found that there were obvious seasonal and weekly variation characteristics correlating with meteorological conditions for the concentration of air pollution. The most important role of meteorology is the effect on the dispersion, transformation, and removal of atmospheric pollutants from the atmosphere and finally affects the spatial-temporal characteristics and pollution levels of atmospheric pollutants (Tian et al. 2014).

The China National Environmental Monitoring Center started evaluating air quality from June 2000 by using the air pollution index (API), which is calculated based on ground monitoring of 24 h average concentrations of PM_{10}, SO_2, and NO_2. $PM_{2.5}$, however, is not included in this routine measurement. The Ministry of Environmental Protection (MEP) started using air quality index (AQI) from March 2012, which is calculated based on six pollutants including NO_2, SO_2, $PM_{2.5}$, PM_{10}, carbon monoxide (CO), and O_3. AQI is an index describing the air quality level of a place and ranges from 0 to 500, larger values indicate worse air quality. Furthermore, AQI is divided into six levels based on the different score, i.e., excellent, good, slight pollution, moderate pollution, heavy pollution. and severely pollution. Table 1 shows the range of AQI and the corresponding air quality levels.

Since January 1st, 2013, Beijing Municipal Environmental Protection Bureau (BJ–MEPB) has publicized daily AQI instead of API in a web platform, which provides a unique way for researches to analyze the variation and spatial patterns of air quality of Beijing. In this paper, we collected daily air monitoring data from January to December 2013 of 16 air quality monitoring stations in Beijing to analyze the spatial and temporal characteristics of air quality and air pollutants. The objectives are (1) to characterize the spatial and temporal variations of air quality and air pollutants in the period of 2013 in Beijing, (2) to explore the spatial and temporal associations of $PM_{2.5}$ in Beijing, and (3) to analyze the effect of meteorological factors on the concentration of $PM_{2.5}$.

Materials and methods

Study area

Beijing, the capital of the People's Republic of China, extends approximately 1° 37′ latitudinal (39° 2′ –41° 03′ N) and 2° 05′ longitudinal (115° 25′ –117° 30′ E), including 14 districts and two counties. The city has a sub-humid, warm temperate continental monsoon climate and four distinct seasons, comprising a cold and windy winter, and a hot and humid summer. Recently, Beijing has undergone tremendous changes due to accelerated economic development and mass immigration under the reform and "opening-up" policy over the past four decades (Qiao et al. 2013). However, economic development and urban sprawl has generated negative environmental consequences, Beijing is currently considered as one of the most air-polluted cities in China (Liu et al. 2012; Che et al. 2009).

Data sources

AQI data of Beijing were collected for a 1-year period from January 1st to December 31st, 2013, at the BJ–MEPB observation stations. We collected the data of 16 air pollution monitoring stations, which cover 14 districts and two counties of Beijing (Dongcheng, Xicheng, Chaoyang, Haidian, Fengtai, Shijingshan, Mengtougou, Fangshan, Tongzhou, Shunyi, Changpi, Daxing, Huairou, and Pinggu district, Miyun, and Yanqing county). The distribution and location of 16 monitoring stations were shown in Fig. 1. In order to clearly illustrate the result, we classified 16 districts into southern, central, north-central and northern region, according to the districts geographical location. Southern region includes Daxing, Tongzhou and Fangshan district, central region includes Haidian, Xicheng, Dongcheng, Shijingshan, Fengtai, Chaoyang, and Mengtougou, north-central region includes Pinggu, Shunyi and Changpi, and then Huairou, Miyun and Yanqing belong to the northern region (see Fig. 1 and Table 2).

An individual score (IAQI) is assigned based on the level of each pollutant, and the maximum among all IAQIs is chosen as AQI. The air pollutant with the highest concentration is considered as the "primary pollutant". If the highest IAQI comes from two or more pollutants, they are jointly regarded as the primary pollutant (MEP 2012). Among all records, the primary pollutant was not reported in 683 records, because it was at acceptable level ($AQI \leq 50$), as described by the Chinese AQI standards. We assumed that the unreported main pollutant in the 683 records where the main pollutant was not

Table 1 The range of AQI and the corresponding air quality levels

AQI	Air quality level	Air quality description	Health implications
0–50	I	Excellent	Air quality is considered satisfactory, and air pollution poses little or no risk.
51–100	II	Good	Air quality is acceptable; however, for some pollutants, there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution.
101–150	III	Slight pollution	Members of sensitive group may experience health effects. The general public is not likely to be affected.
151–200	IV	Moderate pollution	Slight irritations may occur, individuals with breathing or heart problems should reduce outdoor exercise.
201–300	V	Heavy pollution	Healthy people will be noticeably affected. People with breathing or heart problems will experience reduced endurance in activities. These individuals and elders should remain indoors and restrict activities.
>300	VI	Severe pollution	Healthy people will experience reduced endurance in activities. There may be strong irritations and symptoms and may trigger other illnesses. Elders and the sick should remain indoors and avoid exercise. Healthy individuals should avoid outdoor activities.

reported was $PM_{2.5}$. The daily $PM_{2.5}$ mass concentration was calculated from the AQI according to the following relationship (MEP 2012).

$$C = \frac{I - I_{\text{low}}}{I_{\text{high}} - I_{\text{low}}} \left(C_{\text{high}} - C_{\text{low}} \right) + C_{\text{low}}$$

where I is the AQI, C is the pollutant concentration, C_{low} is the concentration breakpoint that is $\leq C$, C_{high} is the concentration breakpoint that is $> C$, I_{low} and I_{high} are the index breakpoints corresponding to C_{low} and C_{high}, respectively. The breakpoints of C and I are displayed in Table 1. Daily $PM_{2.5}$ mass concentrations of the 1761 records whose primary pollutant was not $PM_{2.5}$ were interpolated using the Kriging interpolation method (Isaaks and Srivastava 1989).

Meteorological datasets over 1-year period from January 1st to December 31st, 2013, which include relative humidity, atmospheric pressure, temperature, wind speed, wind direction, and precipitation, are obtained from the website (http://rp5.ru/Weather archive in Beijing, Peking).

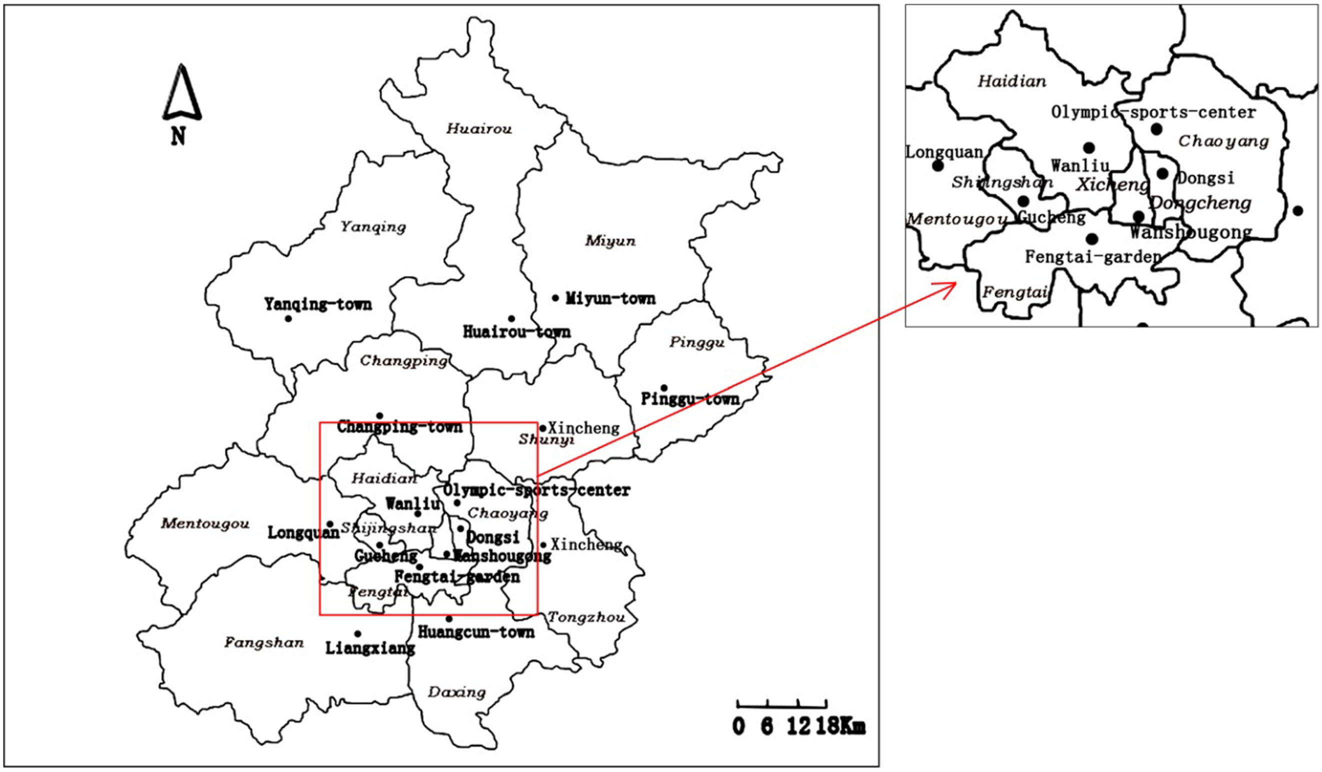

Fig. 1 Spatial distribution of 16 air pollution monitoring stations in 16 districts installed by Beijing Environmental Protection Bureau

Table 2 The distribution of air quality level at 16 districts in 2013 in Beijing (days)

Region	District name	Air quality level						Pollution days[a]	The percentage of pollution days
		I	II	III	IV	V	VI		
Southern region	Daxing	**19**	115	102	45	53	31	231	**63.29**
	Tongzhou	28	115	95	45	59	23	222	**60.82**
	Fangshan	23	124	92	38	63	25	218	59.73
Central region	Haidian	25	125	91	54	48	22	215	58.90
	Xicheng	39	116	94	48	49	19	210	57.53
	Dongcheng	34	122	88	56	49	16	209	57.26
	Shijingshan	34	122	99	48	47	15	209	57.26
	Fengtai	21	137	86	48	51	22	207	56.71
	Chaoyang	33	134	94	43	45	16	198	54.25
	Mengtougou	45	124	93	41	49	13	196	53.70
North-central region	Pinggu	47	123	96	43	45	11	195	53.42
	Shunyi	57	130	76	45	47	10	178	48.77
	Changpi	61	127	72	57	39	9	177	48.49
Northern region	Huairou	65	133	81	43	38	5	167	45.75
	Miyun	65	134	80	40	40	6	166	45.48
	Yanqing	**87**	134	74	41	27	2	144	**39.45**
The Whole region[b]		42.7 ± 19.5	125.9 ± 7.2	88.3 ± 9.2	45.9 ± 5.6	46.8 ± 8.4	15.3 ± 8.0	196.4 ± 23.9	53.80

[a] The number days of AQI > 100

[b] Values are presented as mean ± SE ($n = 16$)

Statistical analysis

The data of AQI and $PM_{2.5}$ mass concentrations for different districts were analyzed, using the one-way analysis of variance (ANOVA), mean values were compared using the least significant difference (LSD) test, and significance was defined as $P < 0.05$. Pearson correlation coefficients were calculated for the relationships between $PM_{2.5}$ and relative humidity, atmospheric pressure, temperature, and wind speed, and significance was defined as $P < 0.01$.

Results

Spatial distribution of air quality levels

The distributions of air quality levels at 16 districts in 2013 in Beijing are shown in Table 2. In Beijing, as of 2013, the days of excellent, good, slight pollution, moderate pollution, heavy pollution and severely pollution are 42.7 ± 19.5, 125.9 ± 7.2, 88.3 ± 9.2, 45.9 ± 5.6, 46.8 ± 8.4, and 15.3 ± 8.0, respectively. There are 196.4 ± 23.9 air pollution days (AQI>100) on average, and the pollution proportion reached to 53.8 % of total annual days. There were differences for air quality in 16 districts. The number of excellent level, for example, was largest in Yanqing, reached to 87; however, it was only 19 in Daxing. The excellent level of air quality gradually increased from south to north. Similarly, the worst air quality was Daxing district with 231 air pollution days, the polluted proportion amounted to 63.29 %. The second worst was Tongzhou, with 222 pollution days and the proportion reached to 60.82 %. Yanqing had 144 pollution days, and the proportion was 39.45 %, in 16 districts, which had the best air quality, while there were still almost 5 months of pollution days. The number of pollution days gradually decreased from south to north, which indicated that the northern region had the least pollution, while the degree of pollution in the southern region was the most severe.

Spatial and temporal variations of AQI

Figure 2 was the monthly average AQI of Beijing in 2013. The air quality was the worst in January, compared with the other months, the AQI was the highest (201.8 ± 31.9), the difference was significant for $P < 0.05$, followed by June and March. The air quality was the best in April, the AQI was the lowest (95.6 ± 5.5), and the difference was also significant ($P < 0.05$). Similarly, as shown in Fig. 2, there were also differences for air quality on spatial variations. Especially, this gradient was the most notable in January and March, the air quality was getting better from the south to the north region, the regional differences were significant ($P < 0.05$). The air quality of northern region was better than that of southern region in general, except May, July, and August.

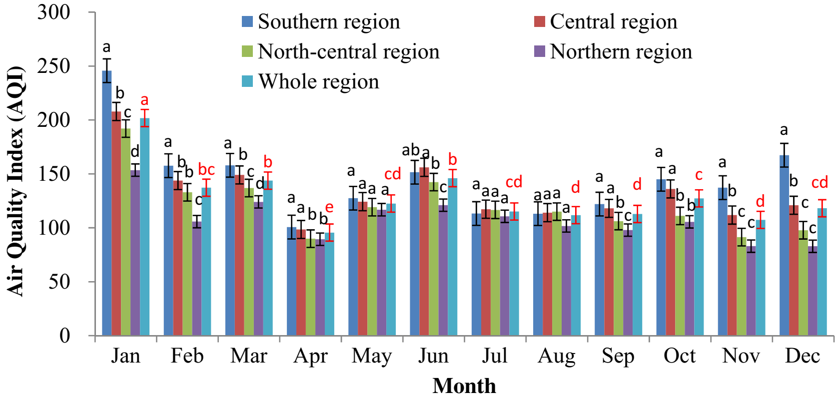

Fig. 2 Monthly variation characteristics of Air Quality Index (AQI) in 2013 in Beijing. AQI is the mean of values measured within each region (the number of values in southern region, central region, north-central region, northern region, and the whole region is 3, 7, 3, 3, 16, respectively). *Bars* indicate standard deviation, *means in each column with different letters* are significantly different at the $P < 0.05$ level. *Black letters* indicate the significant differences of AQI among four regions of each month, and *red letters* indicate the significant differences among the 12 months in Beijing

In Beijing, four seasons are distinct. As shown in Fig. 3, the air quality was the worst in winter (December–February) with the AQI of 152.4 ± 45.3, and the difference was much significant ($P < 0.05$) than the other seasons where the air qualities were comparable. Among other seasons, the average AQI of autumn (September–November) was the lowest (115.8 ± 18.2), but the difference was not significant ($P < 0.05$) compared to spring and summer. During spring and summer, the air qualities of four regions were comparable, and the differences were not significant. On the other hand, the maximum value of AQI happened in the southern region and the minimum value appeared in the northern region, the differences among the southern, central, and northern region were significant ($P < 0.05$).

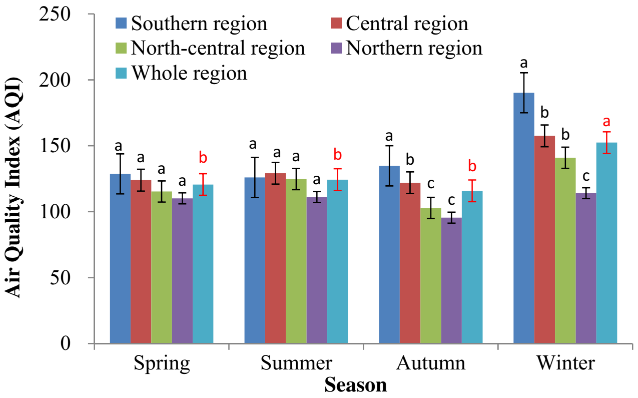

Fig. 3 Seasonal variation characteristics of Air Quality Index (AQI) in 2013 in Beijing. AQI is the mean of values measured within each region (the number of values in southern region, central region, north-central region, northern region, and the whole region is 3, 7, 3, 3, 16, respectively). *Bars* indicate standard deviation, *means in each column with different letters* are significantly different at the $P < 0.05$ level. *Black letters* indicate the differences of AQI among different regions of each season, *red letters* indicate the differences among four seasons in Beijing

Spatial and temporal variations of pollutants

The number of days affected by the primary pollutants, including $PM_{2.5}$, PM_{10}, O_3, SO_2, NO_2 and CO, was different from each other in Table 3. Among all records, $PM_{2.5}$ (including jointly with other pollutants as the primary pollutant) was the primary pollutant in 3396 records, O_3 in 903 records, NO_2 in 495 records, PM_{10} in 424 records, and CO and SO_2 accounted for one record each. Among all of the known primary pollutant records, 65.06 % of them showed the primary pollutant was $PM_{2.5}$. Undoubtedly, $PM_{2.5}$ was the most serious pollutant among the six observed ones, followed by O_3, NO_2, and PM_{10} in Beijing. The frequency distributions of $PM_{2.5}$ were the highest in six air pollutants in 16 districts, the proportion was more than 50 % except in Miyun. Since $PM_{2.5}$ is the major contributor to AQI, $PM_{2.5}$ pollution has become the major environmental problem influencing the air quality in Beijing.

The monthly variation of the number of days with $PM_{2.5}$ as primary pollutant was shown in Fig.4a. Although the number was different in each month, the basic trend was that the highest $PM_{2.5}$ concentration appeared in January, the average number of days with $PM_{2.5}$ as primary pollutant was 25.5 ± 2.0, extremely severe haze pollution happened in Beijing and lasted for almost 1 month, which was characterized by high concentrations of $PM_{2.5}$. The lowest was in August, and the average number of days was 10.4 ± 1.7. The maximum number of days appeared in winter, while the minimum number of days was in summer. Southern region had the highest $PM_{2.5}$ concentrations, and northern region had the lowest.

About PM_{10}, the average number of days with it as the primary pollutant was far lower than $PM_{2.5}$. The highest PM_{10} concentrations values were monitored in April and May (Fig.4b), the average number of days as the primary pollutant was only 7.7 ± 1.3 and 5.9 ± 0.9, respectively. The

Table 3 The number of days with the pollutants as the primary pollutant at 16 districts in 2013 in Beijing (days)

District name	$PM_{2.5}$	O_3	NO_2	PM_{10}	CO	SO_2	$PM_{2.5}$, PM_{10}	NO_2, $PM_{2.5}$	NO_2, PM_{10}	NO_2, O_3	O_3, $PM_{2.5}$	O_3, PM_{10}	The sum of $PM_{2.5}$[a]	The percentage of $PM_{2.5}$
Fangshan	**244**	32	33	28				2	1		1	1	247	67.67
Tongzhou	241	38	27	27			4						245	67.12
Daxing	231	60	33	17			2	2			1		236	64.66
Fengtai	225	34	47	32			3	2	1				230	63.01
Haidian	216	36	**66**	18				3	1				219	60.00
Dongcheng	213	64	39	13				2					215	58.90
Mengtougou	212	57	4	41			1	2	3				215	58.90
Xicheng	209	56	34	21			3	1	1	1			213	58.36
Pinggu	208	73	2	31			3				1		212	58.08
Shunyi	207	61	21	18								1	207	56.71
Shijingshan	203	59	38	25				3	1		1	1	207	56.71
Chaoyang	195	46	64	23		1	1		1	1			196	53.70
Huairou	193	63	11	29	1		1	1			1		196	53.70
Yanqing	192	53	2	28			2		1				194	53.15
Changpi	190	73	17	21			1	1	1				192	52.60
Miyun	171	**87**	25	15			1					1	172	**47.12**
Sum	3350	892	463	387	1	1	22	19	11	2	5	4	3396	**65.06**

[a] The sum of number of $PM_{2.5}$ as the primary pollutant (including jointly with other pollutants as the primary pollutant)

concentrations of PM_{10} increased sharply in April and May which was coinciding with dust weather of Beijing. In terms of seasons, the lowest PM_{10} concentration values were observed in summer. In terms of regions, the PM_{10} concentration values in southern region were higher than other regions in April, while from September to December, the PM_{10} concentration values in southern region were lower than other regions.

About O_3, the average number of days with it as the primary pollutant and the monthly variation was adverse to that of $PM_{2.5}$ and PM_{10}. High daily maximum concentrations were observed in summer, while minimum concentrations in winter (Fig.4c). During summer, the average number of days as the primary pollutant was 13.1 ± 3.2, while the number was 0 in winter. It was interesting that although the lowest $PM_{2.5}$ concentrations were in northern and north-central region, the highest O_3 concentrations tended to be there, followed by central and southern regions.

About NO_2, a kind of waste gas of vehicle, the variation trend was not so obviously as PM and O_3, and the concentration of NO_2 was far lower than the above three kinds of pollutants (Fig.4d). As a primary pollutant, the frequency of occurrence was higher in the autumn with the average number of days as the primary pollutant as 3.9 ± 2.3, and it was lower in summer with the average number of days as 1.5 ± 1.6. Compared to $PM_{2.5}$, PM_{10}, and O_3, the average number of days with NO_2 as the primary pollutant was far lower. It was interesting that the higher concentrations of NO_2 were in central region and southern region had.

Overall, as of 2013, the air quality was greatly influenced by particulate matter ($PM_{2.5}$ and PM_{10}) in spring and winter and by gaseous pollutants (O_3 and NO_2) in summer and autumn.

Spatial and temporal variations of $PM_{2.5}$ mass concentration

The above analysis shows that $PM_{2.5}$ was the main pollutant in Beijing for 2013; thus, the spatial and temporal distribution of $PM_{2.5}$ concentrations is analyzed. Daily $PM_{2.5}$ mass concentrations for the 16 stations over 2013 are summarized in Table 4. The daily $PM_{2.5}$ mass concentration varied greatly, ranging from 12.6 to 500 μg m^{-3} which is the upper bound in each station. The lowest mass concentration was 12.6 μg m^{-3}, which occurred in Huairou district. The number of records reaching the maximum mass concentration in all records was nine, which occurred in eight districts: Xicheng, Fengtai, Shijingshan, Fangshan, Tongzhou, Shunyi, Daxing, and Pinggu. The maximum $PM_{2.5}$ concentrations in Miyun and Yanqing were 376 and 313 μg m^{-3}, respectively. The annual average concentrations of $PM_{2.5}$ were 119.5 ± 13.8 μg m^{-3} in Beijing overall. The highest annual mean value was 140.4 ± 93.7 μg m^{-3} in Daxing, and the lowest was 92.1 ± 64.6 μg m^{-3} in Yanqing. Besides, the annual average $PM_{2.5}$ mass concentration was the highest in winter in the whole of Beijing. The trend of $PM_{2.5}$was similar to AQI that the value was significantly higher in southern region than other regions, followed by central region, north-central, and

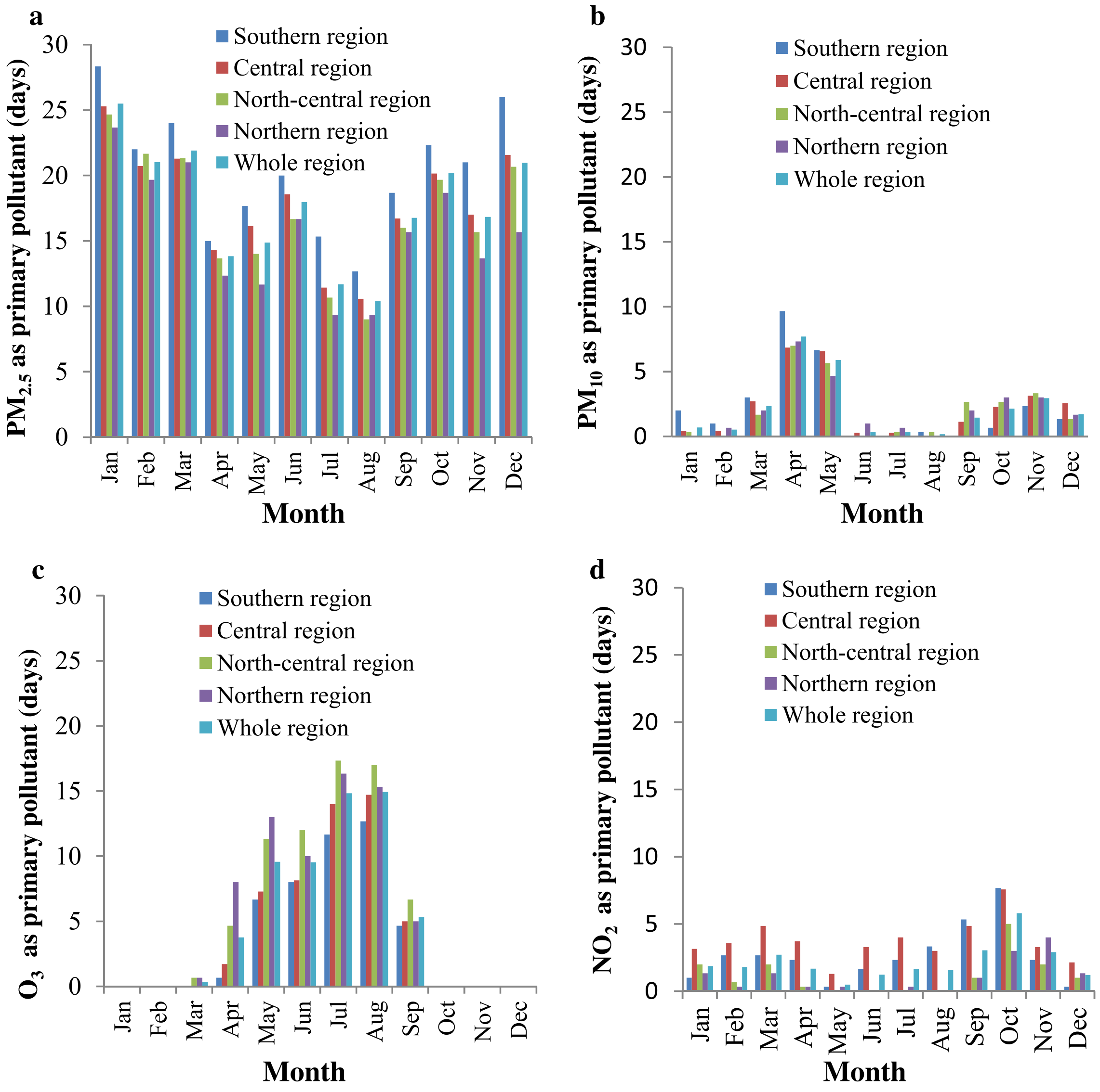

Fig. 4 Monthly variation of the number days with each pollutants as primary pollutant (**a** $PM_{2.5}$, **b** PM_{10}, **c** O_3, **d** NO_2) in 2013 in Beijing. The number days is the mean of values measured within each region (the number of values in southern region, central region, north-central region, northern region, and the whole region is 3, 7, 3, 3, 16, respectively)

northern region, regional differences reached a significant level ($P<0.05$).

According to the air quality guideline (AQG) recommended by the World Health Organization (WHO), the average 24–h $PM_{2.5}$ mass concentration should be less than 25 μg m^{-3}. Three interim targets (ITs) are also recommended by WHO, including: IT–1 (75 μg m^{-3}), IT–2 (50 μg m^{-3}), and IT–3 (37.5 μg m^{-3}) (WHO 2006). The average percentages of daily $PM_{2.5}$ concentrations reaching WHO IT 1–3 and AQG in 2013, Beijing were 37.62, 19.98, 13.30, and 2.41 %, respectively. The percentage differed significantly among the 16 districts. The highest percentage reaching the four targets happened in Yanqing with a percentage 51.5 % for WHO IT–1 and the others less than 50 %. Therefore, $PM_{2.5}$ was much more serious in Beijing, the percentages reaching the WHO AQG were lower than 5 % in all districts except Yanqing.

The relationship between $PM_{2.5}$ and meteorological factors

Meteorological conditions affect the diffusion, dilution, and accumulation of the pollutants. In this paper, the Pearson's correlation coefficients between $PM_{2.5}$ and meteorological factors, including atmosphere pressure, relative humidity, wind speed, and temperature, were analyzed by using the Pearson method to disclose visual the impacts of meteorological factors on $PM_{2.5}$ in different seasons in Beijing (Table 5).

The relationships between $PM_{2.5}$ and meteorological factors were complicated. The complex correlation degrees

Table 4 Statistical summary of the daily $PM_{2.5}$ concentrations at the 16 districts in 2013 in Beijing ($\mu g\ m^{-3}$)

Location	District name	Statistical summary			Seasonal variation[c]				Percentage reaching the standard[a]			
		Min.	Annual Mean[b]	Max.	Spring	Summer	Autumn	Winter	IT-1	IT-2	IT-3	AQG
Southern region	Daxing	21.0	**140.4 ± 93.7**a	500	119.6 ± 73.6	116.2 ± 56.4	129.5 ± 88.0	**197.3 ± 121.9**	29.59	11.51	7.12	0.27
	Fangshan	21.7	136.5 ± 89.0ab	500	124.3 ± 77.8	103.6 ± 58.3	128.3 ± 83.6	190.8 ± 106.5	31.78	14.25	8.77	0.55
	Tongzhou	18.9	135.7 ± 91.4ab	500	117.8 ± 79.8	120.4 ± 58.9	128.4 ± 84.4	177.3 ± 120.6	29.04	13.70	9.04	1.92
Central region	Fengtai	24.5	131.2 ± 89.1ab	500	114.0 ± 74.1	112.4 ± 61.1	129.3 ± 91.4	170.0 ± 111.3	33.97	14.25	7.12	0.27
	Haidian	18.9	129.0 ± 86.9ab	498	119.3 ± 76.2	119.4 ± 65.1	119.0 ± 83.7	158.7 ± 111.0	33.15	14.79	7.95	1.37
	Dongcheng	21.7	124.7 ± 84.9b	499	117.4 ± 73.3	116.7 ± 58.4	116.0 ± 82.1	149.0 ± 113.6	31.78	17.26	10.96	1.64
	Xicheng	16.1	123.7 ± 85.4b	500	110.7 ± 72.8	115.8 ± 57.4	113.9 ± 82.3	155.0 ± 113.3	33.70	20.00	11.51	3.01
	Shijingshan	23.1	122.2 ± 83.2b	500	114.3 ± 71.4	111.6 ± 61.7	110.7 ± 79.4	152.7 ± 107.7	35.07	18.08	11.78	1.92
	Chaoyang	18.9	119.8 ± 83.9bc	457	112.8 ± 74.3	112.8 ± 57.6	110.1 ± 79.8	143.9 ± 111.8	36.71	18.36	10.68	1.64
	Mengtougou	17.5	118.4 ± 81.6bc	406	115.1 ± 75.5	108.4 ± 63.3	103.8 ± 78.9	146.5 ± 99.4	36.44	18.90	14.25	2.74
North-central region	Pinggu	18.2	114.5 ± 81.1bc	500	103.5 ± 69.0	105.8 ± 50.2	94.3 ± 65.3	155.1 ± 113.5	39.18	21.64	14.52	3.56
	Shunyi	19.6	112.4 ± 81.0bc	500	107.3 ± 72.8	111.7 ± 59.8	97.7 ± 71.2	133.3 ± 109.3	41.92	23.56	16.44	4.93
	Changpi	17.5	108.4 ± 77.0c	427	106.9 ± 72.0	106.6 ± 56.5	95.3 ± 74.7	124.8 ± 98.0	44.11	24.93	19.18	3.29
Northern region	Huairou	12.6	102.6 ± 73.6c	433	104.9 ± 70.1	98.8 ± 51.6	90.0 ± 70.4	117.0 ± 94.9	46.58	27.67	18.90	2.19
	Miyun	22.4	100.2 ± 69.7c	376	100.1 ± 63.5	103.7 ± 49.7	91.4 ± 69.7	105.4 ± 90.5	47.40	27.95	18.08	2.47
	Yanqing	18.2	**92.1 ± 64.6**c	313	93.7 ± 63.2	84.4 ± 51.9	83.6 ± 65.7	106.9 ± 74.2	51.51	32.88	26.58	**6.85**
Whole region[d]			119.5 ± 13.8		111.4 ± 8.1	109.3 ± 9.0	108.8 ± 15.6	149.0 ± 12.2				

[a] WHO (2006) gives the air quality guideline (AQG) and three interim targets (ITs)

[b] Values are presented as mean ± SE ($n = 365$). Means in each column with different letters are significantly different at the $P < 0.05$ level

[c] Spring is March to May ($n = 92$), Summer is from June to August ($n = 92$), Autumn is from September to November ($n = 91$), Winter is from December to February ($n = 90$)

[d] Values are presented as mean ± SE ($n = 16$)

varied largely in different seasons, which mean that the dominant meteorological factors influencing the atmospheric pollution were different in each season. For example, the $PM_{2.5}$ was significant negative correlation with atmosphere pressure in winter but insignificant in other seasons. $PM_{2.5}$ was significant positively correlated ($P < 0.01$) with relative humidity in four seasons, with a correlation coefficient of 0.806 in winter, but was negatively correlated with atmosphere pressure and wind speed.

Relative humidity and wind speed were dominant meteorological factor in the whole spring and autumn, and in summer when the air quality was the best, atmospheric pressure, wind speed, and temperature slightly affected $PM_{2.5}$. The influences of relative humidity, atmospheric pressure, and wind speed on $PM_{2.5}$ were most significant in winter with the worst air quality; therefore, $PM_{2.5}$ concentrations were highest during the winter, due to the result of joint action of human activities and meteorological factors. In general, relative humidity was the most important meteorological factor influencing on $PM_{2.5}$, followed by wind speed and atmosphere pressure.

Discussion

The spatial and temporal characteristics of AQI in Beijing in 2013 are analyzed based on the daily records from 16 monitoring stations. Since these stations are located across all of 16

Table 5 The Pearson's correlation coefficients between $PM_{2.5}$ and meteorological factors

Season	Atmosphere pressure	Relative humidity	Wind speed	Air temperature
Spring	−0.084	0.534^{**}	-0.487^{**}	−0.037
Summer	−0.044	0.433^{**}	−0.068	−0.16
Autumn	−0.141	0.582^{**}	-0.497^{**}	0.05
Winter	-0.278^{**}	0.806^{**}	-0.433^{**}	−0.039

** Significant at $P < 0.01$

districts, the records log the whole city's air quality very well. We could find that the AQI and $PM_{2.5}$ mass concentrations of the 16 stations revealed the spatially heterogeneous across the city. There were a south-north gradient of air quality and $PM_{2.5}$, the level of pollution was the highest in the southern region and the lowest in the northern region (Table 2, 3). The reasons for that may be due to the topography, industrial factories, population, vehicle, meteorological factors, and urban forest.

Beijing is located on the northwestern border of the North China Plain and is surrounded by mountains on the north, east, and west sides. This geographical pattern results in that southwest and east winds tend to increase the air pollutants' concentrations while the northwest winds tend to beneficial for the dispersion of the air pollutants' concentrations (Chen et al. 2015). Many heavily populated industrialized cities are close to Beijing on the southwest and southeast (Xu et al. 2011; Wang et al. 2015). Although Beijing has already limited the use of coal as fuel, the southern Heibei has not done what Beijing has does. The air quality, especially in southern Beijing gets worse, indicating that southern region was affected most by neighboring heavy polluted province (Chen et al. 2015). This fact shows that improvement of air quality in Beijing is not a merely local issue but a regional issue requiring cooperation.

The central region in Beijing has the highest population density, so is the number of vehicles. By the end of 2013, the total number of vehicles in Beijing reached 5.43 million (http://zhengwu.beijing.gov.cn/tjxx/tjgb/t1340447). Correspondingly, the growth of the number of vehicles and the resulting exhaust emissions have had substantial impacts on urban air quality (Wu et al. 2011; Wang and Hao 2012).

Urban forest can play important roles in reducing PM concentrations in the air (Janhäll 2015; Song et al. 2015; Tallis et al. 2011). Irga et al. (2015) concluded that urban areas with proportionally higher concentrations of urban forestry may experience better air quality with regard to reduced ambient particulate matter; Tallis et al. (2011) reported London's trees remove between 852 and 2121 tones of PM10 annually. In Beijing, the largest forest area sits in the northern region; therefore, compared with other regions, the air quality is the best over there.

For monthly variation of AQI, the best month for air quality is April (Fig. 2). The reasons for that may be (1) our results show that $PM_{2.5}$ is the major contributor to AQI in Beijing. In April, as the weather becomes warmer, the central heating is stopped (heating ended in March 20th, 2013), which significantly reduces $PM_{2.5}$ emissions, (2) around that time, the emerging prevailing northwest wind help to blow away the air pollutants out of the city to adjacent regions, and (3) zonal vegetation in Beijing is that the temperate deciduous forests and temperate coniferous forest. In April, these deciduous trees begin to sprout leaves, which increases dust capturing capacity. Trees can intercept and accumulate atmospheric particles through leaf pubescence and by providing a large waxy surface on which deposition can occur (Beckett et al. 2000) and also absorb various gaseous pollutants through the stomata (Janhäll 2015). Nowak et al. (2013) reported that total amount of PM2.5 removal annually by trees varied from 4.7 to 64.5 tones. Therefore, urban green space has been proposed as an important means to reduce airborne pollutant concentrations. In July and August, the air quality is also good, because (1) the frequent rainfall washes out PM from the ambient air, so improves air quality, and (2) it was during this period of the growing season of trees, the capacity for trees to capture particulates and aerosols from the atmosphere are more effectively than the other seasons. While in winter, as large amount of coal is used in heating plant to support the central heating system, air quality of Beijing gets worse along with the increase in the amount of PM. Even worse, many tree species that comprise Beijing's urban forestry are deciduous, thus losing all of their leaves during winter, consequently decrease their ability to intercept and accumulate atmospheric particulates, and absorb various gaseous pollutants. Additionally, the traditions of exploding firecrackers have a direct effect on the air pollution aggravation during Chinese New Year (Ye et al. 2016).

O_3 plays an important role in the atmospheric energy budget and chemistry (Wang et al. 2015). O_3 pollution may contribute to climate change and cause adverse effects in humans as well as ecosystems (Pellegrini et al. 2014; Sikder et al. 2013). Since O_3 absorbs infrared radiation from the surface and heats the atmosphere; therefore, Tropospheric O_3 is an important greenhouse gas (Lin et al. 2008). Because O_3 is a key component of photochemical smog, tropospheric O_3 is also an important air pollutant (Chen et al. 2015; Sun et al. 2011). There are two main sources of O_3 in the troposphere, the first is the downward transport of O_3 from the stratosphere, and the second is from the reactions of its precursors (CH_4, CO, VOCs, NOx, etc.) (Ganguly and Tzanis 2011; Nishanth et al. 2014; Ryerson et al. 2001).

Our results show that O_3 has become the second largest pollutant in Beijing. O_3 concentrations variation is very different to the other pollutants ($PM_{2.5}$, PM_{10}, NO_2) with the highest concentration in summer and the lowest concentrations in winter. The reason for that may be (1) photochemical effect has increased the concentration of O_3 during summer, attributed to the more intense sunlight to promote photochemical reactions and generate abundant O_3 (Zhang et al. 2015b); (2) during periods of extended hot, dry weather conditions, the vegetation becomes stressed by high temperatures and soil moisture deficits. As a consequence, vegetation reduces the stomatal conductance to limit water loss. In addition, increased ozone levels lead to stomatal closure (Anav et al. 2011), which results in less gasses absorption and less ozone absorb, and causes high atmospheric ozone concentrations

(Lorenzini et al. 2014; Vieno et al. 2010). From Fig.4c, we can see that the highest O_3 concentration is in the northern-central, and northern regions, while the lowest concentration is in central, and southern regions. Some studies reported that frequent high O_3 events occur not only in cities but also in rural areas, where local emission of anthropogenic pollutants is not important. This phenomenon is usually caused by the transport of polluted air masses and photochemical formation of O_3 (Wang et al. 2015; Xu et al. 2008). Zhang et al. (2015b) reported that O_3 at the northern region is mainly attributed to the transport of pollutants from southern and central regions of Beijing and south-central region of Hebei Province with southwesterly winds.

The number of days with PM_{10} as the dominant pollution was 26.5 ± 8.2 on average, accounting for only 6.63 % of total, which shows that PM_{10} concentration is decreasing significantly. The concentrations of PM_{10} have decreased steadily in recent years, declining from 142 μg m^{-3} in 2005 (Chan and Yao 2008) to 120 μg m^{-3} in 2008, and to 114 μg m^{-3} in 2011 (Hu et al. 2013). This is attributed to a series of protective measures taken to reduce the number of pollution sources (Liu et al. 2012).

For NO_2, the higher concentrations were in central region and southern region. The reason for that may be of population and vehicles. The population in the central and south areas is larger than that in the north region, and this is also reflected on the number of vehicles in this region. Plus, many people live in suburban areas and work in the center of the city, a lot of traffic pollution is produced from their every commute. Another reason for the high concentration is those dense and high buildings in Beijing which obstruct the diffusion of pollutants (Liu et al. 2005).

Conclusion

In this paper, we explore the spatial and temporal variation in air quality and primary pollutants and analyze the influences of meteorological factors on $PM_{2.5}$. As a result, although the government in Beijing has adopted a series of control measures and actions, such as relocation of the capital steel factory, banning of diesel cars, enclosing dusty and other construction sites, and reducing private vehicles on roads, air pollution is still a serious problem in Beijing.

So, how to reduce the pollutants concentration in the atmosphere? From the foregoing analysis, the following aspects should be paid attention: (1) controlling vehicle emission pollution; (2) adjusting energy structure and increasing clean energy supply, and strengthening ‘energy-saving and environment-friendly’ access threshold and optimizing industrial layout; (3) establishing regional coordination mechanism and making overall arrangement for regional environmental management; (4) continuing the efforts to not only strengthen the research in the field, but also strengthen environmental education.

Moreover, further investigation is required on several topics. First, additional research is necessary to determine the extent and underlying mechanisms of the increasing trend of $PM_{2.5}$ and O_3 and the possible synergistic relationship among the pollutants. Second, our key task in the next stage is to investigate how to reduce the concentrations of $PM_{2.5}$ and O_3 in the air in Beijing, and we should take the corresponding management according to the spatial and temporal distribution of pollutants. Third, the relationship between meteorological factors and air pollution was neglected, which restricts the potential measures to reduce and control the air pollution. Fourth, we could not ignore the role of urban green space, which can be used as an effective measure to reduce airborne pollutant levels. Current and future PM deposition to the urban green space of Beijing should be estimated.

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