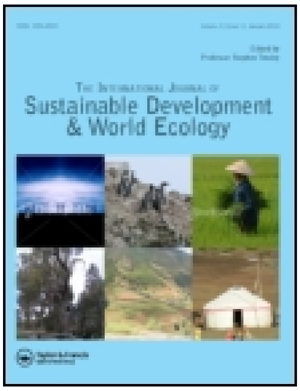

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Application of the Environmental Internet of Things on monitoring $PM_{2.5}$ at a coastal site in the urbanizing region of southeast China

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Particulate matter pollution, nowadays, is one of the most concerning environmental problems in Chinese cities, and yet monitoring of $PM_{2.5}$ (aerodynamic diameter of particle $\leq$2.5 μm) by means of Environmental Internet of Things (EIoT) is still limited in the urbanizing regions in China. A real-time 1 year continuous observation of $PM_{2.5}$ by EIoT was carried out at a coastal site in Xiamen City during 2012, with the objective to explore the temporal variations and possible sources of $PM_{2.5}$ in this urbanizing region. The annual average $PM_{2.5}$ mass concentration was 32.7 ± 9.6 μg m^{-3}, with the highest level in spring (43.6 ± 5.0 μg m^{-3}) and lowest in summer (21.0 ± 2.5 μg m^{-3}). The mean diurnal pattern of $PM_{2.5}$ mass concentrations had an obvious morning peak and low values from midnight to dawn. Additionally, the concentrations on workdays were clearly higher in contrast to those on weekends. These results indicate that particulate matter in this region is mainly influenced by anthropogenic activities, and could be effectively scavenged by precipitation. Pollution rise suggested that particulate matters were mainly from civil engineering during the construction of new urban area. A distinct characteristic of particulate matters in this urbanizing region was the low ratio (0.40) of $PM_{2.5}/PM_{10}$, which might result from the increment of coarse particles emission from freeways, construction, and sea spray. The outcomes also show that EIoT technology is convenient for the management of particulate matter pollution.

Keywords: $PM_{2.5}$; Environmental Internet of Things (EIoT); temporal variations; urbanizing region; Xiamen City

Introduction

Particulate matters have great adverse effects on public health and atmospheric environment. Many epidemiological studies have demonstrated that fine particulate matters ($PM_{2.5}$: aerodynamic diameter of particle $\leq$2.5 μm) are related to cardiopulmonary morbidity and mortality (Delfino et al. 2005; Pope et al. 2006; Ito et al. 2011; Zhou et al. 2011; Cao et al. 2012). Particulate matters, especially $PM_{2.5}$, contribute substantially to the reduced visibility and radiative balance (Environmental Protection Agency 1999; Yu et al. 2000; Yu et al. 2001; Watson 2002; Han et al. 2012). Thus, particulate matter pollution has aroused worldwide concerns in recent decades.

Particulate matter, nowadays, is one of the most concerning problems of atmospheric pollution in Chinese cities. The high frequency of haze events that occurred in the north of China aroused a debate on $PM_{2.5}$ among the governors, public, and experts in 2011 (Yuan et al. 2012), which promoted the implementation of a stricter national ambient air quality standard. Based on the public requirement, the Ministry of Environmental Protection (MEP) of the People's Republic of China revised the ambient air quality standards and set the annual and daily average $PM_{2.5}$ standards as 35 μg m^{-3} and 75 μg m^{-3}, respectively (2012). The new standard required the key cities in China to perform and report $PM_{2.5}$ measurements in addition to PM_{10} (aerodynamic diameter of particle $\leq$10 μm). However, longtime $PM_{2.5}$ monitoring in China is still limited, especially on the southeast coast, which is undergoing a fast urbanization process.

Xiamen City is a famous tourist city in the southeastern coastline of China and also an important window for international links. Due to the rapid urbanization in Xiamen City in recent years (Hua et al. 2010; Zhao et al. 2010), Jimei District has become a new urban area of Xiamen City. Substantial particulate matters are emitted to the atmosphere from the burning of fossil fuel, motor vehicles, and municipal construction etc., despite some mitigation measures having been taken. As a result, the occurrences of haze events showed an increasing trend in this urbanizing region (Wang et al. 2009). Hence, it is meaningful to study the pollution characteristics of $PM_{2.5}$ at this coastal site. Nowadays, the Internet of Things (IoT) is a promising approach to monitor and manage environmental quality, which can report real time what happens, when every ordinary object is connected by the internet (Atzori et al. 2010; Dlodlo 2012). This work presents here with the objective to understand the level and temporal variations of $PM_{2.5}$ by the EIoT technology in the rapid urbanizing area in Xiamen City.

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Methods

Site description

As shown in Figure 1, the sampling site (24.61°N, 118.06°E) is located on the roof (8 m above the ground) of a building in the Institute of Urban Environment, Chinese Academy of Sciences in Jimei District, Xiamen City, southeast coast of China. It is located at the southern foot of mountains, surrounded by schools, residential districts, freeways, construction sites, and Xinglin Bay, facing Xiamen Island across the sea. Xiamen City has a subtropical oceanic monsoon climate, with an annual average temperature of 21°C. The annual average precipitation in Xiamen City is 1100 mm, concentrated from May to September (Zhao et al. 2010).

Measurement

The real time online mass concentrations of $PM_{2.5}$ and PM_{10} were measured by a Tapered Element Oscillating Microbalance (TEOM) sampler (RP1400, Thermo Fisher Scientific, Waltham, MA, USA), which detected a heated (50°C) air sample and had a sampling period as short as 5 min. The TEOM data have artifacts due to the volatilization of water and other volatile components; thus, TEOM mass averaged over 24 h tends to be less than the filter based methods (Russell et al. 2004). The TEOM mass concentrations were calibrated regularly by filters with measured masses. Besides, regular cleaning and maintenance were carried out for this instrument. Wind speed, wind direction, and temperature were measured with automatic meteorological instruments (Met One Instruments, Inc., Grants Pass, OR, USA). Precipitation was recorded daily by the pluviograph. The measurement period covered a whole year of 2012, from 1 January to 31 December.

The data of $PM_{2.5}$ were managed by the means of EIoT, which was composed of monitoring instruments, an information transmission system, and a computer system unit. When the $PM_{2.5}$ concentrations exceeded the level of national ambient air quality standards for $PM_{2.5}$ (35 μg m^{-3}) (MEP 2012), or there was a malfunction of the instruments, the EIoT system will send a message to remind the manager. Following are the variations of $PM_{2.5}$ managed by this EIoT system (Zhao et al. 2013).

Results and discussion

Seasonal and monthly variations of $PM_{2.5}$

Figure 2 presents the monthly and seasonal variations of $PM_{2.5}$ at the coastal site during the 1 year. The mass concentrations of $PM_{2.5}$ varied from 19.0 ± 10.3 μg m^{-3} in July to 46.7 ± 18.9 μg m^{-3} in March, with an average of 32.7 ± 9.6 μg m^{-3}. The annual average concentration is slightly lower than the national ambient air quality standards for $PM_{2.5}$ (35 μg m^{-3}) (MEP 2012). The concentration at this site is much lower than that in Beijing (79.4–208.4 μg m^{-3}) (Yang et al. 2005), Shanghai (94.6 μg m^{-3}) (Wang et al. 2006), Guangzhou (105.9 ± 71.4 μg m^{-3}) (Cao et al. 2003), Xi'an (130.8–375.2 μg m^{-3}) (Cao et al. 2007), and cities in northeast China (130.8–375.2 μg m^{-3}) (Han et al. 2010). However, the concentration exceeds that of cities in Spain (20–35 μg m^{-3}) (Querol et al. 2008), Switzerland (7.9–24.4 μg m^{-3}) (Gehrig & Buchmann 2003), and United States (6.0–31.3 μg m^{-3}) (Pinto et al. 2004; Yu et al. 2004, 2007).

The quarterly average mass concentrations followed the order of summer (21.0 ± 2.5 μg m^{-3}) < autumn (29.8 ± 4.8 μg m^{-3}) < winter (36.3 ± 6.4 μg m^{-3}) < spring (43.6 ± 5.0 μg m^{-3}). The lower concentrations in summer might be interpreted by the abundance of precipitation, strong atmospheric convection, and the clean air parcels originating from the open ocean during the summer months. A distinct seasonal characteristic at this site was that the highest concentration was observed in spring, while other studies in cities in northern China usually reported highest values in winter (Yang et al. 2005; Cao et al. 2007; Yang et al. 2007; Han et al. 2010). The seasonal differences might be interpreted as that (1) there are substantial combustions of fossil and biomass fuels for heating during the cold seasons in northern China, while there is no heating facilities in Xiamen City due to the mild winter, and (2) the Asian dust storms occurring usually in spring will bring significant amount of $PM_{2.5}$ from

Figure 1. The location and terrain of the sampling site in southeast coast of China.

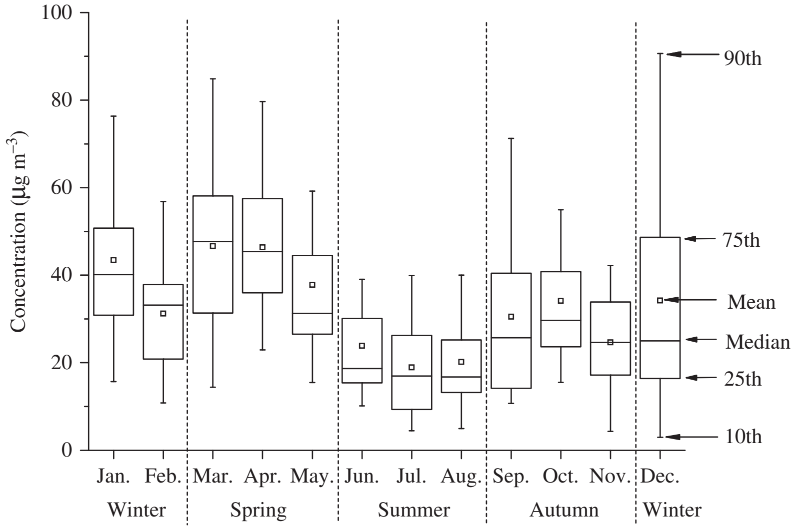

Figure 2. Monthly and seasonal variations of $PM_{2.5}$ mass concentrations. The box plots indicate the mean concentration (square) and the 10th, 25th, 50th, 75th, and 90th percentiles. The markers have the same meaning in the following figures.

the desert regions of central Asia to the southeast coast of China (Tsai and Chen 2006).

Diurnal variations of $PM_{2.5}$

Figure 3 shows the mean diurnal variations of $PM_{2.5}$ mass concentrations from hourly averaged TEOM data in 2012. The most distinct characteristic of this diurnal pattern was the pronounced morning peak, which occurred from 6:00 AM to 10:00 AM. Except autumn, the obvious morning peaks were also observed in spring (8:00–10:00), summer (6:00–8:00), and winter (8:00–10:00) (Figure S1, online only). The morning peaks were also observed in Hangzhou (Xiao et al. 2011), central California (Chow et al. 1999), and southeast Texas (Russell et al. 2004) etc., which could be explained by the increment of particulate matter emissions from traffic, factories, and catering, and the bursts of photochemical activity after sunrise. After the morning peaks, the values begin to decline until 14:00. A slight peak was also observed during the evening rush hours (18:00–20:00). The lower points during a day were found from midnight to early morning. The diurnal pattern indicated that the particulate matters in this urbanizing region closely linked with the anthropogenic activities.

Diurnal variations of $PM_{2.5}$ on workdays and weekends

As shown in Figure 4, the mean diurnal pattern of $PM_{2.5}$ mass concentrations on workdays is consistent with that on weekends. Both of them had a morning peak and lower

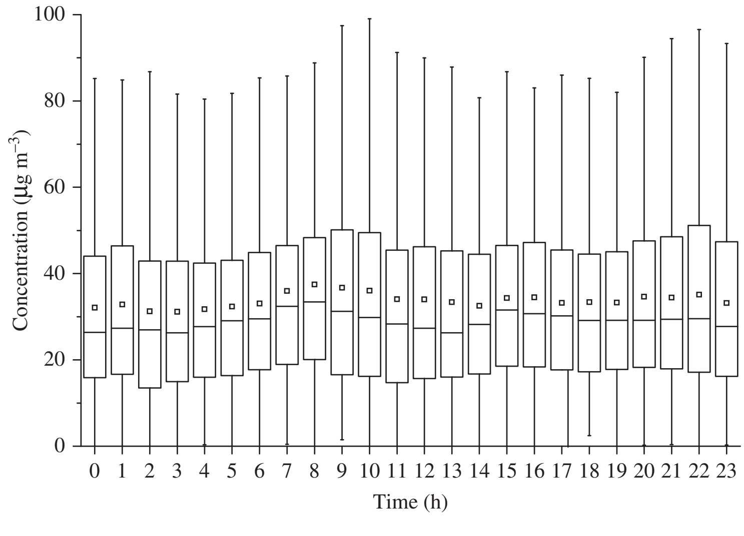

Figure 3. The mean diurnal variations of $PM_{2.5}$ mass concentrations. The box plots indicate the mean concentration (square) and the 10th, 25th, 50th, 75th, and 90th percentiles.

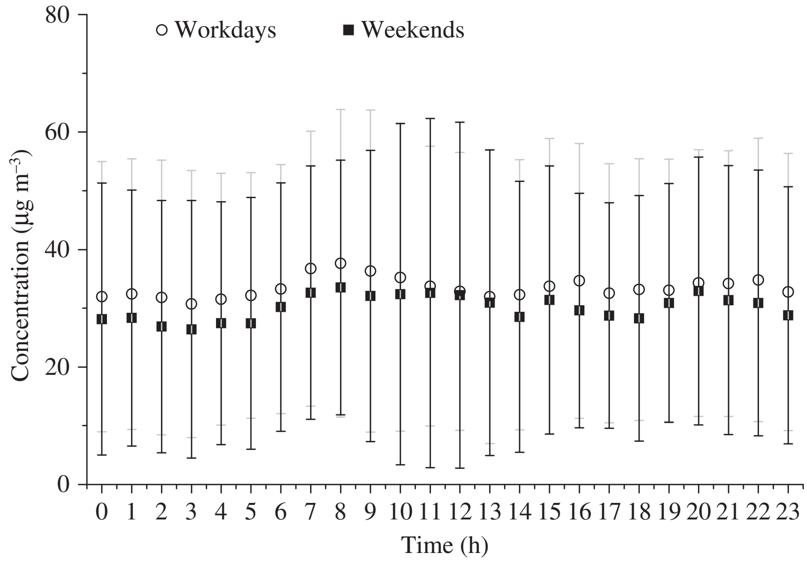

Figure 4. The mean diurnal variations of $PM_{2.5}$ mass concentrations on workdays and weekends.

points from midnight to early morning. However, the $PM_{2.5}$ mass concentrations on workdays were evidently higher than those on weekends at each clock, which might result from the less emission from traffic and factories on weekends. Charron and Harrison (2005) also found higher levels of $PM_{2.5}$ and coarse particles ($PM_{2.5–10}$) on workdays in contrast to weekends in London, and ascribed this phenomenon to traffic. Molnár et al. (2002) observed that the hourly mean number concentrations of particles on workdays exceeded those on weekend at a major road north of Gothenburg, especially during the morning rush hours.

Pollution rise of $PM_{2.5}$

The $PM_{2.5}$ mass concentration, wind frequency, and speed are plotted against wind direction in Figure 5. Due to the obstacles, i.e., the mountains on the north of the

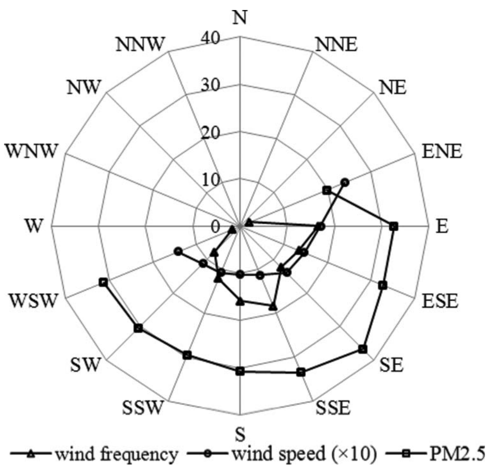

Figure 5. Concentration of $PM_{2.5}$ as a function of wind direction frequency (%) and speed (m s^{-1}). The wind speeds are scaled in order to be clearly shown.

sampling site (Figure 1), the wind is mainly from the ENE – WSW (clockwise) directions, with few occurrences in the W – NE (clockwise) directions. The higher $PM_{2.5}$ concentrations were observed as the wind came from the E – WSW (clockwise) directions, with the highest concentration found in the SE direction. Additionally, the $PM_{2.5}$ showed relatively low concentrations in the ENE direction despite the wind speed in this direction being high. Thus, it could be concluded that the particulate matters at this site were mainly from the ESE – SSE directions due to the development of new urban area. Long-range transports of air pollutions from Taiwan and Guangdong are one of the biggest reasons for the heaviest acidic rain in the spring season in Xiamen City (Yu 1994; Yu et al. 1998). Therefore, they might also have some impact on the highest $PM_{2.5}$ concentrations in the spring in Xiamen City.

The effect of precipitation on $PM_{2.5}$

The daily variations of $PM_{2.5}$ concentrations and precipitations in each season are presented in Figure 6. It was clearly shown that $PM_{2.5}$ had low concentrations in the precipitation events. Especially, the $PM_{2.5}$ concentrations decreased remarkably as the precipitation was above 10 mm, such as on 1 January, 6 March, 18 May, 23 June, 3 September, and 30 November. Graedel and Crutzen (1992) reported that a raindrop might contain as many as 10,000 small particles as it reached the ground. Thus, precipitation is an effective way to scavenge particulate matters from the atmosphere.

The ratios of $PM_{2.5}/PM_{10}$

Figure 7 shows the correlation between $PM_{2.5}$ and PM_{10} in spring, summer, autumn, and winter. The high correlation ($R^2 = 0.88$) in summer suggested that there were similar sources for $PM_{2.5}$ and PM_{10}, and the low correlation

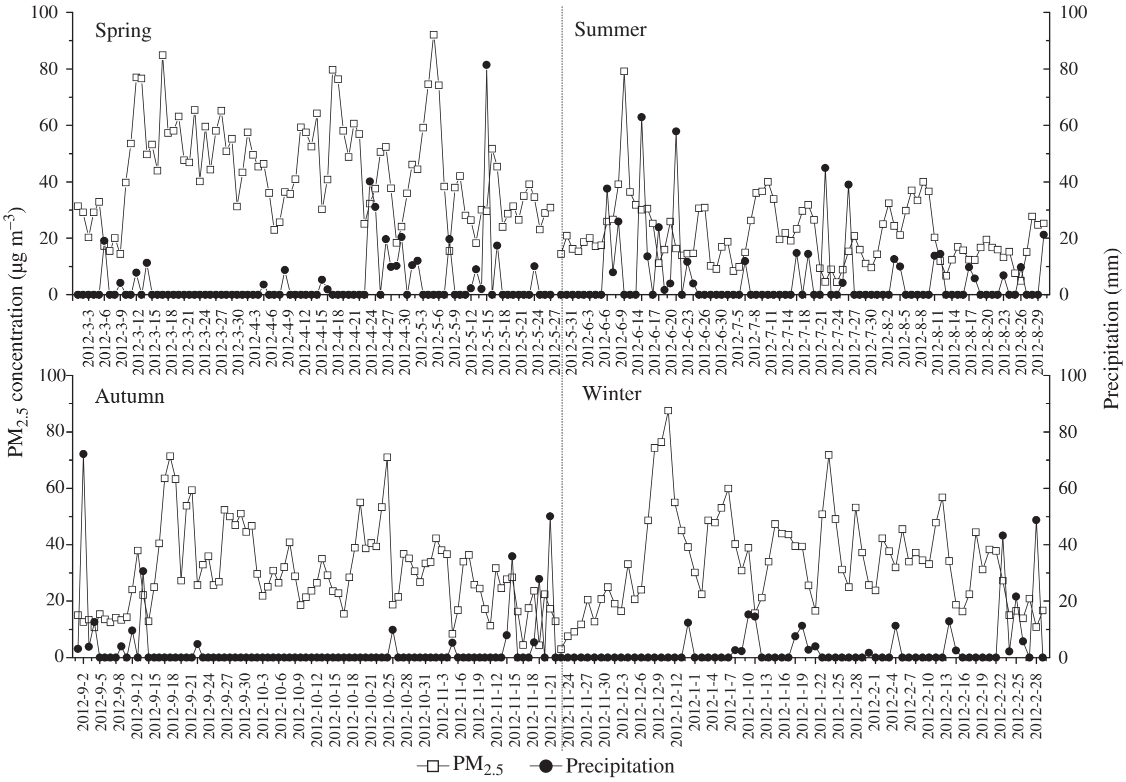

Figure 6. Temporal variations of $PM_{2.5}$ and precipitations in (a) spring, (b) summer, (c) autumn, and (d) winter.

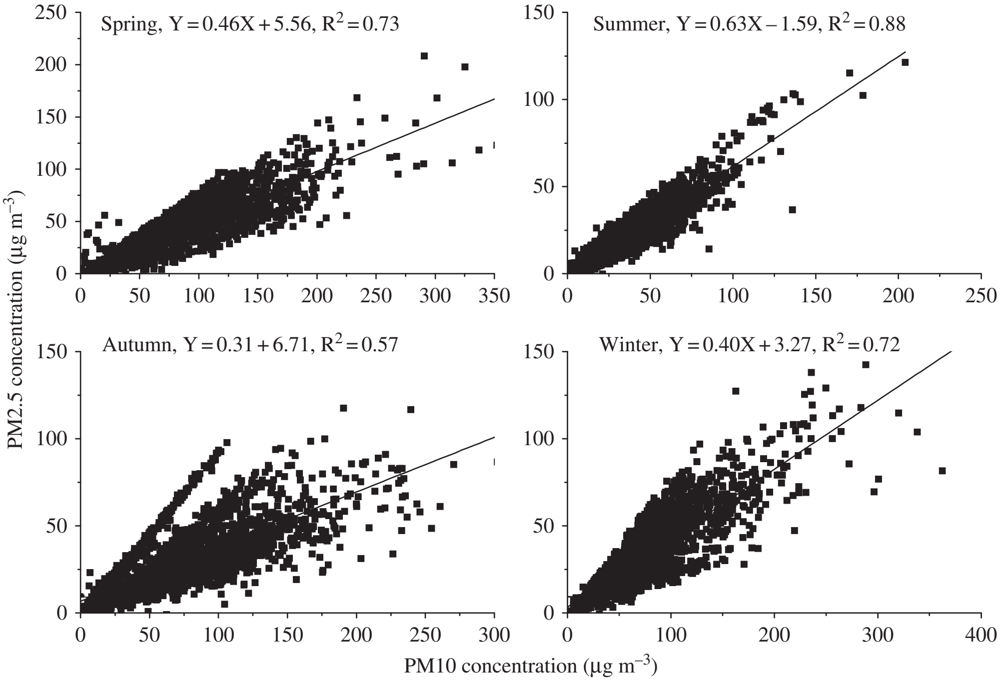

Figure 7. Scatterplots of $PM_{2.5}$ versus PM_{10} at the sampling site in (a) spring, (b) summer, (c) autumn, and (d) winter.

($R^2 = 0.57$) implied the complexity of emission sources of $PM_{2.5}$ and PM_{10} in autumn. The ratios of $PM_{2.5}/PM_{10}$ were not constant over the year, which varied from 0.57 in autumn to 0.63 in summer, with an annual average of 0.40 (Figure S2). The annual average ratio in this urbanizing region is lower than that in Guangzhou (0.68) (Cao et al. 2003), cities in northeast China (0.54–0.67) (Han et al. 2010), Switzerland (0.59−0.75) (Gehrig & Buchmann 2003), and Spain (0.50−0.75) (Querol et al. 2008). Possible explanations for the relatively lower ratio in this urbanizing region include: (1) the emission of coarse particles arising from traffic-induced abrasion and resuspension processes (Gehrig & Buchmann 2003; Charron & Harrison 2005), for there are freeways near this site; (2) emissions from civil construction work as Jimei District is undergoing a fast urbanization process; (3) contribution of the evaporation of sea spray for this site is close to the seashore.

Conclusion

The results of the 1 year continuous observation of particulate matters by means of EIoT technology indicate the annual average mass concentration ($32.7 \pm 9.6\ \mu g\ m^{-3}$) of $PM_{2.5}$ in this urbanizing region is lower than that in many cities in China, but higher than that in cities in developed countries. The highest concentration ($43.6 \pm 5.0\ \mu g\ m^{-3}$) was found in spring, which was different from the studies in north China. The diurnal pattern of $PM_{2.5}$ mass concentration showed obvious morning peak and lower points from midnight to dawn. The concentrations on workdays were evidently higher in contrast to that on weekends. The particulate matters at this site were mainly influenced by human activities. High concentrations found in the SE direction suggested that the particulate matters were mainly from civil engineering during the construction of new urban area. The low ratio of $PM_{2.5}/PM_{10}$ (0.40) in this urbanizing region indicates that there are substantial coarse particles emission sources nearby.

Acknowledgments

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