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Variations of PM_{10} concentrations in Wuhan, China

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Abstract Concentrations of PM_{10} (particulate matter as a key urban air pollutant) were obtained from nine monitor stations within the city of Wuhan for analysis after an intensive observational data collection period that commenced in January 2006 and concluded in December 2008. According to our data, PM_{10} pollution intensified and reached a high alert level of air pollution during the month of November each year. It remained at a high alert level until the following April where it again decreased to a low alert level during the summer months. During the winter and spring months, the occurrence rate (in percent) of PM_{10} was five to eight times higher (high alert level) than measurements detected during the summer months. The effects of intrinsic factors (pollution sources) and remote preconditions (dust storm propagation and formation of secondary aerosol) on severe PM_{10} concentrations in Wuhan are first analyzed. After which, suggestions to reduce PM_{10} pollutants are provided.

Keywords PM_{10} pollutants · Sources · Wuhan

Introduction

The capital of Hubei Province, Wuhan (latitude 29°58′ to 31°22′ and longitude 113°41′ to 115°05′) is located in the eastern region of the province that lies within central China (Fig. 1a). The Yangtze River, the third longest river in the world, meets Hanshui, its largest tributary, in Wuhan where it divides the city into three parts: Hankou, Wuchang, and Hanyang, namely, the "Three Towns of Wuhan" (Fig. 1b). Hankou, located on the northern bank of the Yangtze River, is the metropolitan area that hosts government organizations, shopping centers, and residential districts. Wuchang, on the southern bank of Yangtze River, is where tertiary schools, scenic spots as well as heavy industrial and high technology zones are located. Hanyang, on the western plain, is comprised of residential areas, automobile factories, and scenic spots. The population of Wuhan is approximately 8.58 million, and its total area is 8,494 km^2. Wuhan boasts a subtropical humid monsoon climate dominated by hot and humid summers each year. The average daily temperature in July is 37.2°C where the maximum often

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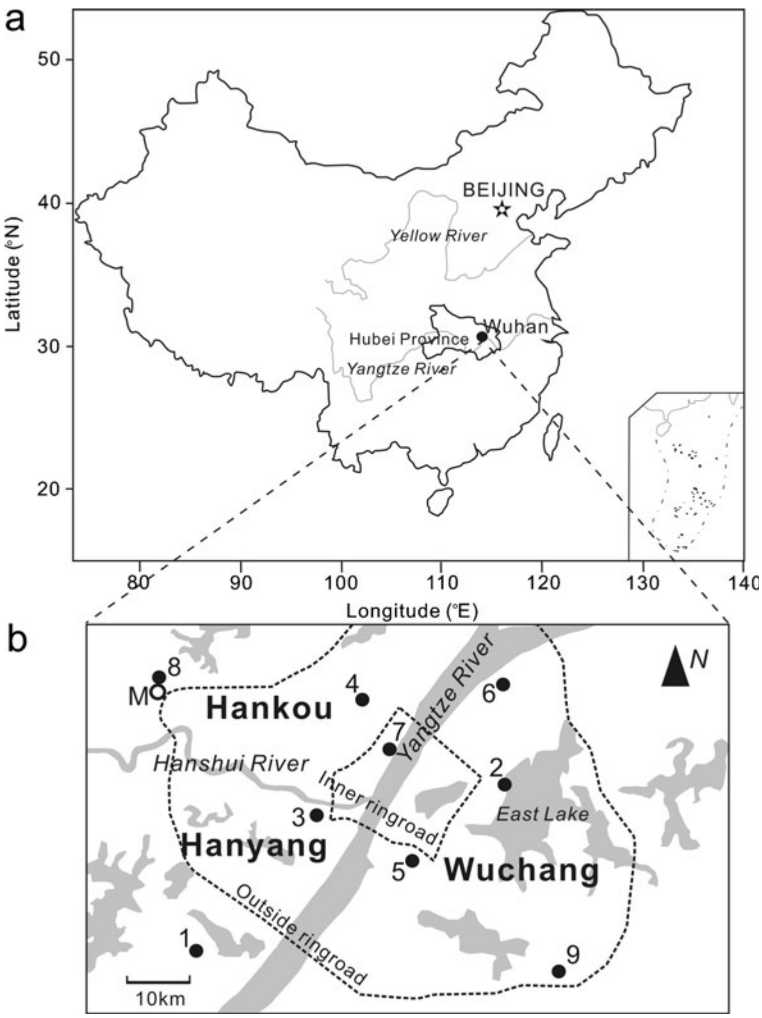

Fig. 1 Wuhan: **a** geography and **b** location of observation stations

exceeds 40°C. Seasonal climatic variations match that of the East Asian monsoon climatic region since the city is located on the eastern region of the Jianghan Plain (where above surface height ranges from 20 to 100 m). Surrounding Wuhan is the Exi mountainous region (where the above surface height ranges from 1,000 to 3,000 m) in the west, Tongbai Mountain (where the above surface height ranges from 200 to 1,000 m) in the north, Dahong Mountain (where the above surface height ranges from 200 to 1,000 m) in the northwest, Dabie Mountain (where the above surface height ranges from 800 to 1,000 m) in the east, and Mufu Mountain (where the above surface height ranges from 200 to 1,000 m) in the south (Fig. 2). Wuhan is ranked first among major Chinese cities in water resources due to areas of water bodies within its territory totaling 25.8%. East Lake (Fig. 1a), the largest lake in China located within a cityscape, covers an area of 33 km^2. Wuhan is one of the biggest junctions of land, water, and air transportation in China being the political, economic, and cultural center of Hubei Province.

Several investigations have previously been carried out to study urban environmental and atmospheric pollutants in certain Chinese megacities (Zhou et al. 2007; Chu et al. 2008; Chana and Yao 2008; Chan et al. 2005; Chau et al. 2002; Chang and Lee 2008). Wuhan, currently undergoing rapid urbanization and social and economical development, is facing increasing pressure in

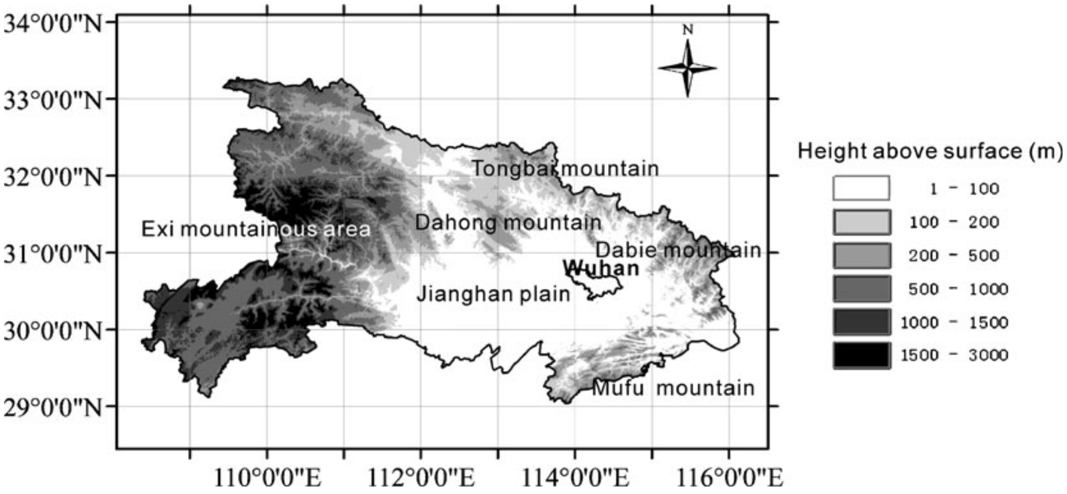

Fig. 2 Topography of Hubei Province

terms of environmental protection and the restoration of its natural environment from anthropogenic destruction like other metropolitan cities within China. Recent research has indicated that the major sources of air pollution in Wuhan derive from automobile exhaust and the use of coal for domestic cooking, heating, and industrial processes (Qian et al. 2007). The topographic characteristics (Fig. 2) make Wuhan a passage for freezing air going down to the south and the east. Moreover, weather changes are fierce in Wuhan. Due to these diffused conditions, PM_{10} concentrations experience seasonal variation characteristics (Li et al. 2004).

The air quality standard issued (promulgated) by the Environmental Protection Agency of China (EPA-China) focuses on smaller particles that are likely responsible for adverse health effects because of their ability to reach the lower regions of the respiratory tract. The PM_{10} standard for ambient air establishes threshold levels for the concentration of the particles with a diameter of 10 μm or less (up to 10 μm). The EPA-China health-based national air quality standard for PM_{10} is 0.04 mg m^{-3} (annual mean) and 0.05 mg m^{-3} (daily concentration; Table 1). Major concerns in human health from exposure to PM_{10} include effects on breathing and the respiratory system, damage to lung tissue, cancer, and premature death. The elderly, children, and people with chronic lung disease, influenza, and asthma are especially sensitive to the effects of particulate matter. The annual mean second-level and third-level air pollution criteria for PM_{10} is 0.10 and 0.15 mg m^{-3}, respectively (Table 1). The daily mean second-level and third-level air pollution criteria for PM_{10} is 0.15 and 0.25 mg m^{-3}, respectively (Table 1). The Chinese EPA alerts the Wuhan population when the PM_{10} concentrations are reaching the second-level criteria.

For this study, particulate air pollution in Wuhan was investigated by means of intensive measurements of PM_{10} from January 2006 to December 2008, applying air quality monitoring systems as well as associated meteorological observations. Figure 1b identifies the locations of nine sampling stations where St-1 to St-9 measured PM_{10} concentrations and St-M measured meteorological records. The objectives of this study were to detect detailed temporal and spatial

Table 1 Air quality standards for annual/daily mean PM_{10} pollutant concentrations (in milligrams per cubic meter) from the Chinese National Environmental Protection Agency

Level of criterion	Annual	Daily
1	0.04	0.05
2	0.10	0.15
3	0.15	0.25

variability of PM_{10} to evaluate air quality objectively and quantitatively, to analyze pollutant sources, and to discover favorable meteorological conditions for pollutant dispersion. The comparison between observed PM_{10} concentrations and EPA-China criteria gives the level of the particulate pollution. Linking the meteorological observations with the measured PM_{10} concentrations may help in detecting the different causes of the particulate pollution. The temporal and spatial variability of the PM_{10} concentrations are presented in the "PM_{10} monitoring and statistics" section. The possible causes for particulate pollution are discussed in the "Source discussion" section and the conclusions and suggestions are given in the "Conclusions and suggestions" section.

PM_{10} monitoring and statistics

Data was taken from the Wuhan Environmental Protection Bureau (WEPB) and the Wuhan Meteorological Bureau (WMB). WEPB air quality data were collected at observational stations (St-1 to St-9) from January 2006 to December 2008.

Airborne PM_{10} at each observational station was collected by a tapered element oscillating microbalance (TEOM) 1400a. The sampling system was placed on the roof of a 3-m-tall building, resulting in an effective inlet height above the ground of 4.5 m. At the exit of the PM_{10} inlet, the design flow (16.67 L min^{-1}) was isokinetically split into a 3.0-L min^{-1} main flow and a 13.67-L min^{-1} bypass flow, which is sent to the TEOM sensor unit and the automatic cartridge collection unit, respectively.

The TEOM 1400a monitor collected particles from the main flow continuously on a Teflon-coated borosilicate glass fiber filter mounted on the tip of a glass element that oscillates in an applied electric field. The resonant frequency of the element decreases as mass accumulates on the filter, directly measuring the inertial mass. Temperatures were maintained at a constant value, typically 50°C in this study, to minimize thermal expansion of the tapered element. Readings of mass concentrations were logged every 6 min and averaged over 1 h.

WMB routine meteorological data were collected concurrently at St-M.

The data capture for all stations and all months ranged between 90% and 99%. Measurements confirmed that the total temporal mean PM_{10} concentration exceeded or reached the second-level annual mean PM_{10} concentration criterion (0.10 mg m^{-3}) at all stations (Table 2). Among all measurements, St-6, located within a heavy industrial area, showed the highest concentration values (0.13 mg m^{-3}).

Figure 3 illustrates the monthly mean, the minimum, and the maximum PM_{10} concentrations (in milligrams per cubic meter) at all nine stations as well as the urban average. The monthly maximum urban average in January was calculated by the following equation:

$$M_{\mathrm{maxJ}} = \mathrm{MAX}\left\{\frac{\sum_{i=1}^{9}\mathrm{St}_{i,1}}{9}, \frac{\sum_{i=1}^{9}\mathrm{St}_{i,2}}{9}, \ldots \frac{\sum_{i=1}^{9}\mathrm{St}_{i,31}}{9}\right\} \tag{1}$$

where M_{maxJ} is the urban average monthly maximum in January (in milligrams per cubic meter) and $St_{i,1}$ is the PM_{10} value of station i on January 1 (in milligrams per cubic meter).

The three dashed horizontal lines represent the first-level (bottom), second-level (middle), and third-level (top) criterions of the annual mean concentrations (Table 1). Monthly mean PM_{10} concentrations exceeded the first-level annual

Table 2 Locations of observational stations and total temporal mean PM_{10} concentrations (in milligrams per cubic meter)

Site	Location	PM_{10}
St-1	Suburb residential area	0.11
St-2	East Lake Park	0.10
St-3	Residential area in Hanyang	0.12
St-4	Residential area in Hankou	0.12
St-5	Commercial and shopping center	0.12
St-6	Heavy industry area	0.13
St-7	Yangtze Bank Park	0.11
St-8	Electrical and mechanical industrial zone	0.13
St-9	High technology industrial zone	0.12
St-M	Residential area in Hankou	

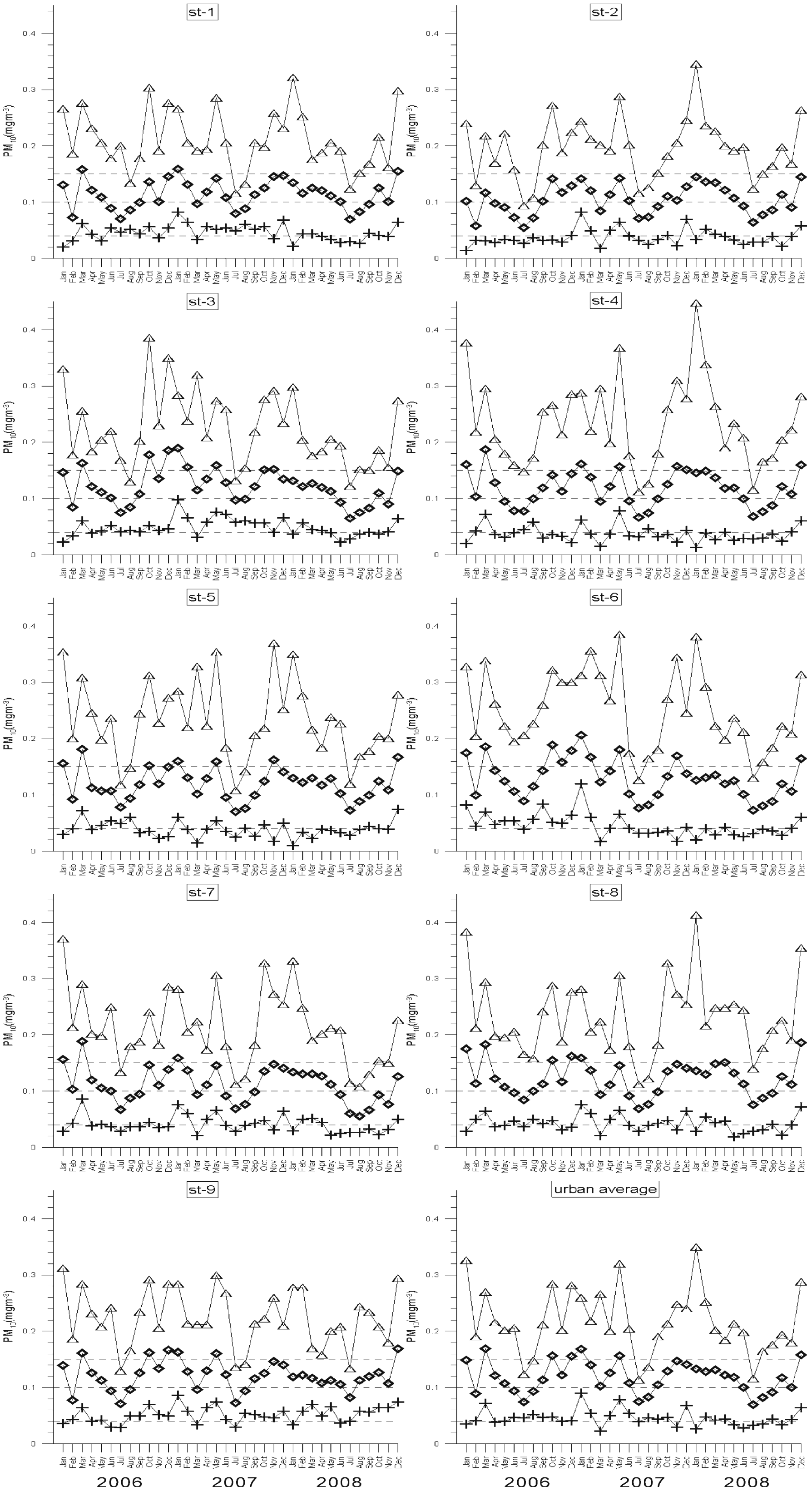

Fig. 3 Monthly mean, maximum, and minimum PM$_{10}$ concentrations (in milligrams per cubic meter) at St-1 to St-9 and urban average from January 2006 to December 2008

Table 3 PM_{10} concentration (in milligrams per cubic meter) in March 2006

	St-1	St-2	St-3	St-4	St-5	St-6	St-7	St-8	St-9	Urban average
Max	0.28	0.22	0.26	0.30	0.31	0.34	0.29	0.29	0.28	0.27
Min	0.06	0.03	0.06	0.07	0.07	0.07	0.09	0.06	0.06	0.07
Mean	0.16	0.12	0.16	0.19	0.18	0.19	0.19	0.18	0.16	0.17

Table 4 PM_{10} concentration (in milligrams per cubic meter) in July 2008

	St-1	St-2	St-3	St-4	St-5	St-6	St-7	St-8	St-9	Urban average
Max	0.12	0.12	0.12	0.12	0.12	0.13	0.11	0.14	0.13	0.12
Min	0.05	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.06	0.04
Mean	0.07	0.06	0.07	0.07	0.07	0.06	0.08	0.08	0.07	0.07

Table 5 Month mean PM_{10} (in milligrams per cubic meter) concentration of urban average from 2006 to 2008

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2006	0.15	0.09	0.17	0.12	0.11	0.09	0.07	0.09	0.11	0.16	0.12	0.16
2007	0.17	0.14	0.10	0.13	0.16	0.11	0.08	0.08	0.10	0.13	0.15	0.14
2008	0.13	0.13	0.13	0.12	0.12	0.10	0.07	0.08	0.09	0.12	0.10	0.16

Table 6 Occurrence rate (in percent) of PM_{10} alert of 2007, which is the ratio between the days with PM_{10} concentration exceeding the daily second-level criterion and the total days of observation of 2007

2007	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
St-1	55	30	10	27	37	11	0	0	17	30	50	43	26
St-2	42	26	3	20	37	15	0	0	3	20	7	27	17
St-3	74	52	23	30	50	19	0	3	27	43	43	30	33
St-4	52	44	10	23	50	15	0	0	7	30	43	53	27
St-5	61	33	13	33	53	7	0	0	7	30	43	46	28
St-6	81	52	35	37	60	15	0	3	17	33	57	40	36
St-7	55	48	10	13	30	11	0	0	7	33	43	37	24
St-8	61	52	26	33	50	26	0	0	13	33	40	40	31
St-9	58	26	10	30	47	22	0	0	17	27	43	43	27

Table 7 Occurrence rate (in percent) of PM_{10} alert for four seasons

Season	Spring (271 observational days) Mar, Apr, May	Summer (263 observational day) Jun, Jul, Aug	Fall (267 observational day) Sep, Oct, Nov	Winter (264 observational day) Dec, Jan, Feb
St-1	26	4	24	33
St-2	18	3	15	27
St-3	32	5	28	41
St-4	34	4	22	41
St-5	32	3	30	41
St-6	41	6	35	46
St-7	25	4	16	38
St-8	39	8	28	45
St-9	24	7	31	38
Mean	30	5	26	39

mean PM_{10} standard (0.05 mg m^{-3}) at all times and at all stations within the urban area of Wuhan. And in winter, the monthly mean PM_{10} concentration might exceed the annual mean third-level PM_{10} standard (0.15 mg m^{-3}) at most of the stations.

Taking March 2006 as an example due to it being the month that experienced the highest levels of PM_{10} pollution in the 3-year study period, the monthly mean PM_{10} concentration was greater than the annual mean third-level criterion (0.15 mg m^{-3}) at most stations except for St-2 located in East Lake Park. Furthermore, the maximum PM_{10} concentration was higher than the daily mean third-level criterion (0.25 mg m^{-3}) in all stations except for St-2 (Table 3). The reason for the exception was the excellent location for St-2, which is located in East Lake Park which is surrounded by dense trees, so it is not easily influenced by PM_{10} pollution event and its PM_{10} concentrations were always the lowest among the nine stations.

During the 3-year study period, the minimum monthly mean appeared in July. Nearly all stations reached the minimum monthly mean in July except for St-7 (located in the Yangtze Bank Park) in 2008 (Fig. 1). The reason for the exception may be caused by sand from the river bank with dry wind as local source. The maximum, minimum, and mean values for July 2008, the month in which the least amount of PM_{10} pollution was detected throughout the 3-year study period, are provided in Table 4.

The monthly mean urban average PM_{10} concentration exceeded the annual mean first-level criterion at all times. The annual mean second-level criterion was exceeded or reached during 28 months of the 3-year study period, including 7 months in which the annual mean third-level criterion was exceeded or reached (Table 5). The maximum monthly mean urban average PM_{10} concentration appeared in March 2006.

The occurrence rate of PM_{10} (high alert level) is the percentage between the number of days that PM_{10} concentrations exceeded the daily second-level criterion and the total number of observational days (Table 6). Percentage either did or did not exceed 40% at most stations during the months of December and January. Certain stations exceeded 60% such as St-3 (residential area) and St-6 (heavy industrial area) in December 2006; St-3 and St-5 (commercial areas) as well as St-6 and St-8 (electrical and mechanical industrial areas) in January 2007; and St-8 and St-9 (high technological industrial areas) in December 2008.

High-level PM_{10} pollution occurred more frequently during winter (39%) and spring (30%; Table 7). The occurrence rate of PM_{10} (high alert level) was much smaller during summer months (5%). In winter, pollution ratios exceeded 40% at St-3, St-4, St-5, St-6, and St-8. The stations St-3, St-4, and St-5 are situated near the inner ring road (Fig. 1b) of Wuhan, in an area that combines commercial and residential functions with high population density. St-6 and St-8 are located in an area with heavy industry situated outside the ring road. For all seasons, the pollution ratios are much lower at St-2 located in the East Lake Park.

Source discussion

Local sources

Coal consumption by industry and residents in Wuhan is one of the important sources for the pollution by PM_{10} particulates. One point source of this type of particulate is located in the northeastern corner of the urban area in which lies the heavy industrial zone harboring both iron and steel smelts. Due to coal burning for industrial use in the neighborhood, St-6 has, during most of the time, the highest PM_{10} alert ratio of all the nine stations. The zone additionally experienced high concentrations in winter since coal is used as a local source of heating.

Automobiles and road dust are two other sources of PM_{10} pollution where maximum concentrations are reached during daytime hours when automobile traffic peaks (between 0700 and 0900 and between 1600 and 1900; Li et al. 2007). The number of automobiles in Wuhan increased from 703,481 in 2006 to 818,626 in 2008 (Wuhan Statistical Yearbook). Meanwhile, automobiles, including the 20,000 illegally operated vehicles that fall short of the emissions standard the most, may enter into the city center. These sources are responsible for the higher PM_{10} alert ratio

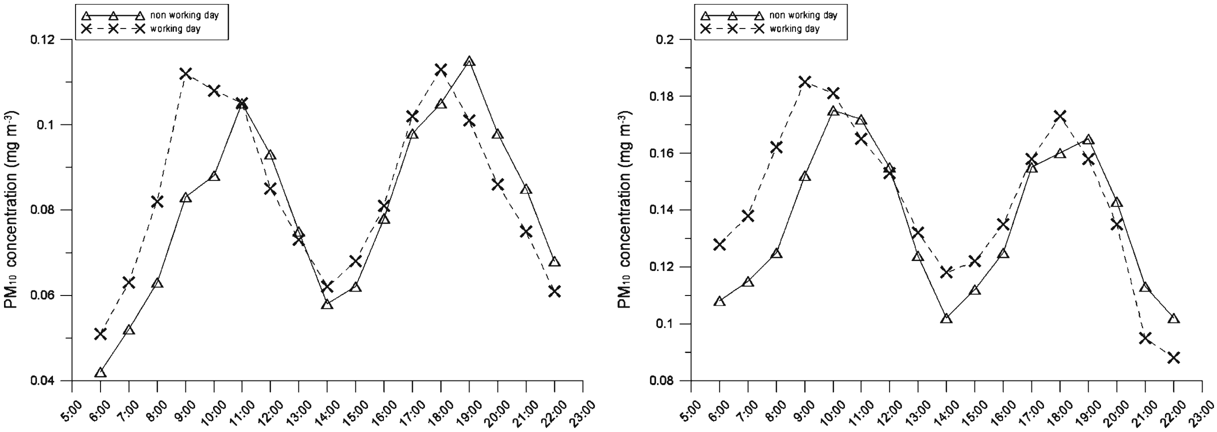

Fig. 4 Hourly PM_{10} concentrations (in milligrams per cubic meter) at St-5 on working days and nonworking days in summer (*left*) and winter (*right*)

at stations St-3, St-4, and St-5 compared to St-1 (Table 6).

Figure 4 shows data for working days and nonworking days in summer (from June 2007 to August 2007) and winter (from December 2006 to February 2007), which gives an example of a vehicle emission-dominated episode. High concentrations of traffic-generated pollutants were observed in St-5 (located at a commercial and shopping center). The data are typified by the twin diurnal peaks in concentration of PM_{10}, indicative of vehicle-derived pollution.

Dust from city construction projects is another source of PM_{10} pollution. Using St-8 in the electrical and mechanical industrial zone as an example, the total occurrence rate (in percent) of PM_{10} is highest (21%) in February 2006. The lack of dust reduction initiatives from nearby road activity as well as residential construction during this period made St-8 the most polluted one. We can see more detail in Fig. 5.

When a windy day appears with dry air in spring, road dust and dust from city construction or bared land were easily blown up into the air to make high PM_{10} concentrations. As shown in Table 8, March 19, 2006 has the highest PM_{10} pollution in March 2006 (see Fig. 8).

Celebrations that include fireworks displays are another major local PM_{10} pollution source. This is especially true during the Spring Festival Holiday (SFH, Chinese New Year) where it is tradition for people to set off fireworks. For various reasons, fireworks were banned in Wuhan from 1994 to 2006. Starting in 2007, however, fireworks were allowed to be set off in specified places in Wuhan during the Spring Festival. The SFHs were celebrated from January 28 to February 12 in 2006, from February 17 to March 4 in 2007, and from February 6 to February 21 in 2008. Records show

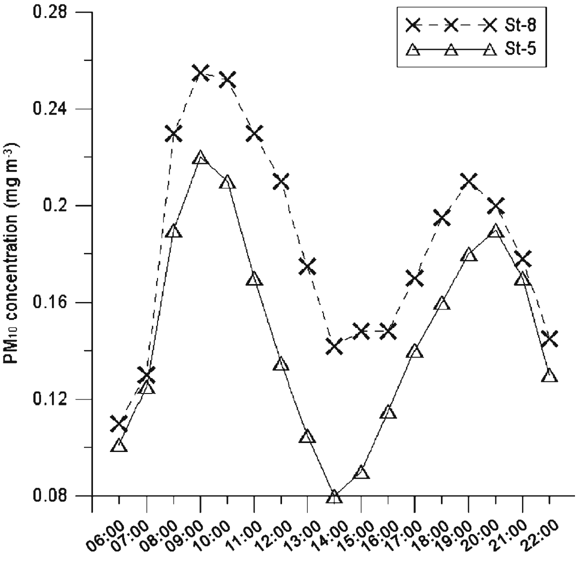

Fig. 5 Hourly PM_{10} concentrations (in milligrams per cubic meter) at St-8 which is affected by road constructions compared with St-5, which has no construction activities nearby in February 2006

Table 8 PM_{10} concentrations and meteorology conditions on March 19, 2006 and March 25, 2007

Occurring time	Daily PM_{10} concentrations ($mg\ m^{-3}$)	Daily relative humidity (%)	Daily wind speed ($m\ s^{-1}$)	Daily temperature (°C)
3/19/2006	0.27	52	1.4	13.4
3/25/2007	0.27	74	1.5	17.7

that PM_{10} pollution was higher for the most part during the 2008 SFH than it was for the 2006 SFH. There were 5 days in total when the daily mean PM_{10} concentration of the urban average exceeded or reached the daily second-level criterion during the 2008 SFH. In contrast, there was only 1 day each year where this occurred during the 2006 and 2007 SFH.

The highest pollution levels were observed at St-4 within the residential area of the city center. During the SFH period of 2008, the daily mean PM_{10} concentrations of St-4 exceeded or reached the second-level criterion for 6 days. The highest value appeared at the second day of SFH, when even the daily third-level criterion was exceeded.

Figure 6 illustrates the hourly PM_{10} concentrations at St-4 (residential area in Hankou) during the 2007 (February 17 to February 18, 2007) New Year's Eve and February 20 to February 21, 2007. From the graph, we can see that high PM_{10} concentrations caused by fireworks displays would persist for several hours with adverse meteorological conditions leading to poor dispersion, such as the combination of low wind speed.

Remote preconditions

Dust storms often occur in northern China during the spring. Table 9 lists selected dust events in northern China that occurred in March 2006 and March 2007. Research has shown that dust storms over northwestern China may extend into the northern Pacific Ocean, Japan, and Korea (Duce et al. 1980). Severe dust storms can even travel across the Pacific Ocean and reach the western coast of North America as was the case on April 18, 1998 (Wang et al. 2003). The primary sources of dust storms are the Gobi Desert that lies within Mongolia and northern China and the Taklimakan Desert in western China (Sun et al. 2001).

Though Wuhan is far from north China, its air quality can still be influenced by dust storms

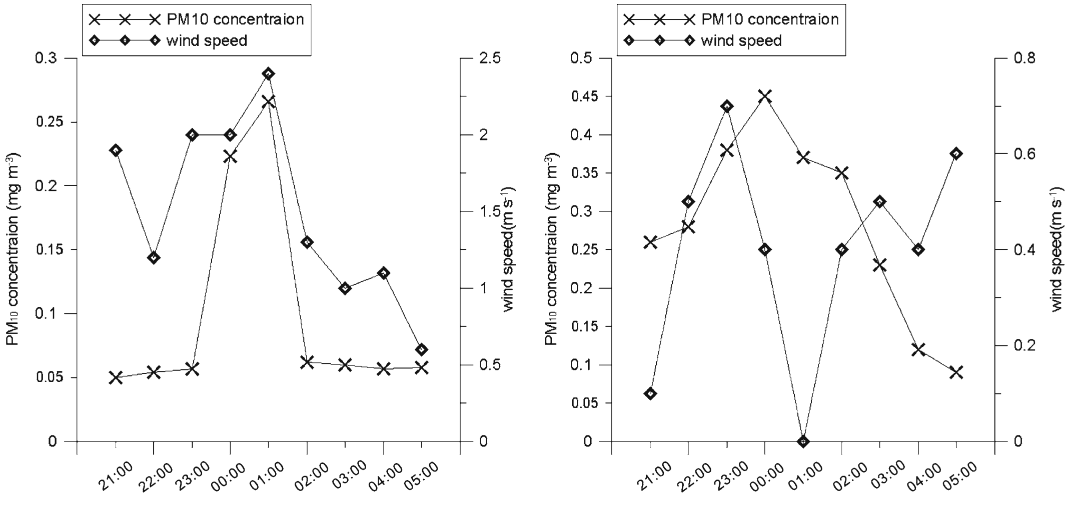

Fig. 6 Hourly PM_{10} concentrations (in milligrams per cubic meter) and wind speed (in meters per second) at St-4 which is affected by fireworks displays during February 17 to February 18, 2007 (*left*) and February 20 to February 21, 2007 (*right*)

Table 9 Dust storm statistics in northern China in March 2006 and March 2007

Occurring time	Wind velocity ($m\ s^{-1}$)	Least visibility (m)	Number of stations in north and northwest China where the dust storm has been observed
3/9/2006	13–21; max, 23	<100	33
3/12/2006	10–20; max, 23	<300	10
3/10/2006	11–25; max, 28	<100	26
3/26/2006	10–15; max, 18	<100	16
3/27/2006	11–15; max, 18	<100	8
3/31/2006	11–16; max, 18	<300	8
3/27/2007	12–16; max, 20	<300	6
3/28/2007	13–17; max, 20	<300	7
3/30/2007	11–24; max, 28	<200	30
3/31/2007	12–23; max, 27	<100	32

under certain conditions. Taking April 2, 2007 as an example, dust storm from the north desert with dry strong wind makes the PM_{10} concentrations of all nine stations exceed the daily mean second-level criterion. This is a typical high concentrations process caused by remote source during the daytime. Figure 7 illustrates the process of hourly mean PM_{10} change and correlative meteorology. A sharp increase of PM_{10} appeared and stayed for several hours with high wind speed and low relative humidity on the specific day.

As described in the "PM_{10} monitoring and statistics" section, the maximum monthly mean PM_{10} concentration of the urban average appeared in March 2006. Occurrences of high PM_{10} concentrations are associated with the propagation of dust storms. Daily PM_{10} concentrations of the urban average over all nine stations in March 2006 (the record of March 20 was missing) and March 2007 are illustrated separately in Figs. 8 and 9, respectively. Dust storms from northern China are marked by the black diamonds and vertical dash-dotted lines. Three horizontal dashed lines refer to the first-level (top), second-level (middle), and third-level (bottom) criterions of daily mean concentrations. Associated observational data are provided and listed in Table 10.

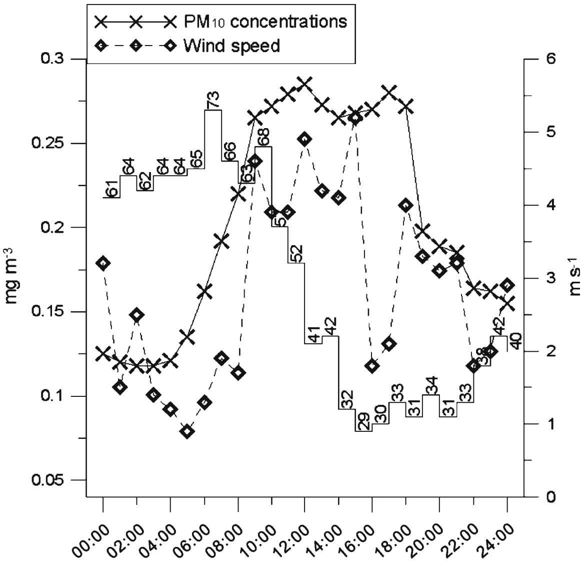

Fig. 7 Hourly PM_{10} concentrations (in milligrams per cubic meter), wind speed (in meters per second), and relative humidity (in percent) of April 2, 2007

A recent report from the WEPB shows that daily mean PM_{10} concentrations reached 0.41 mg m^{-3} on April 26, 2009 and 0.57 mg m^{-3} on April 25, 2009. These values are the highest detected since 2000. Both of these severe pollution events were the result of dust storms originating from northern China (monthly report of Wuhan air quality, 2009; see more detail in Table 10).

A conclusion can be drawn from the above evidence. When the air is dry, strong winds blowing over the northern and northwestern deserts cause the propagation of dust storms and, consequently, produce high PM_{10} concentrations in Wuhan during the spring. Dust storms from the northern regions of China are, therefore, a major remote source of PM_{10} pollution in Wuhan.

Ammonium salts are one of the major components of PM_{10} in some Chinese area during spring, and the formation of secondary aerosol is responsible for the high PM_{10} concentrations (Cao et al. 2009; Wang et al. 2002, 2008).

Fig. 8 Daily mean PM_{10} concentrations (dust storm represented by the black diamonds and vertical dash-dotted lines) in March 2006

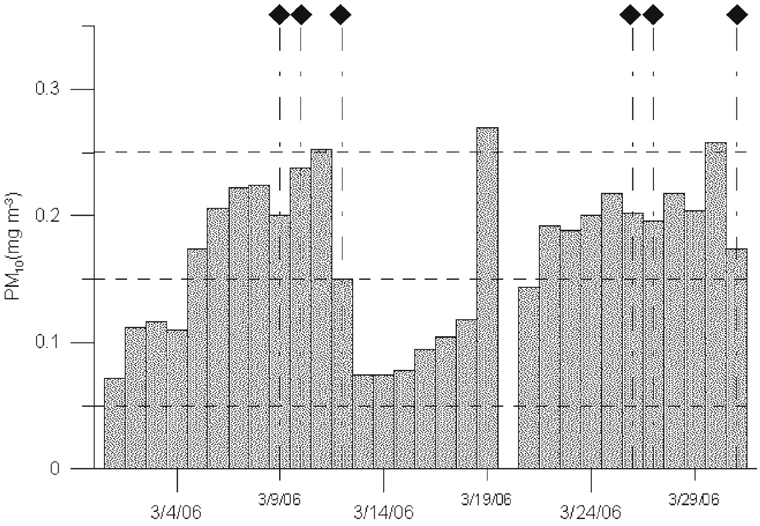

Fig. 9 Same as Fig. 5 except for March 2007

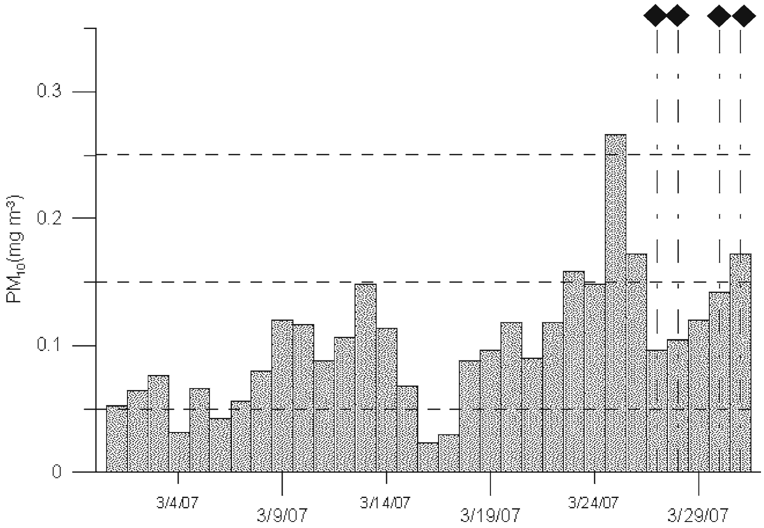

Table 10 Daily meteorological and PM_{10} concentrations of typical days

	Mean PM_{10} concentrations (mg m^{-3})	Total precipitation (mm)	Daily wind speed (m s^{-1})	Relative humidity (%)
3/9/2006	0.20	0	1.3	Not available
3/10/2006	0.24	0	1.1	Not available
3/11/2006	0.25	0	2.2	Not available
3/12/2006	0.15	0	3.3	57
3/26/2006	0.20	0	1.0	58
3/27/2006	0.20	0	1.2	62
3/31/2006	0.17	0	1.2	65
3/27/2007	0.09	0.5	1.0	78
3/28/2007	0.10	0	1.3	65
3/30/2007	0.14	0	1.7	68
3/31/2007	0.17	0	1.9	74
4/25/2009	0.57	0	1.4	55
4/26/2009	0.41	0	1.0	42

Wuhan is located in Jianghan Plain (see Fig. 2); this plain is one of the largest rice production bases of China. In this plain, fields are always over fertilized to improve rice production, so that the needs of the nearby cities and provinces are met. Data from the Wuhan Statistical Yearbook shows that the use of nitrogenous fertilizer for nearby field is 332.5 kg ha^{-1} in 2006, 334.6 kg ha^{-1} in 2007, and 325.0 kg ha^{-1} in 2008.

So it is possible that the formation of secondary aerosol (formation of ammonium salts) has some effect on the PM_{10} pollution in spring in Wuhan. Especially during spring, at conditions of moderate temperature and high humidity range (Stelson and Seinfeld 1982), the formation of secondary aerosol caused high PM_{10} concentration in Wuhan. This would make March 25, 2007 highest in PM_{10} pollution in March 2007 (see Table 8 and Fig. 9).

Conclusions and suggestions

Observational studies from January 2006 to December 2008 demonstrate that heavy PM_{10} pollution was more serious during winter and spring months. March 2006 was the most severely polluted month with a monthly mean 0.17 mg m^{-3} PM_{10} concentration. Frequencies of high-level PM_{10} pollution occurrences during all four seasons were 30% in spring, 5% in summer, 26% in fall, and 39% in winter.

Topographic features of the Wuhan metropolitan area make particulate pollution possible both in winter and spring. Both local and remote sources account for this pollution. Local pollution sources include industrial and residential coal burning, automobiles that mostly fall short of the emission standard, road dust, dust from city construction projects, and fireworks displays during the SFH celebrations. On the other hand, mountain breezes from remote areas contributed to the effect of particulate pollutants sinking into the Jianghan Plain, which caused severe pollution during dry days in the spring. Data analysis shows that dust storms occur often in northern and northwestern China and lead to higher PM_{10} concentrations in Wuhan. Another potential source is the formation of secondary aerosol from nearby fertilized fields, which has some effect on the PM_{10} pollution in spring. The maximum PM_{10} concentration of 0.17 mg m^{-3} was observed in March 2006.

The reduction in PM_{10} concentrations is an urgent air quality control issue that must be addressed in Wuhan. This may be achieved by (1) improving the efficiency of industrial and residential coal burning, (2) introducing street sweeping and washing (Chang et al. 2005) or road sweeping (Gertler et al. 2006) before high traffic hours, (3) banning vehicles that seriously fall short of the emission standard, (4) restricting fireworks displays, (5) preventing dust during roadwork and construction, and (6) forecasting dust storm events.

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