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# Temporal and Spatial Characteristics of Ambient Air Quality in Beijing, China

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## ABSTRACT

The ambient air quality in Beijing was comprehensively assessed based on the real-time pollutant concentrations monitored at urban, suburban, roadside, and background sites in 2013. The results showed that the annual average concentration for CO, $NO_2$, $SO_2$, $O_3$, $PM_{2.5}$ and $PM_{10}$ in 2013 was 2.0 mg $m^{-3}$, 55.6 μg $m^{-3}$, 28.5 μg $m^{-3}$, 48.0 μg $m^{-3}$, 92.2 μg $m^{-3}$ and 118.6 μg $m^{-3}$, respectively. The annual average concentration of CO, $NO_2$, $SO_2$, $PM_{2.5}$ and $PM_{10}$ was highest in roadside, while that of $O_3$ was highest in background stations. The mean monthly statistics indicated the maximum concentration of CO, $NO_2$, $SO_2$, $PM_{2.5}$ and $PM_{10}$ occurred in January because of larger emissions in heating season, lower wind speed and higher relative humidity (RH), while the minimum was found in July or August due to larger precipitation or photochemical degradation. The peak concentrations of $O_3$ occurred during May to August due to higher temperature and solar radiation which could promote the photochemistry activity. The monthly variation is also reflected in the corresponding season. Diurnally analysis showed the CO, $NO_2$, $SO_2$, $PM_{2.5}$ and $PM_{10}$ in urban and roadside area had two increase phases accompanying with the traffic peaks. Beside the temporal variation, we also found the spatial variation that higher concentrations of $O_3$ and other pollutants occurred in northern and southern districts/counties, respectively. It could be attributed to the spatial distribution of various pollutant emissions in Beijing and the impact of pollutant transport from neighboring provinces. Moreover, we examined the visibility in Beijing and found its significant correlation with $PM_{2.5}$ concentration and RH, respectively. Lastly, the air quality in Beijing was compared with that in other mega cities in the world. The higher pollutant concentrations and $PM_{2.5}/PM_{10}$ ratio indicated that the mitigation of the air pollution especially the $PM_{2.5}$ pollution in Beijing still had a long way to go.

***Keywords:*** Ambient air quality; Temporal-spatial characteristics; Visibility; Meteorological conditions; Beijing.

## INTRODUCTION

Air pollution appeared with the increasing human activity and had aroused widely attention in the whole world during the past decades (Ozden *et al.*, 2008; Krupinska *et al.*, 2012; Fann and Risley, 2013; Ferreira *et al.*, 2013). It had significantly adverse impact on human health and could cause many kinds of diseases (e.g., asthma, chronic obstructive pulmonary disease, and cardiovascular diseases) (Langrish *et al.*, 2012; Krall *et al.*, 2013; Rom *et al.*, 2013). Acid rain caused by high $SO_2$ and $NO_x$ concentration could bring serious negative effects on ecosystems (soil and water PH value change, crops plants injury, etc.) (Jalali and Naderi, 2012; Wang *et al.*, 2013). In addition, air pollution could also reduce the atmospheric visibility and change the climate (Ramana *et al.*, 2010; Langridge *et al.*, 2012). Consequently, air pollution characteristics investigation is important and helpful for providing scientific bases to develop effective mitigation measures.

China has long suffered from serious air pollution (You, 2014), especially in the capital city—Beijing (Wang and Hao, 2012; Xu *et al.*, 2013). And as an important and famous mega city in both China and the world, the ambient air quality in Beijing has received lots of attention. (Gurjar *et al.*, 2008) ranked the air quality in 18 mega cities of the world and found that the $NO_2$ and $SO_2$ concentration in Beijing was the second highest in 2000. (Gros *et al.*, 2007) compared the PM concentrations in Paris and Beijing, and showed that the concentration in Beijing was about 3.1–3.8 times higher than that in Paris. (Chan and Yao, 2008) reviewed previous studies and the state of air pollution problems in Beijing and other mega cities in China. It is indicated that the particle pollution is severe and is the major air pollution problem in these cities. (Sun *et al.*, 2011) conducted a measurement of $SO_2$, $NO_x$, $NO_y$, and $O_3$ in one

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site of Beijing during the period from Jul. 28, 2008 to Sep 2, 2008, and analyzed the photochemical pollution. (Tang *et al.*, 2009) analyzed the surface ozone and $NO_x$ concentration in Beijing between the months of July and September from 2001 to 2006, and found that the $NO_x$ concentrations decreased after 2002 while the $O_3$ concentrations increased continuously. Huang *et al.* (2014) launched a research about characteristic and sources of particulate matter at urban locations in four cities including Beijing during January 2013. Our previous study conducted intensive monitoring covering the period of December 2010 to January 2012 in Beijing to obtain the detailed proportions of different components in the ambient $PM_{2.5}$ (Cheng *et al.*, 2013).

It could be found that most of studies researched the air quality characteristics in Beijing based on the observation of several pollutants in one sites or one kind of pollutant in some sites, during specific period. However, the comprehensive analysis including multi-pollutants and considering both temporal and spatial characteristics of the ambient air quality was limited due to the lack of detailed and wide monitoring data covering various areas in Beijing. Fortunately, the real-time monitoring concentrations of ambient carbon monoxide (CO), nitrogen dioxide ($NO_2$), sulfur dioxide ($SO_2$), ozone ($O_3$) and particulate matters (i.e., $PM_{2.5}$ and $PM_{10}$) from all the 35 stations in Beijing are publicly available since autumn 2012. This not only helps people understand the air quality of their living environment better, but also provide a good opportunity to the researchers to carry out the comprehensive study on the air pollution characteristics of Beijing.

The purpose of this study was to comprehensively analyze the ambient air quality in Beijing for multi-pollutants based on the real-time monitoring concentrations from various sites in 2013. Temporal (monthly, seasonal and diurnal variation) and spatial characteristics of CO, $NO_2$, $SO_2$, $O_3$, $PM_{2.5}$ and $PM_{10}$ were examined together with the emission and meteorological factors. As an important factor related to air pollution, the visibility was also investigated in this paper. Moreover, the concentrations of the air pollutants in Beijing were compared with those in other mega cities in the world.

## STUDY AREA

Beijing is located in northern China, with Taihang Mountains on its southwest and Yan Mountains on its northwest (as shown in Fig. 1). The basin-like topography can facilitate the air pollutants transport to Beijing from the southern provinces (e.g., Hebei and Shanxi) and accumulate in the local region, as a result easily lead to high pollutant concentrations. From the perspective of administrative division, there are 14 subordinate districts and 2 counties in Beijing as shown in Fig. 1, covering a total area of 16410.5 $km^2$. The urban area of Beijing includes 6 subordinate districts (i.e., Dongcheng, Xicheng, Chaoyang, Haidian, Fengtai, and Shijngshan), covering 8.3% of Beijing's geographical area, accounting for 59.3% of Beijing's total population, and contributing to 69.7% of the total GDP in Beijing. The suburban area includes 8 subordinate districts (i.e., Fangshan, Daxing, Tongzhou, Shunyi, Pinggu, Huairou, Changping and Mentougou) and 2 counties (i.e., Miyun and Yanqing). The resident population was 20.69 million in 2012 (BMSB, 2013). In view of the economic, the GDP of Beijing in 2012 was 283.2 billion US dollars, with proportions of 0.8%, 22.7% and 76.5% for the primary, secondary and tertiary industries, respectively. From the energy consumption (EC) point, the total EC was 71.8 million tce (ton of standard coal equivalent). The EC per thousand US dollars GDP was about 0.253 tce, much higher than this for Japan and England (about 0.14 and 0.17, respectively) (NBSC, 2011). The consumption of coal, gasoline, diesel and natural gas was 22.70, 4.16, 2.16 million tons and 9.21 billion cubic meter, accounting for about 34.9%, 13.2%, 6.8% and 26.4% of the total fuel consumption, respectively. It can be found that coal was a main fuel in Beijing. Another point should be paid attention in Beijing was the motor vehicles. With rapid development of economic, the population of motor vehicles had increased sharply in the past decades. Although Beijing has brought in restriction on car ownership

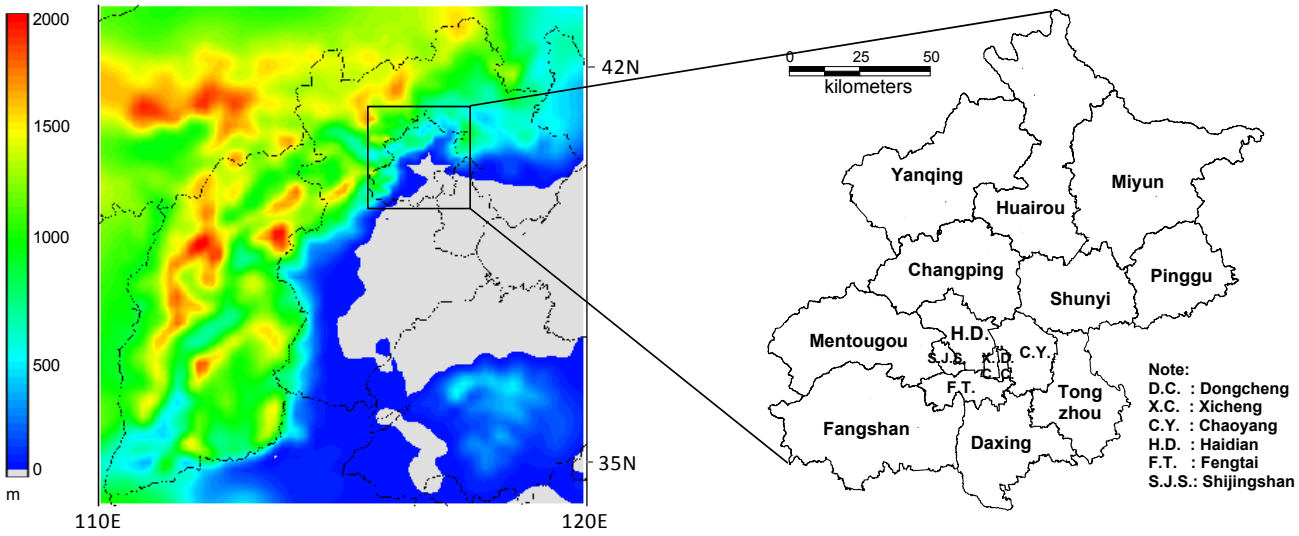



**Fig. 1.** Location, terrain and administrative division of Beijing (the color contours in the figure show the altitude).

to slow the increment speed since 2011, the population of the motor vehicles has reached 5.2 million by the end of 2012. The large population and vehicle numbers, high energy consumption and the basin-like topography all have negative impact on the air quality in Beijing.

## MATERIALS

The air quality data used in this study are cited from the official website about the air quality monitoring network in Beijing. It is operated by the Beijing Municipal Environmental Protection Bureau, who is responsible for the supervision and maintenance of the monitoring equipment and data validation. By the end of 2013, there are 4 types and 35 active stations in the network, including 12 urban stations distributed in the 6 urban areas, 11 suburban stations distributed in the 10 suburban areas, 5 roadside stations and 7 background/regional stations. The detailed location could be obtained from the website (http://www.bjepb.gov.cn/). The continuous concentrations on a 1-h basis of $SO_2$, $NO_2$, $O_3$, CO, $PM_{2.5}$ and $PM_{10}$ are monitored in all the 35 stations. The meteorological data, including temperatures, relative humidity, wind speed and precipitation were obtained from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/).

## AIR QUALITY ASSESSMENT

### *Annual Average Concentrations*

Table 1 lists the annual average concentrations of CO, $NO_2$, $SO_2$, $O_3$, $O_3$-Maximum daily 8 h average ($O_3$ 8 h-max), $PM_{2.5}$ and $PM_{10}$ for the four types of monitoring sites and overall Beijing in 2013. It could be found that annual average concentrations of $SO_2$ accounted for approximately 47.5% of national standard (Grade II) for annual average limit, whereas the annual average concentration of $NO_2$, $PM_{2.5}$ and $PM_{10}$ exceeded the national standard by 139%, 263% and 169%, respectively. It indicated that the $PM_{2.5}$ pollution was the most serious atmospheric environment problem in Beijing. Considering the complexity of the $PM_{2.5}$ components (including various primary and secondary particles, such as OC, EC, sulfate, nitrate and ammonium) and their formation (Yang *et al.,* 2011), the $PM_{2.5}$ pollution was also the most difficult to mitigate. As for CO and $O_3$, there are no annual average concentration standards. The 24 h, 1 h or maximum daily 8h average concentration standards were used to be compared with the annual average concentrations of CO and $O_3$. Table 1 showed that CO and $O_3$ didn't exceed the corresponding standard. The annual average concentration of $O_3$ and $O_3$ 8 h-max accounted for 24% and 51% of corresponding standard.

The concentrations in the roadside sites were highest for CO, $NO_2$, $SO_2$, $PM_{2.5}$ and $PM_{10}$ among different types of monitoring stations, while those in the background sites were the lowest. The concentrations in roadside were approximately 1.08–2.25 times higher than those for other sites. The probable reason for this phenomenon is high vehicular emissions. Based on our previous study, vehicular emissions and road dust accounted for approximately 40%–96% of the total NOx, CO, VOC and $PM_{2.5}$ emissions in the urban area of Beijing (Lang *et al.*, 2012; Zhou, 2012; (Cheng *et al.*, 2013). In addition, the higher $SO_2$ concentration in roadside indicated that the vehicular $SO_2$ emission also had un-neglected effect on the local ambient air quality. Many of the previous studies mainly focused on the $SO_2$ emissions from coal combustion (Zhang *et al.*, 2009). However, the $SO_2$ emission exhausted from motor vehicles also should be paid attention. The concentration of CO, $NO_2$, $SO_2$, $PM_{2.5}$ and $PM_{10}$ in background sites accounted for 44%–80% of those in other sites; this was because the background stations were usually set in the clean areas with less human activity (e.g., tourism area, reservoir, etc.). In addition, particularly for $O_3$, the highest average concentration occurred in background sites, while the lowest average concentration occurred in roadside sites. In order to explain this phenomenon, the correlation between $O_3$ and $NO_2$ were investigated. Fig. 2 illustrated that the $O_3$ and $NO_2$ concentration had a negative exponential correlation. This was mainly caused by the reason that $NO_2$ is precursor of the $O_3$. In the photochemical reaction, the production of $O_3$ in the daytime is associated with the consumption of the precursor (An *et al.*, 2008). Moreover, the $O_3$ concentration monitored in the roadside sites is lower than in other sites because of $NO_x$ emission due to road traffic activity. Meanwhile, it should be noted that control measures only aimed at $NO_x$ is not enough to cope with the $O_3$ pollution (Xing *et al.*, 2011).

### *Temporal Characteristics*

*Monthly Variation*

Fig. 3 showed the monthly average concentrations of different pollutants in Beijing. The monthly average $PM_{2.5}$/$PM_{10}$ ratio in 2013 was also listed in Table 2. Several characteristics could be found: (a) the maximum monthly average concentrations for all the pollutants except for $O_3$ occurred in January and the concentrations were much higher (1.4–9.1 times) than those in other months; (b) the concentration of CO, $NO_2$ and $PM_{10}$ had the similar monthly variation, the peak value occurred in January and the valley value occurred in July or August; (c) as for the monthly average concentration of $PM_{2.5}$, there were two obvious peak values occurred in January and June and two valley values occurred in April and August; (d) as for the monthly average $PM_{2.5}/PM_{10}$ ratio, the maximum value occurred in January and the minimum value occurred in April; (e) as for $O_3$, the peak concentrations occurred during the period of May to August. Detailed analysis was mentioned below aimed at characteristic (a)–(e).

The ambient concentrations of CO, $NO_2$, $SO_2$, $PM_{2.5}$ and $PM_{10}$ were significantly impacted by the pollutant emissions. Heating boilers were an important contributor emission sources in Beijing (Lin *et al.*, 2011; Zhou *et al.*, 2012). In January, the emissions from heat sources reached the maximum because the lowest temperature (–5.13°C) occurred in this month (Table 2). In addition to the emission, the wind speed (WS) was another factor influencing the pollutant concentrations. We calculated the daily average concentrations for different pollutants under various wind

**Table 1.** Annual average concentration of various pollutants in Beijing, 2013*.

| | CO | $NO_2$ | $SO_2$ | $O_3$ | $O_3$ 8 h-max | $PM_{2.5}$ | $PM_{10}$ |
|---|---|---|---|---|---|---|---|
| Urban | 2.1 | 59.7 | 28.3 | 46.8 | 81.2 | 92.8 | 120.7 |
| Suburban | 2.0 | 49.7 | 26.1 | 51.2 | 84.6 | 88.9 | 115.0 |
| Roadside | 2.2 | 79.6 | 36.5 | 35.1 | 61.1 | 102.3 | 132.0 |
| Background | 1.5 | 35.3 | 20.8 | 59.8 | 88.9 | 65.6 | 81.8 |
| **Average** | **2.0** | **55.6** | **28.5** | **48.0** | **80.5** | **92.2** | **118.6** |
| National standard(Grade II) | 4.0** | 40.0*** | 60.0*** | 200.0** | 160.0**** | 35.0*** | 70.0*** |

* The unit for CO was mg $m^{-3}$, for other pollutants was μg $m^{-3}$.
** 24 h average concentration standard.
*** Annual average concentration standard.
**** Maximum daily 8 h average concentration standard.

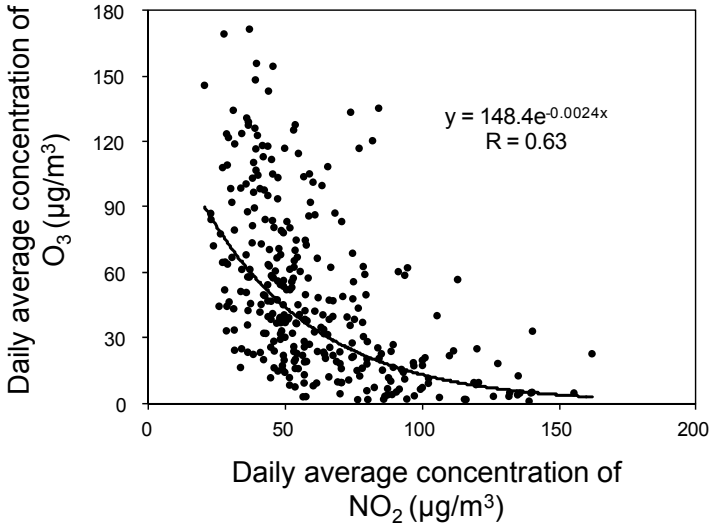



**Fig. 2.** Correlation between ambient $O_3$ and $NO_2$ concentrations in Beijing.

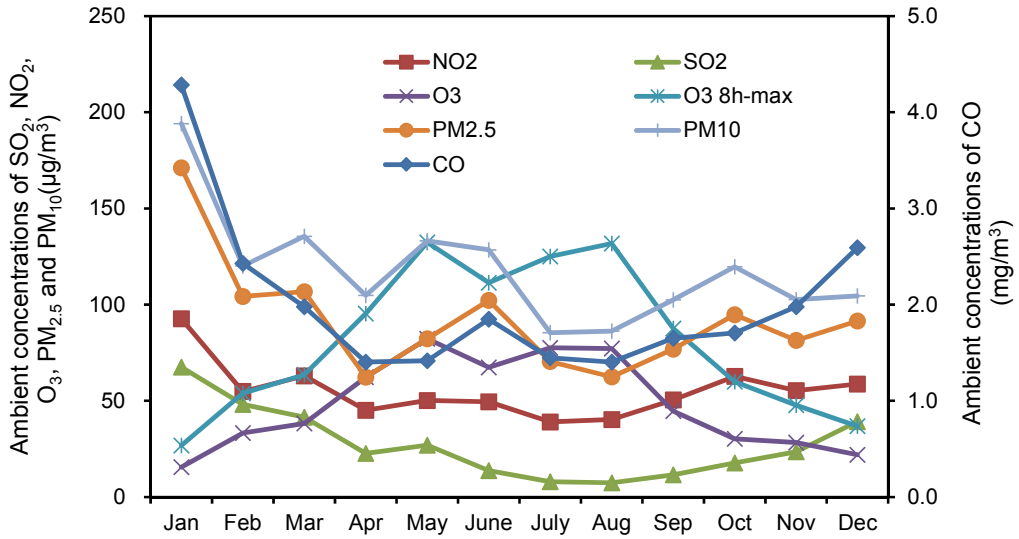



**Fig. 3.** Monthly variation of ambient air pollutant concentrations in Beijing, 2013 ($O_3$: concentration calculated based on hourly value; $O_3$ 8 h-max: concentration calculated based on maximum daily 8-h value).

speed during 2013 (as shown in Table 3). It clearly showed that high WS was beneficial for the diffusion of air pollutants, and it could decrease the ambient concentrations. In January, the wind speed was 2.1 m $s^{-1}$, lower than most of that in other months (except for September) (Table 2). Low wind speed facilitated the accumulation of air pollutants in local area and

**Table 2.** Monthly meteorological conditions, visibility and $PM_{2.5}/PM_{10}$ ratio of Beijing, 2013.

| Month | Temperature °C | Relative humidity % | Wind speed m s$^{-1}$ | Precipitation mm | Visibility km | $PM_{2.5}/PM_{10}$ - |
|---|---|---|---|---|---|---|
| Jan | –5.13 | 63.90 | 2.21 | 1.53 | 7.61 | 0.86 |
| Feb | –2.04 | 49.04 | 2.84 | 3.05 | 12.14 | 0.80 |
| Mar | 5.97 | 47.35 | 2.81 | 6.09 | 10.94 | 0.75 |
| Apr | 12.10 | 37.00 | 3.69 | 3.04 | 16.47 | 0.53 |
| May | 21.00 | 48.26 | 2.58 | 23.87 | 11.90 | 0.60 |
| June | 23.73 | 70.23 | 2.22 | 100.82 | 7.00 | 0.71 |
| July | 26.87 | 68.74 | 2.22 | 170.68 | 10.35 | 0.65 |
| Aug | 26.35 | 63.16 | 2.37 | 85.10 | 12.42 | 0.64 |
| Sep | 19.73 | 65.47 | 1.95 | 40.62 | 9.23 | 0.69 |
| Oct | 12.16 | 56.48 | 2.12 | 3.56 | 9.39 | 0.73 |
| Nov | 5.50 | 33.37 | 3.23 | 0.00 | 13.43 | 0.63 |
| Dec | –0.69 | 31.86 | 3.21 | 0.00 | 13.52 | 0.71 |

**Table 3.** Daily average concentrations for different pollutants under various wind speed.

| Wind speed (m s$^{-1}$) | CO mg m$^{-3}$ | $NO_2$ μg m$^{-3}$ | $O_3$ μg m$^{-3}$ | $PM_{2.5}$ μg m$^{-3}$ | $PM_{10}$ μg m$^{-3}$ | $PM_{2.5}/PM_{10}$ - |
|---|---|---|---|---|---|---|
| 0–2 | 2.53 | 78.71 | 38.69 | 131.00 | 155.05 | 0.79 |
| 2–3 | 1.57 | 56.21 | 24.76 | 74.16 | 101.49 | 0.68 |
| 3–4 | 1.50 | 48.27 | 22.50 | 63.77 | 92.77 | 0.64 |
| 4–6 | 1.31 | 40.45 | 14.56 | 36.42 | 82.71 | 0.44 |
| 6–9 | 1.06 | 28.51 | 7.28 | 15.22 | 43.23 | 0.44 |

led to the increase of ambient concentrations. The analysis result of correlation between pollutant concentrations and relative humidity (RH) showed that the RH was also an important factor impacting the ambient air quality. Fig. 4 illustrated that positive correlation existed between the RH and the $PM_{2.5}$, $PM_{10}$ concentrations. According to our previous statistic result (Cheng *et al.*, 2013), the proportion of secondary aerosols in $PM_{2.5}$ is about 47% in Beijing. The higher RH could promote the reactions of secondary particles formation (Cheng *et al.*, 2015; Zhou *et al.*, 2015). Table 2 showed that the RH is January was 63.9%, much higher than the annual average value (52.9%). Hence high RH had negative impact on the air quality. Therefore, it could be concluded that the large emissions, low wind speed and the high relative humidity resulted in the high concentrations of CO, $NO_2$, $SO_2$, $PM_{2.5}$ and $PM_{10}$ in January (explanation for characteristic (a)).

Beside the factors mentioned above (emissions, wind speed and RH), the precipitation was another important factor affecting the ambient concentration through wet deposition process. The maximum precipitation usually occurred from June to August in Beijing. In 2013, the total precipitation of these three months was 356.6 mm, accounting for 81.3% of the annual precipitation (Table 2). Large precipitation decreased the concentration of $NO_2$ and PM in July or August. In addition, photochemical degradation of CO in summer might be an important reason for the lower concentration of CO in July or August (explanation for characteristic (b)).

As for $PM_{2.5}$, it was comprised of primary (e.g., elements, element carbon and primary organic aerosol) and secondary components (e.g., sulfate, nitrate, ammonium and secondary organic). These two type particles accounted for approximately 33% and 47% of the total $PM_{2.5}$ concentration in Beijing, respectively (Cheng *et al.*, 2013). Humidity has a negative effect on the diffusion of primary $PM_{2.5}$. It's easy to form the fog with the situation of higher humidity. In this case, water vapor and $PM_{2.5}$ in the air may form the stable aerosol, and it's not easy to spread in the atmosphere (He *et al.*, 2011). In addition, higher humidity could also provide reaction medium to facilitate the formation of secondary particles ((Ianniello *et al.*, 2011). As a result, the impact on the formation of $PM_{2.5}$ pollution from high humidity was more obvious than the impact on CO, $NO_2$ and $SO_2$. The correlation coefficients (CC) between concentrations and relative humidity for different pollutants also verified it from another viewpoint. The CC was 0.51 for $PM_{2.5}$, and much higher than that for other pollutants (0.09–0.39) (Fig. 4). Consequently, beside the peak value in January and the valley value in August, another valley and peak value of the $PM_{2.5}$ concentration occurred in April and June, respectively, because the relative humidity was low in April and high in June (Table 2). In addition, solar radiation also have effect on $PM_{2.5}$. The relative higher $PM_{2.5}$ concentration in June may be attributed to production of secondary aerosols with increasing solar radiation and temperature (Tiwari *et al.*, 2015) (explanation for characteristic (c)). The correlation between daily average $PM_{2.5}/PM_{10}$ ratio and relative humidity were also investigated (Fig. 4). Similar to $PM_{2.5}$, the $PM_{2.5}/PM_{10}$ ratio was also influenced by the relative humidity to a great extent. Moreover, wind speed also had obvious impact on the $PM_{2.5}/PM_{10}$ ratio. The maximum $PM_{2.5}/PM_{10}$ ratio in January might could be attributed the relative lower wind speed and higher RH. In addition, higher wind speed could bring more coarse dust to the air. As a result, the obviously

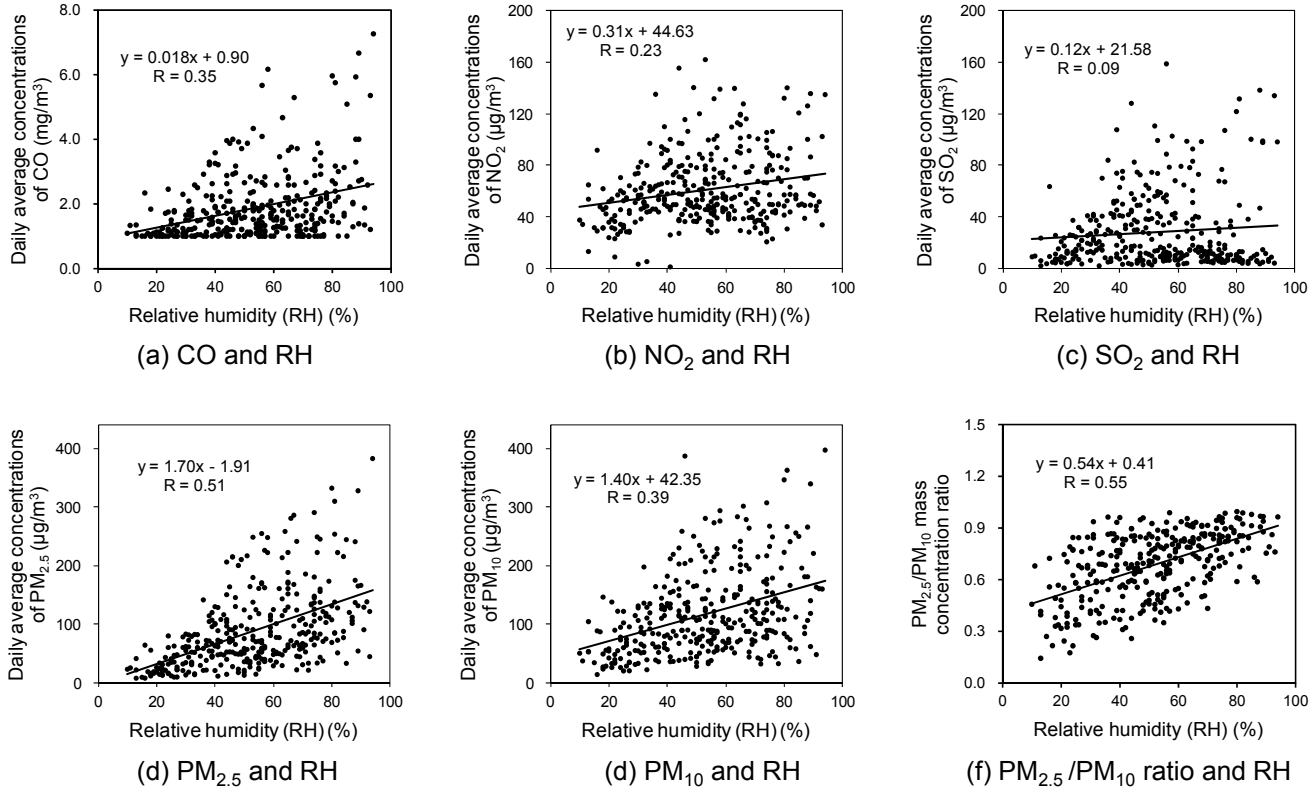



**Fig. 4.** Correlation between ambient air pollutant concentrations, $PM_{2.5}/PM_{10}$ ratio and relative humidity (RH).

maximum speed in April (3.69 m $s^{-1}$) led to a minimum $PM_{2.5}/PM_{10}$ ratio (0.53). As influenced by the above multi-factors, the peak and valley value occurred in January and April, respectively (explanation for characteristic (d)).

As for $O_3$, it can be found that the high concentrations usually occurred in the months from May to August with high temperature and solar radiation which could promote the photochemistry activity. The average temperature in these four months was 24.5°C, while that in other months was 5.95°C. The correlation between daily average $O_3$ concentrations and temperatures were also investigated and good positive correlation was found (Fig. 5). High temperature could promote the formation of $O_3$ (Chou *et al.*, 2011). In addition, the high solar radiation during the period from May to August was also an important factor affecting the photochemical reaction for $O_3$ formation (Tang *et al.*, 2006) (explanation for characteristic (e)).

*Seasonal Variation*

The air pollutant concentrations in different seasons were further calculated (Fig. 6). In order to study the seasonal variation, the 12 months in a year are grouped into four seasons, as December–January–February for winter, March–April–May for spring, June–July–August for summer and September–October–November for autumn. As described in section 4.2.1, because of the impact from emission, temperature, wind speed, relative humidity and precipitation, the seasonal average ambient air pollutant concentrations in Beijing were higher in winter for CO, $NO_2$, $SO_2$, $PM_{2.5}$ and $PM_{10}$, while higher in summer for $O_3$. The lowest concentration occurred in winter for $O_3$ but in summer for other pollutants. In addition, the seasonal average concentration in spring was also high for $SO_2$ and $PM_{10}$. This was mainly caused by the following reason. (1) In Beijing, the $SO_2$ were affected by heating sources (Huang *et al.*, 2012). It is well known that the heating season in Beijing is from November to the March in the next year. This leads to obvious increase of $SO_2$ concentration in heating seasons and high $SO_2$ concentration in spring. (2) In spring, the higher wind speed (3.03 m $s^{-1}$, about 10%–33% higher than that in other three seasons) could greatly increase the emission of wind erosion dust. According to Wei's (2013) study, the emission of wind erosion dust in spring accounted for more than 60% of annual emission. The emission of wind erosion dust consisted of mainly coarse particles. As a result, the $PM_{10}$ concentration was high in spring.

*Diurnal Variation*

Fig. 7 illustrated the hourly variation of ambient pollutant concentrations in urban, roadside and background stations. Because the hourly characteristic in suburban area was similar to that in urban area, the hourly variation in suburban was not analyzed individually here. The hourly variation of ambient air quality was mainly affected by the diurnal emissions and temperature/solar radiation. In Beijing, the diurnal variation of emission was mainly caused by motor vehicles. There are two rush hours for the traffic flow: the morning peak (~7:00–9:00) and the evening peak (~16:00–19:00). As for the temperature/solar radiation, it increases

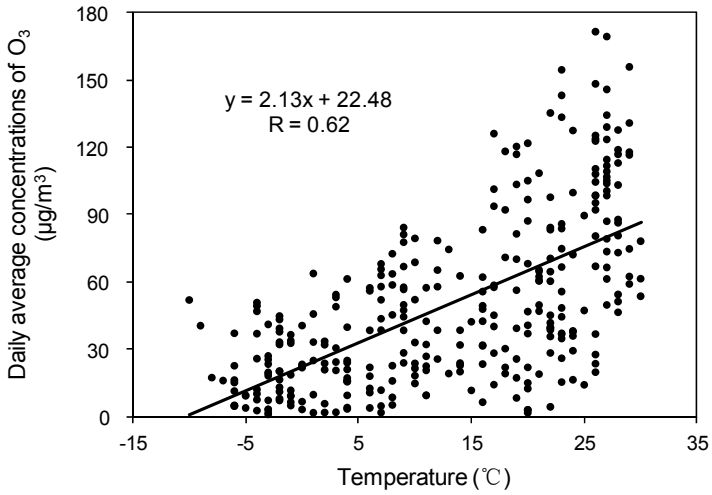



**Fig. 5.** Correlation between daily average $O_3$ concentration and ambient temperature.

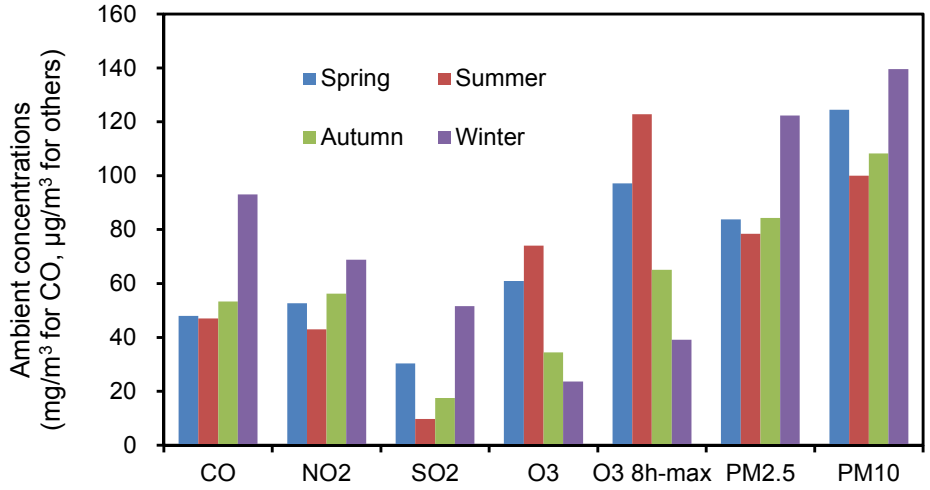
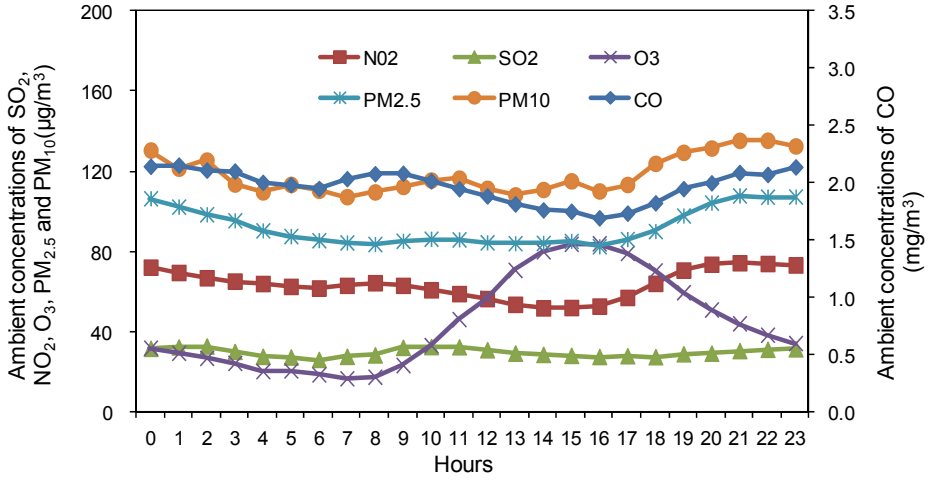



**Fig. 6.** Seasonal variation of ambient air pollutant concentrations in Beijing, 2013 ($O_3$: concentration calculated based on hourly value; $O_3$ 8 h-max: concentration calculated based on maximum daily 8-h value).

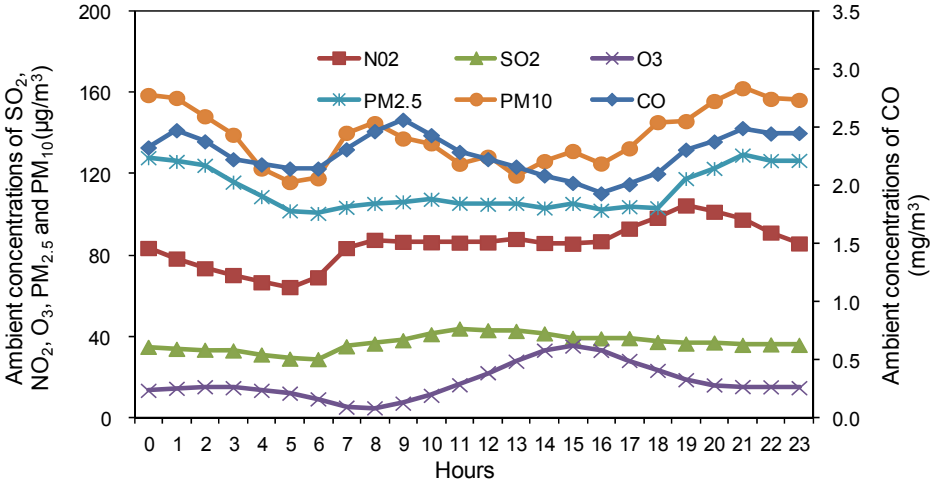
from lower value in the morning to the maximum at noon, and then begins to decease. Because of the conditions mentioned above, the following variation could be found. (a) Generally, there were two rise phase for CO, $NO_2$, $PM_{2.5}$ and $PM_{10}$ in urban area and roadside accompanying with the two traffic peaks. Meanwhile, the diurnal variation was more obvious in roadside due to more significant effect introduced by motor vehicle. (b) In background stations, the concentrations of CO and $NO_2$ had no obvious hourly variation, but there was one rise phase for $PM_{2.5}$ and $PM_{10}$ concentration from approximately 12:00 and 9:00, respectively. There were much less anthropogenic emissions in the background areas, and the increase of the concentrations for $PM_{10}$ and $PM_{2.5}$ mainly came from the pollutant transport from urban or suburban areas. As a result, the diurnal variation of pollutants in background was quite different from that in other stations and a delay of the concentration increase beginning time could also be found. (c) The diurnal variation of $SO_2$ was not obvious in all the three types of stations because it was mainly influenced by the emission with a relatively small diurnal variation (e.g., industry or heating boilers). (d) The $O_3$ concentration began to rise from 7:00–9:00, reached the peak at 14:00–16:00 and then declined to the valley value at night.

***Spatial Characteristics***

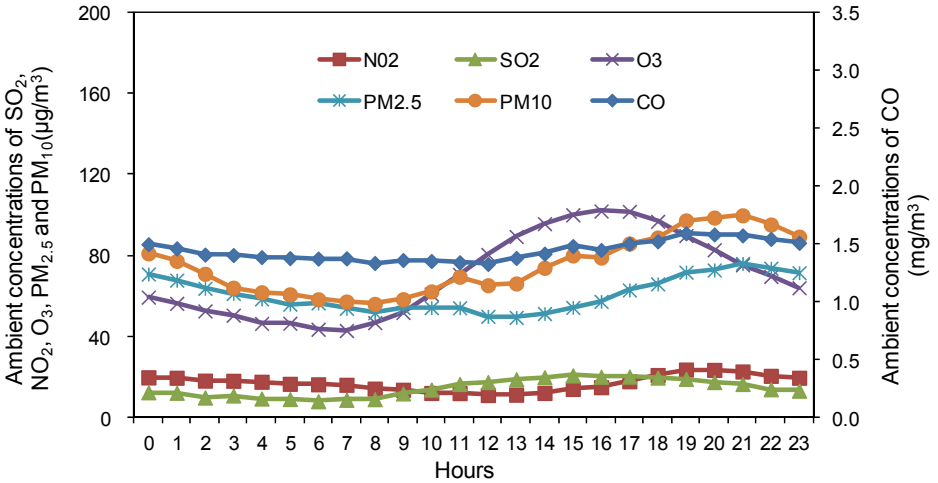
The annual average concentrations for CO, $NO_2$, $SO_2$, $O_3$, $PM_{2.5}$ and $PM_{10}$ in different districts/counties were calculated. Fig. 8 illustrated that the concentrations for the pollutants except for $O_3$ were higher in the southern region, including Fangshan, Daxing and Tongzhou. Large emission was one of the reasons leading to the high concentration. The emissions in these three districts accounted for 21.5%–33.2% of the total emissions in the 16 districts/counties (Zhou, 2012). Moreover, previous studies indicated that southwest, southeast and east were three important pathways for pollutants transporting from Hebei and Tianjin to Beijing as due to the impact from terrain and meteorological conditions (Su *et al.*, 2004; (Wang et al., 2010; Zhu et al., 2011). The annual average contribution ratio to the $PM_{2.5}$ concentration of




(a) Urban station




(b) Roadside station




(c) Background station

**Fig. 7.** Diurnal variation of ambient air pollutant concentrations in Beijing, 2013.

Beijing was 38.0% and 5.1% for Hebei and Tianjin, respectively (Lang *et al.*, 2013). Consequently, the three districts locating at the three pathways suffered more pollution contributed from neighboring provinces with much more emissions. As for $O_3$, the high concentration occurred in northern districts/counties: Miyun and Pinggu, where were the downwind rural area, especially in summer (Xu *et al.*, 2011). Polluted air masses arriving in rural area were more aged with higher $O_3$ concentrations than those in urban area. Urban plume transported both $O_3$ and its precursors.

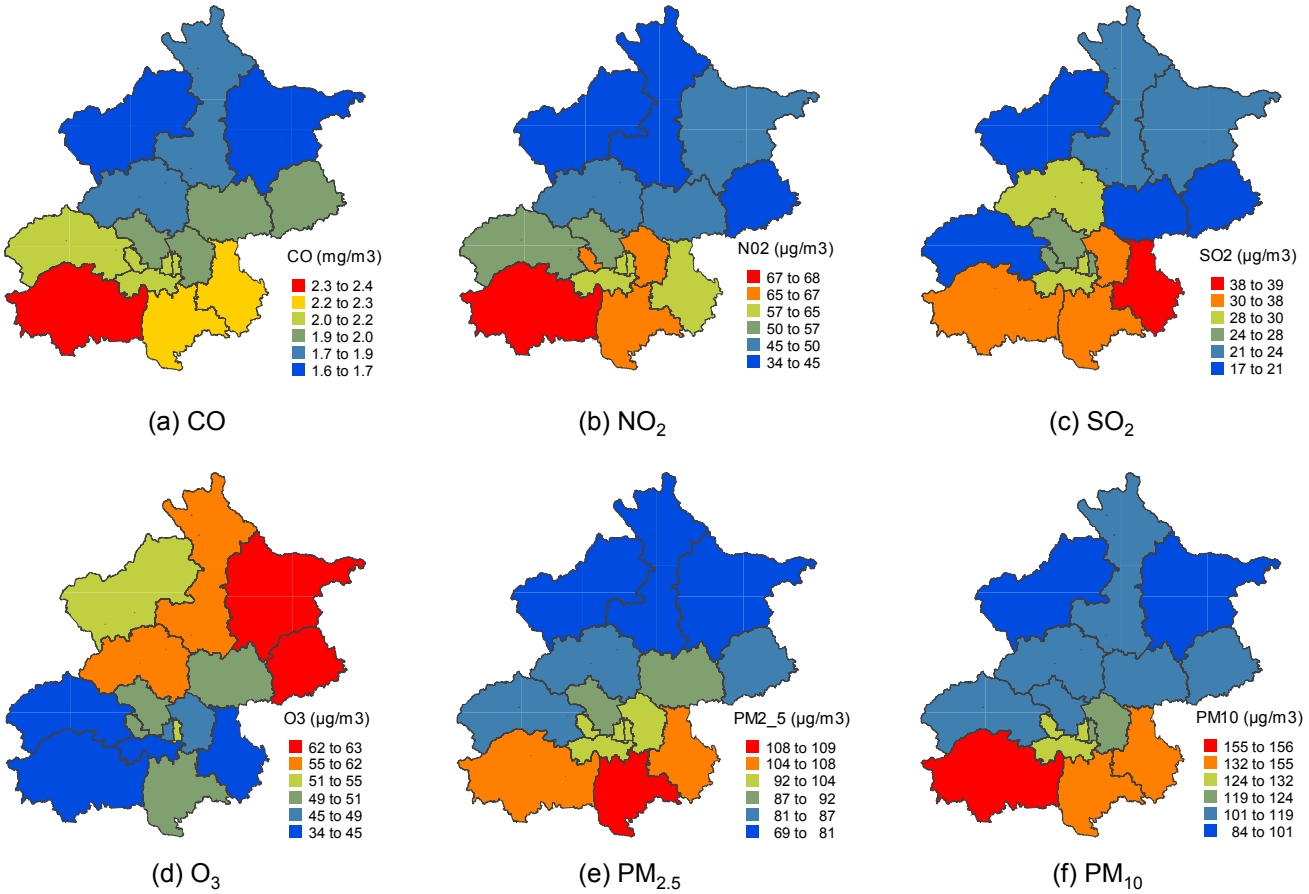



**Fig. 8.** Spatial distribution of annual pollutant concentrations in Beijing, 2013.

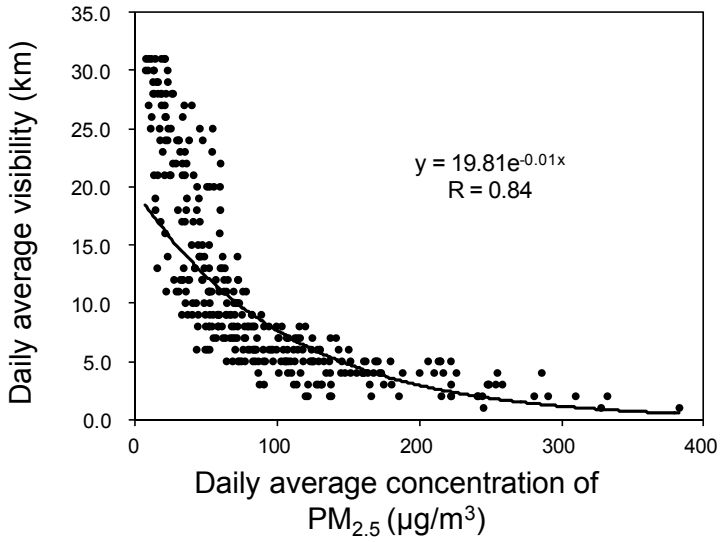
Precursors leading more $O_3$ production when being mixed with background atmosphere in the downwind rural area (Ge *et al.*, 2012). In addition, VOCs was another key factor affecting the $O_3$ formation and it had positive contribution to the $O_3$ in Beijing (Atkinson, 2000; Xing *et al.*, 2011). The vegetative cover area was larger in the above districts/counties with higher vegetation VOCs emissions (Zhou, 2012).

### *Visibility and Its Main Affecting Factors*

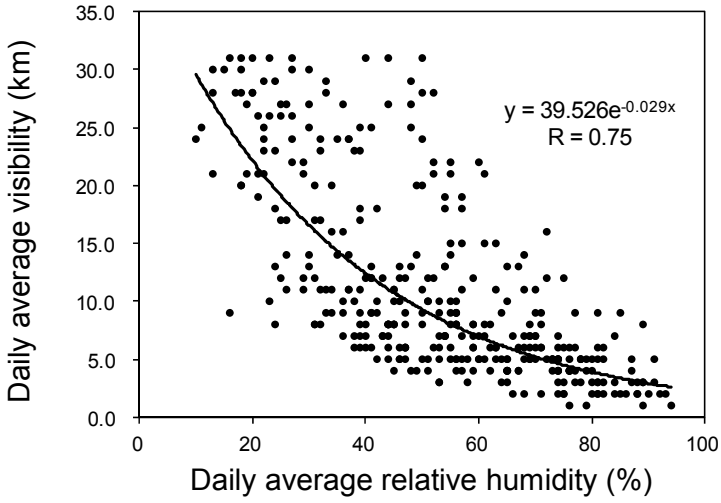
Visibility was an important and visual indicator of ambient air quality (Chen *et al.*, 2014). In this study, the monthly and annual average visibility was also analyzed based on the daily average data (http://www.wunderground.com/) (Table 2). The maximum and the annual average visibility of Beijing in 2013 were 31.0 km and 11.2 km, respectively. The annual average visibility was close to that in Guangzhou, but a little higher than that in Chengdu, Shanghai and Shenyang in China (Chang *et al.*, 2009). The monthly variation was similar to that for $PM_{2.5}$. Among different months, the visibility was lower in January and June, but higher in April and August. The correlation between visibility and $PM_{2.5}$ concentration, visibility and humidity was also studied. Fig. 9 showed that the visibility in Beijing was influenced by the $PM_{2.5}$ and relative humidity to a great extent. When the daily average $PM_{2.5}$ concentration was higher than 100 µg $m^{-3}$, the maximum and average visibility was 8.0 km and 4.3 km, respectively. While the daily average $PM_{2.5}$ concentration was lower than 50 µg $m^{-3}$, the daily average visibility was 20.1 km. In the days with daily relative humidity higher than 75%, the maximum and average visibility was 12.0 km and 4.0 km, respectively. However, in the days with daily relative humidity lower than 50%, the average visibility was 16.4 km.

### *Comparison with Other Mega Cities*

The ambient air quality in Beijing was also compared with that in other mega cities in the world. As shown in Fig. 10, the ambient concentration of CO and $PM_{2.5}$ were much higher than that in Shanghai, London, Mexico City, Tokyo and New York. The concentration in Beijing was approximately 2.3–9.6 times and 1.9–10.0 times higher than that in other cities for CO and $PM_{2.5}$, respectively. The $PM_{10}$ concentration in Beijing was a little higher than that in Mexico City (~14%), but much higher than that in Shanghai (~67%) and London (378%). As for $SO_2$, the concentration in Beijing was close to that in Mexico City, a little higher than that in Shanghai (~24%) and much higher than that in London (494%) and Tokyo (389%). The difference for $NO_2$ was not obvious among these cities, with the concentration ranging from 46.7 µg $m^{-3}$ to 76.7 µg $m^{-3}$. The concentration of $NO_2$ in Beijing was a little higher than that in Shanghai and Tokyo, but a little lower than that in London and Mexico City. In developed mega cities, the motor vehicles numbers




(a) Visibility and $PM_{2.5}$ concentration




(b) Visibility and relative humidity

**Fig. 9.** Correlation between $PM_{2.5}$ concentration, relative humidity and daily average visibility.

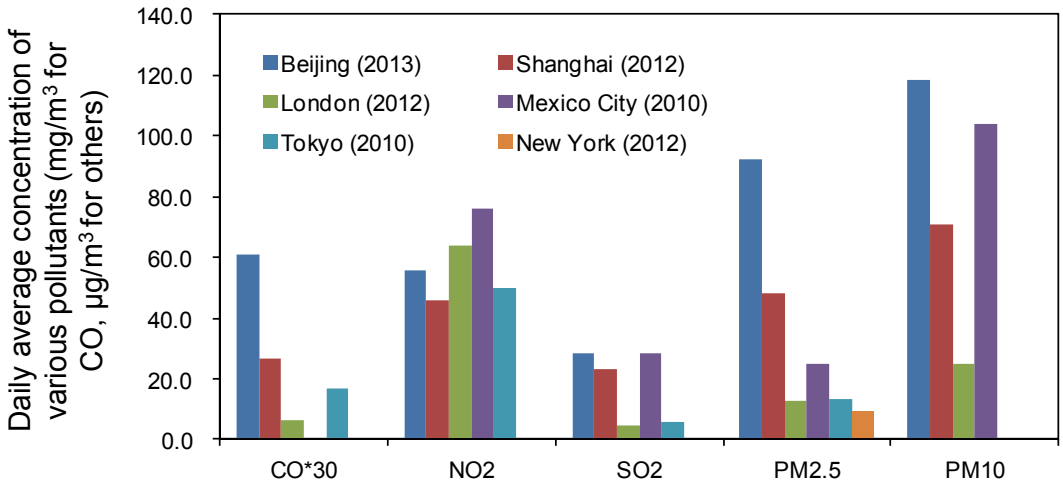



**Fig. 10.** Comparison of the ambient air quality between Beijing and other mega cities in the world (the data sources: Shanghai, SEPB, 2012; London, http://www.londonair.org.uk/; Mexico City, http://www.mexicocityvibes.com/; Tokyo, http://www.kankyo.metro.tokyo.jp/; New York: http://www.epa.gov/).

were large and the vehicular $NO_x$ emissions were high (SNY, 2012; NBSC, 2013). This made the relatively similar and high $NO_2$ concentrations in the above cities. In addition, $PM_{2.5}/PM_{10}$ ratio in Beijing (> 0.70) was also larger than that in other mega cities (0.24–0.51), reflecting that the fine particle pollution in Beijing was more serious from another point of view. The comparison results indicated that although great efforts in pollution control had made and achieved preliminary effect during the past decade, the mitigation of air pollution in Beijing still had a long way to go.

## CONCLUSION

The ambient air quality in Beijing was assessed based on the first public real-time monitoring concentrations in 2013 and the meteorological conditions. The annual average concentration for CO, $NO_2$, $SO_2$, $O_3$, $O_3$ 8h-max, $PM_{2.5}$ and $PM_{10}$ in 2013 was 2.0 mg $m^{-3}$, 55.6 μg $m^{-3}$, 28.5 μg $m^{-3}$, 48.0 μg $m^{-3}$, 80.5 μg $m^{-3}$, 92.2 μg $m^{-3}$ and 118.6 μg $m^{-3}$, respectively. The annual average $SO_2$ concentration was lower than national standard (Grade II), while that for $NO_2$, $PM_{2.5}$ and $PM_{10}$ exceeded the national standard (Grade II). The ratio of concentration to air quality standard was highest for $PM_{2.5}$ (2.63), indicating the $PM_{2.5}$ pollution was the most serious problem in Beijing. Among different types of monitoring stations, the roadside sites had the highest concentrations for CO, $NO_2$, $SO_2$, $PM_{2.5}$ and $PM_{10}$. The annual average concentration for $O_3$ was highest in background stations.

The temporal (including monthly, seasonal and diurnal) variation and spatial characteristic were further analyzed. Monthly, the maximum average concentration of CO, $NO_2$, $SO_2$, $PM_{2.5}$ and $PM_{10}$ occurred in January because of the large emissions, low wind speed and the high relative humidity, while the minimum was found in July or August due to the large precipitation. In addition, another valley and peak value of $PM_{2.5}$ concentration occurred in April and June, respectively, as the relative humidity was relatively lower in April and higher in June than most other months. The monthly variation of $PM_{2.5}/PM_{10}$ ratio showed the peak value in January and the valley value in April. As for $O_3$, the peak concentrations occurred during the period of May to August due to the high temperature and solar radiation which could promote the photochemistry activity. Seasonally, the ambient concentration was higher in winter for CO, $NO_2$, $SO_2$, $PM_{2.5}$ and $PM_{10}$, while higher in summer for $O_3$. The seasonal average concentration in spring (March, April and May) was also high for $SO_2$ and $PM_{10}$. Diurnally, there were two rise phase for hourly CO, $NO_2$, $PM_{2.5}$ and $PM_{10}$ concentration in urban area and roadside accompanying with the two traffic peaks, and the diurnal variation was more obvious in roadside. The $SO_2$ in urban and roadside stations and the CO, $NO_2$ and $SO_2$ in background stations had no obvious diurnal variation. However, the $PM_{2.5}$ and $PM_{10}$ concentration in background had one rise phase from approximately 12:00 and 9:00, respectively. The $O_3$ concentration rose from 7:00–9:00, reached the peak at 14:00–16:00 and then declined to the valley value at night. The spatial characteristic analysis showed that the annual average concentrations for CO, $NO_2$, $SO_2$, $PM_{2.5}$ and $PM_{10}$ was high in the southern districts (Fangshan, Daxing and Tongzhou) because of high emissions and impact of pathways for pollutants transport from neighboring provinces to Beijing. The higher annual $O_3$ concentration occurred in northern districts/counties (Miyun, Pinggu) which were the downwind rural area with more $O_3$ production and higher vegetation VOCs emissions.

In addition, the visibility in Beijing was also collected and analyzed. The maximum and the annual average visibility in Beijing in 2013 were 31.0 km and 11.2 km, respectively. Further analysis indicated that $PM_{2.5}$ concentration and relative humidity was two important factors impacting the visibility in Beijing. Moreover, the air quality in Beijing was also compared with that in other mega cities in the world. The ambient concentration of CO, $SO_2$, $PM_{2.5}$ and $PM_{10}$ in Beijing were higher than that in Shanghai, London, Mexico City, Tokyo and New York. The difference for $NO_2$ concentration was not obvious among these cities. The $PM_{2.5}/PM_{10}$ ratio was also higher in Beijing than that in other cities. The comparison results indicated that although preliminary effect in pollution control was achieved due to great efforts during the past decade, the mitigation of the air pollution especially the $PM_{2.5}$ pollution in Beijing still had a long way to go.

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