Progress and prospects of atmospheric environmental sciences in China

Fahe Chai, Abdelwahid Mellouki, Yujing Mu, Jianmin Chen, Huiwang Gao, Hong Li
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Estimation of PM$_{10}$ in the traffic-related atmosphere for three road types in Beijing and Guangzhou, China

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A B S T R A C T

The levels of roadside PM$_{10}$ in Beijing, China, were investigated in 2011 and 2012 on a seasonal basis to estimate the population exposure to particulates for three road types. The measurements of PM$_{10}$ were also conducted in the southern Chinese megacity of Guangzhou for comparison purposes. The results showed that roadside PM$_{10}$ in Beijing correlated strongly with the PM$_{10}$ background in the urban atmosphere. The levels of PM$_{10}$ in street canyons were markedly higher than those along the open roads and in crossroad areas because of limited ventilation. An elevation of PM$_{10}$ was observed in April, which was possibly due to the sand storms that frequently occur in the spring. Based on these observations, roadside PM$_{10}$ in Beijing could have multiple origins and was to some extent dispersion-governed. In Guangzhou, the roadside PM$_{10}$ did not closely relate to the background values. The PM$_{10}$ pollution was greatly affected by local traffic conditions. The simulation of PM$_{10}$ for different road types was completed during the study period using the Motor Vehicle Emissions Factor Model (MOBILE6.2) as an emission model and the California Line Source Dispersion Model (CALINE4) and Operational Street Pollution Model (OSPM) as dispersion models. The MOBILE6.2/CALINE4 software package was demonstrated to be sufficient for the simulation of PM$_{10}$ in the open roads and crossroad areas in both Beijing and Guangzhou, and the simulation results of roadside PM$_{10}$ in the street canyons by the MOBILE6.2/OSPM package were in close agreement with those of the measurements.

Introduction

Elevated levels of particulate matter (PM) are related to a number of health problems (e.g., mortality, morbidity, respiratory and cardiovascular problems) (Ackermann-Liebrich et al., 1997; de Hartog et al., 2003). The European Air Quality Standards for PM$_{10}$ were released in 1999 (DIRECTIVE 99/30/EC) with a daily maximum of 50 µg/m$^3$ and an annual maximum of 40 µg/m$^3$. In China, ambient air quality standards (GB3095) were established in 1996 with the same limit values as in Europe for the daily mean and annual mean PM$_{10}$ levels.

Beijing, with 19 million residents, is currently one of the most densely populated cities in the world. The economic boom and rapid urbanization have placed great pressure on its municipal construction and environmental aspects. The number of automobiles exceeded 5.00 million in early 2012, almost double the value of 5 years ago (2.73 million in 2007). Vehicular emission has become a major source of air pollution since large manufacturing industries were removed from Beijing before 2008 to improve the ambient air quality for the 29th Olympic Games (Westerdahl et al., 2009). Many measurements have been made in recent years to estimate the effects of the traffic control programs (i.e., stricter emission standards, downtown travel restrictions, odd-even plate restrictions, etc.) by the government on air pollution reduction (Hao et al., 2006; Zhou et al.,...
However, regular measurements of ambient urban air in many cases are not representative of the real population exposure in a specific local area. For example, fuel consumption and exhaust emission of vehicles are highly dependent on road design (Vardoulakis et al., 2002; McAdam et al., 2011). At traffic intersections, air quality is generally poor due to heavy traffic flows and variations in the speed of vehicles as they approach and leave (Pandian et al., 2009). In the last decade, the pollution of roadside particulate matter in urban Beijing has been studied in many aspects. Chan et al. (2005) studied the vertical profiles of PM$_{10}$ in August 2003 and discussed the sources. Wang et al. (2006) studied the physicochemical characteristics of ambient particles settling upon the leaf surfaces of eleven roadside plants at four sites in Beijing. Wang and Xie (2009) selected 12 major roads in the urban area to calculate the concentrations of PM$_{10}$ before and during the Olympic traffic control days with an Operational Street Pollution Model (OSPM) model. Cai and Xie (2011) used an integrated urban air quality modeling system to assess the effects of a short-term odd-even day traffic restriction scheme on traffic-related PM$_{10}$. In 2012, Tian et al. (2012) investigated the chemical compositions and toxicity of ambient particulate matter associated with traffic emissions. These studies undoubtedly broadened our knowledge about roadside PM$_{10}$ in Beijing as a fast-growing metropolitan area. However, the profile of roadside PM$_{10}$ under different traffic and road scenarios was far from well understood.

This article aims to investigate roadside PM$_{10}$ levels for different road types for a better understanding of the population exposure to this particulate matter. PM$_{10}$ estimation using California Line Source (CALINE) 4 and OSPM dispersion models was conducted for comparison with the measurements and for a possible forecast of PM$_{10}$ under different circumstances in the future.

1 Experimental

1.1 Location of sampling sites

The megacities of Beijing (39°56′N, 116°20′E) and Guangzhou (23°07′N, 113°15′E) were selected for a comparison study (Fig. 1a). Beijing, the capital of China, has a typical monsoon-influenced continental climate with hot rainy summers and cold dry winters. Guangzhou is the largest city in Southern China, and has a humid subtropical climate.
climate influenced by the East Asian monsoon.

In Beijing, the sampling sites for crossroad, street canyon and open road were at the crossing of Tsinghua East Road (THE) and Xueyuan Road (XY), in Suzhou Street (SZ) and in Xueyuan Road (XY), respectively (Fig. 1b). In Guangzhou, the sampling sites for the same three road types were in Chigang Road (CG), Shipai East Road (SPE) and Keyun Road (KY), respectively (Fig. 1c and d).

Samples were also collected on the campuses of Beijing Forestry University in Beijing and Jinan University in Guangzhou. The sampling sites were both > 300 m away from the surrounding streets. The meteorological conditions during the period of sampling were recorded.

1.2 Sampling

Samples for PM$_{10}$ measurements were collected on prefired and pre-weighted quartz fiber filters using TH-150C high-volume samplers (100 L/min, Tianhong, China). The level of PM$_{10}$ was determined gravimetrically in accordance with Chinese standard method (HJ/T93-2003) using a balance with a readability of 0.01 mg (Sartorius R200D, Germany). PM$_{10}$ sampling in Beijing was performed in April (5 to 14), October (7 to 16) and December (10 to 20) of 2011 and April (14 to 23) and July (21 to 30) of 2012. In Guangzhou, PM$_{10}$ was sampled in December (11 to 20) of 2011 and July (15 to 24) of 2012. The investigation was conducted on the three types of roads simultaneously at the scheduled times, and all of the samples were taken in duplicate. The samplers were installed in both cases on the pavement at roadsides at 1.5 m above the ground and 1.0 m from the curb. Samples were collected during 4 typical periods each day: 7:30–9:30 (morning), 11:00–13:00 (noon), 14:00–16:00 (afternoon) and 17:00–19:00 (evening). The traffic density was recorded during the sampling of PM$_{10}$.

1.3 Correlation of PM$_{10}$ with six influencing factors

Experimental data were analyzed by Pearson product-moment correlation coefficients (two-tailed) using SPSS package 15.0 (SPSS Inc., Chicago, IL, USA) to evaluate the interrelationships of the PM$_{10}$ levels with six influencing factors, i.e., temperature, humidity, wind speed, atmospheric pressure, traffic density and PM$_{10}$ background.

1.4 PM$_{10}$ simulation

Simulation of roadside PM$_{10}$ was conducted using emission and dispersion models. The Motor Vehicle Emissions Factor Model (MOBILE6.2) was selected for calculating the emission factors of PM$_{10}$ for all road types. The dispersion of PM$_{10}$ was simulated using a CALINE4 for open roads and crossroads and OSPM (by the National Environmental Research Institute, Denmark) for street canyons.

MOBILE6.2 was localized by substituting the traffic and meteorological data of Beijing into the model for better reliability. The revised parameters included vehicle registration distribution, average speed, annual mileage accumulation rate, idle PM emissions, sulfur content and fuel Reid vapor pressure. The distribution of vehicle registration was obtained from the China Statistical Yearbook (NBSC, 2011-2012). The average speed was set at 23 km/hr based on other studies (unpublished data). The sulfur content in the diesel fuel was 50 ppm. The fuel Reid vapor pressure was 88 and 74 kPa in winter and summer, respectively. The calculated emission factor was then modified by considering the effect of dust ($E$, g/km) re-entrainment. The emission factor of resuspended dust was determined according to Eq. (1) as the US EPA recommended.

$$E = k(sL/2)^{0.65}(W/3)^{1.5}$$

where, $k$ (g/km) is the particle size multiplier (4.6 for PM$_{10}$), $sL$ (g/m$^2$) is the road surface silt loading and $W$ (ton) is the average weight of the vehicles traveling the road. Therefore, the final emission factor of PM$_{10}$ ($C_{PM_{10}}$), is obtained by Eq. (2).

$$C_{PM_{10}} = C_{PM_{10}(Modeled)} + E$$

The CALINE4 package, specifically designed for calculating the concentrations of carbon monoxide near a busy road, was adapted for the analysis of PM$_{10}$ generated by vehicles on open roads and crossroads with the assumption that the dispersion of PM$_{10}$ from traffic and dust re-suspension was similar to the case of CO (Benson, 1992; Gramotnev et al., 2003). Emission factors of PM$_{10}$ for vehicles were substituted using the above addressed values ($C_{PM_{10}}$). Worst-Case Wind Angle was chosen as the run type since the wind direction near ground was highly variable. The aerodynamic roughness coefficient was set to be central business district. The altitudes of Beijing and Guangzhou were 43.5 and 11 m, respectively. The average mixing heights by season in Beijing and Guangzhou were 751.3 and 550 m, respectively (Cheng et al., 1997). The temperature, hourly wind speed, roadway geometry and traffic counts were substituted according to the measured values. The receptor position was set at 1.5 m in height and 1.5 m from the curb.

A special mode of OSPM was employed for the simulation of PM$_{10}$ in street canyons. The input parameters included street configuration, meteorological conditions, traffic density and emission factors. The average height of the buildings, the width and length of the streets, the average wind speed, the traffic density and the fleet composition were obtained from the on-site measurements. The receptor height was set to 1.5 m as in the monitoring experiments. The emission factors of PM$_{10}$ were from the MOBILE6.2 modeled results.
Table 1  Pearson correlation coefficients of PM$_{10}$ with the influencing factors

<table>
<thead>
<tr>
<th>Correlation coefficient (excluding the background)</th>
<th>Beijing</th>
<th>Guangzhou</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>0.312</td>
<td>−0.091</td>
</tr>
<tr>
<td>Humidity</td>
<td>0.097</td>
<td>−0.276</td>
</tr>
<tr>
<td>Traffic counts</td>
<td>0.375*</td>
<td>0.381*</td>
</tr>
<tr>
<td>Wind speed</td>
<td>−0.132</td>
<td>−0.324*</td>
</tr>
<tr>
<td>Atmospheric pressure</td>
<td>−0.395*</td>
<td>0.504*</td>
</tr>
<tr>
<td>PM$_{10}$ background</td>
<td>0.884**</td>
<td>0.448*</td>
</tr>
</tbody>
</table>

**Correlation is significant at the 0.01 level (2-tailed); * correlation is significant at the 0.05 level (2-tailed).

2 Results and discussion

2.1 Correlation of roadside PM$_{10}$ with influencing factors

Table 1 shows the correlation between the roadside PM$_{10}$ levels and the six possible influencing factors, which was based on 204 groups of data from Beijing and 84 groups of data from Guangzhou. The levels of PM$_{10}$ measured in the three types of roads in Beijing showed a significant positive correlation with the background value of PM$_{10}$; the correlations of traffic volume and atmospheric pressure with PM$_{10}$ were weak. In other words, the background PM$_{10}$ level in Beijing strongly affected the PM$_{10}$ concentrations in the streets. This result was in agreement with previous studies (Sun et al., 2004; Cheng et al., 2007; Wang et al., 2008; Zhang et al., 2007), in which the particulate pollution in Beijing was proved to be of multiple origins instead of simply traffic-related. In Guangzhou, the traffic volume, wind speed, atmospheric pressure and PM$_{10}$ background all correlated with the levels of roadside PM$_{10}$ to a certain extent, which suggested that the PM$_{10}$ pollution was influenced by both the sources and meteorological conditions. The results agreed with the observations that the background levels of PM$_{10}$ in Guangzhou (32–129 μg/m$^3$) were much lower than in Beijing (62–245 μg/m$^3$).

In order to focus on the relationship between roadside PM$_{10}$ and road traffic, PM$_{10}$ values were modified by subtracting the background levels. The updated correlation coefficients are shown in Table 1. The level of PM$_{10}$ in the streets in Beijing did not show a significant correlation with either traffic activities or local meteorology; whereas PM$_{10}$ values in Guangzhou strongly correlated with local traffic volume after its background was deducted. The results confirmed the presence of multiple sources of PM$_{10}$ pollutants in Beijing; on the contrary, PM$_{10}$ in Guangzhou in the studied period was more likely to be local traffic-dominated.

2.2 Relation of PM$_{10}$ with road types

Figure 2 presents the variations of roadside PM$_{10}$ (modified) for three road types during different seasons in Beijing in 2011 and 2012. In most cases, the levels of PM$_{10}$ in the street canyon SZ were significantly higher than that in the open road XY and the crossroad THE.

![Fig. 2 Variation of roadside PM$_{10}$ (modified) in Beijing (a) and Guangzhou (b) with different road types.](image-url)
However, the traffic volume in SZ was considerably smaller compared with those in XY and THE areas (e.g., on average 1959 counts/hr in SZ  4508 counts/hr in XY and 5834 counts/hr in THE in April 2011), and the value at each site did not vary significantly during the investigation period. This indicated that elevated levels of PM\(_{10}\) in the street canyon could be attributed to the limited ventilation in the area. Moreover, the PM\(_{10}\) values along XY road were greater than in the THE area. The vehicular density on XY was slightly lower than in the THE area, but the average traveling speed on XY was clearly higher than in the intersection. This result suggested that the high traveling speed could have caused re-entrainment of dust as a secondary pollutant, leading to an increase in the roadside PM\(_{10}\) level (Amato et al., 2012; Kupiainen and Pirjola, 2011). Thus, roadside PM\(_{10}\) was not only influenced by traffic volume but was also related to certain factors, e.g., traffic speed and local ventilation. Marked rises in the levels of PM\(_{10}\) in April were observed for all the road types (Fig. 2a), which could be explained by the frequent sand storms in the spring months in Beijing (Wang et al., 2004; Xie et al., 2005). This was consistent with the fact addressed in Section 2.1 that the PM\(_{10}\) in Beijing was affected more by the local traffic. Compared with PM\(_{10}\) levels in SZ and THE, the PM\(_{10}\) value in XY was less dynamic with season changes except in April. This is because PM\(_{10}\) in XY was more likely influenced by the traffic-induced dust re-entrainment. Similar results were also reported in previous literature. For example, the concentration of PM\(_{10}\) in the open road air decreased by 16.5% during the 2008 Beijing Olympic Games due to the traffic control measures (Liu et al., 2011).

In Guangzhou, the open road KY, with a vehicular intensity of 7902 counts/hr, was a main road connecting the two sides of the Pearl River, which separates the city (Fig. 1d). The busy traffic explained the high levels of roadside PM\(_{10}\) observed on the road (Fig. 2b). SPE is a one-way narrow street (18 m in width) with shops and restaurants and a low traffic volume (1112 counts/hr). However, the level of PM\(_{10}\) in this street was found comparable to that in the CG crossroad area with a considerably higher traffic volume (4633 counts/hr). Because the levels of PM\(_{10}\) in downtown Guangzhou were closely related to the local traffic, the results herein indicated the contribution of the reduced dispersion in SPE, as a street canyon, to the elevated PM\(_{10}\) values. For all three monitoring sites, the PM\(_{10}\) pollution became more severe in the winter season because temperature inversion layers developed easily, especially in SPE where mass and heat exchange were slow.

### 2.3 Comparison of roadside PM\(_{10}\) pollution in Beijing and Guangzhou

According to the observations of roadside PM\(_{10}\) in Beijing and Guangzhou in December 2011 and July 2012, a conclusion can be drawn that the patterns of PM\(_{10}\) pollution in the two megacities were apparently different. The PM\(_{10}\) values in July 2012 in Guangzhou were markedly lower than in December 2011; whereas similar results were not observed in Beijing (Table 2). The improved air quality in the summer in Guangzhou was also reflected by the reduced PM\(_{10}\) background. Busy roads in Guangzhou, such as KY, showed a significant rise in the level of roadside PM\(_{10}\) due to increased emissions of particulates with high traffic volumes. In the street SPE with a small vehicular density, the PM\(_{10}\) values decreased, although the limited ventilation in the canyon could cause an accumulation of pollutants. In the case of Beijing, the most polluted site of PM\(_{10}\) was not where the greatest traffic density was found (THE), but instead in a street canyon (SZ) with fewer vehicles and poor air circulation. This revealed that the PM\(_{10}\) in Beijing was more dispersion-governed than in Guangzhou.

The difference in the pattern of PM\(_{10}\) pollution in the two cities can be further demonstrated by the percentages of the background values in the total PM\(_{10}\) level: 66%–92% for Beijing and 26%–59% for Guangzhou. The results were in agreement with the correlation studies addressed in Section 2.1.

### 2.4 Simulation of roadside PM\(_{10}\)

Table 3 shows the emission factors of PM\(_{10}\) for different types of vehicles from the MOBILE6.2 calculation. Except for the light duty gasoline vehicle/truck, the emission factors of PM\(_{10}\) had a small decrease from 2011 to 2012.

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**Table 2** Comparison of the PM\(_{10}\) and traffic volumes in Beijing and Guangzhou

<table>
<thead>
<tr>
<th>Date</th>
<th>Road type</th>
<th>Beijing</th>
<th>Guangzhou</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PM(_{10}) (µg/m(^3))</td>
<td>Traffic volume (counts/hr)</td>
<td>PM background (µg/m(^3))</td>
</tr>
<tr>
<td>Dec, 2011</td>
<td>Street canyon</td>
<td>162 ± 59</td>
<td>2011 ± 195</td>
</tr>
<tr>
<td></td>
<td>Crossroad</td>
<td>125 ± 41</td>
<td>6556 ± 730</td>
</tr>
<tr>
<td></td>
<td>Open road</td>
<td>171 ± 22</td>
<td>5030 ± 671</td>
</tr>
<tr>
<td>Jul, 2012</td>
<td>Street canyon</td>
<td>319 ± 42</td>
<td>2240 ± 215</td>
</tr>
<tr>
<td></td>
<td>Crossroad</td>
<td>225 ± 16</td>
<td>6712 ± 710</td>
</tr>
<tr>
<td></td>
<td>Open road</td>
<td>121 ± 19</td>
<td>4812 ± 750</td>
</tr>
</tbody>
</table>
Taking secondary dust into consideration, the emission factors of PM$_{10}$ for all the vehicles increased sharply by more than an order of magnitude (Table 3). Therefore, dust re-entrainment was one of the major sources of roadside PM$_{10}$ in Beijing. This was similar to the results of some studies performed in both China and other countries (Amato et al., 2009). The results highlighted the necessity of calculating secondary dust, especially for megacities with severe air pollution and heavy traffic. Based on the fleet compositions, the final emission factors of PM$_{10}$ for vehicles in Beijing were determined to be 0.588 g/km (0.947 g/mile) in 2011 and 0.587 g/km (0.946 g/mile) in 2012.

The values of roadside PM$_{10}$ calculated by CALINE4 showed a good agreement with those measured in the XY and THE areas in Beijing (Fig. 3a and b), indicating the applicability of the MOBILE6.3/CALINE4 software package to PM$_{10}$ simulation. CALINE4 had previously been demonstrated to successfully predict the propagation of fine and ultra-fine particle aerosols (Gramotnev et al., 2003; Zhang and Batterman, 2010). The present study further showed the flexibility of the software package.
in modeling PM$_{10}$ dispersion. This finding was probably due to the high proportions of fine particulates in the total PM$_{10}$ content in the urban atmosphere of Beijing as reported elsewhere (Artiñano et al., 2004). Satisfactory agreement was also observed when applying CALINE4 to Guangzhou, where the PM$_{10}$ pollution pattern was different (Fig. 3c and d). Thus, the CALINE4 package based on local measurements in the USA was also useful for Chinese megacities with much greater traffic densities and, consequently, higher pollution levels. As for the PM$_{10}$ levels in street canyons, the OSPM-calculated results closely agreed with those from onsite measurements in both Beijing and Guangzhou (Fig. 3e and f). Therefore, the MOBILE6.2/OSPM package was also validated as a sufficient tool to predict the average levels of roadside PM$_{10}$ in street canyons, regardless of the large differences in its correlation with the local traffic conditions.

3 Conclusions

This article investigated the pollution of PM$_{10}$ in the traffic-related atmosphere of urban Beijing and Guangzhou for comparison. The results indicated that the levels of roadside PM$_{10}$ in Beijing strongly correlated to the PM$_{10}$ background, whereas in the southern megacity of Guangzhou, the correlation was not significant. Roadside PM$_{10}$ in Beijing could be attributed to multiple sources and was mostly dispersion-governed. In contrast, the pollution of PM$_{10}$ in Guangzhou was likely of local origin and was more affected by the traffic conditions. Although the patterns of PM$_{10}$ pollution in the two cities differed greatly from each other, the MOBILE6.2/CALINE4 package was demonstrated to be sufficient for PM$_{10}$ simulation in the open road and crossroad areas in both Beijing and Guangzhou, and the MOBILE6.2/OSPM package worked well in predicting roadside PM$_{10}$ in the street canyons in the two Chinese megacities.

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