Origin of PM$_{10}$ Pollution Episodes in an Industrialized Mega-City in Central China

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ABSTRACT

The origin of atmospheric particulate matter (PM) events in an industrialized mega-city of Central China (Wuhan) was investigated. Wuhan constitutes an ideal case scenario for the study of atmospheric pollution episodes, given that it is representative of densely populated and industrialized Chinese cities. Levels of PM$_{10}$, NO$_x$ and SO$_2$ were evaluated and automatic PM levels were corrected following EU-guidelines, aiming to achieve comparability with results from outside China (Europe and US). This correction evidenced that PM$_{10}$ levels were underestimated with the automatic instrumentation by 26–38%. This correction is thus essential for the potential use of ambient PM data in epidemiological and climate studies within China and abroad. Several types of peak PM$_{10}$ events were identified: winter pollution events (daily mean PM$_{10}$ = 200–350 µg/m$^3$), Asian desert dust events (PM$_{10}$ increments of 60–70 µg/m$^3$ on the daily means) and biomass burning episodes (scarce during the study period). Natural contributions are thus a significant PM source to be taken into account for the evaluation of air quality in the area, the application of daily or annual limit values and the potential assessment of the data from an epidemiological point of view. In addition, the influence of the Wuhan pollution plume was detected in the Mulanhu regional site, which is 40 km far from the city, underlining the large area of influence of atmospheric pollution from Wuhan on the regional-scale. Finally, the results from this work evidence that a detailed knowledge of PM episodes and sources at a given site may be obtained by means of relatively straightforward and economic routine measurements (PM$_{10}$, NO$_2$, SO$_2$).

Keywords: PM$_{10}$; Gobi desert dust; Wuhan; SO$_2$; NO$_2$.

INTRODUCTION

China has experienced a very high economic growth in recent years (~10% per year). Because of increased industrial activities and power production (mainly based on coal consumption) and the demands of a rapidly developing society, China has become one of the main emitters of air pollutants in the world (Statistics China, 1983–1996). In addition to industrial activity, road traffic is also a significant source of air pollutants. The number of cars in Beijing is estimated at ~2 million, with the rate of car sales per year currently increasing in many Chinese cities. Although the emission of some pollutants could be reduced in the future because of the implementation of advanced technologies, a large increase in power production (~50%) and in diesel vehicle sales is expected for the coming decade (Streets and Waldhoff, 2000; Streets et al., 2001). PM$_{10}$ emissions in China increased from 2000 to 2005 (Lei et al., 2011). The evolution of the emissions is still uncertain and will affect differently to air quality (Xing et al., 2011). It has been estimated that roughly one-fourth of global anthropogenic emissions of black-carbon particles occurs currently in China (Streets et al., 2001). Moreover, desert dust outbreaks, mainly occurring in spring, further complicate the PM cocktail (Kim and Kim, 2003; Zhang et al., 2003; Guo et al., 2004; Wang et al., 2004; Wang et al., 2005; Zhao et al., 2010).

With a current population exceeding 9 million, the city of Wuhan is an emerging mega-city in Central China, being one of the ten largest Chinese cities. Wuhan is one of the areas with highest industrial development in the country, with coal burning power plants, steel and iron manufactures,
cement factories, petrochemical and other chemical-based plants and construction related factories operating within the conurbation. According to emission inventories (Streets and Waldhoff, 2000), the industrial SO\textsubscript{2} emissions per inhabitant in Wuhan are around 1.5 times higher than in Beijing (where the population is 1.7 times greater than in Wuhan). Earlier studies at Wuhan have shown that PM exhibits a complex mixture (Waldman et al., 1991; Wei et al., 1999) and have reported the adverse effects on health of exposure to PM (He et al., 1993; Qian et al., 2001, 2004; Xie et al., 2011). Road traffic in the area is also a major source of atmospheric pollutants, even though reliable data on the number of motor vehicles in Wuhan city during the study period were not available given that motor vehicles from neighbouring cities or rural areas come to Wuhan city daily but they are not registered with the Bureau of Transportation of Wuhan Municipality (Sun et al., 2006).

As a result of these considerations, Wuhan constitutes an ideal site for the study of atmospheric pollution episodes, representative of densely populated and industrialized Chinese cities (Querol et al., 2006).

In this paper we aimed to link the roles of the meteorology and local anthropogenic emission sources (industrial and urban) with the development of PM\textsubscript{10} episodes in the city of Wuhan. The transport of Asian desert dust and other distant PM sources was also evaluated. Our final goal was to find out if detailed analyses of PM episodes and sources may be carried out using relatively available and economic routine measurements of particulate and gaseous pollutants.

**METHODS**

**The Study Area**

The study area is located at Wuhan, Hubei Province (Fig. 1). This area extends over the Eastern part of Jianghan plain in the valley of the Yangtze River. The Jianghan plain is bounded by mountainous chains: the Tongbai-Dabie Mountain Range (500–800 m.a.s.l.) to the north; the Wu and Daba Mountain Range (1500–2200 m.a.s.l.) to the west; the Xuefeng Mountain Range (500–1500 m.a.s.l.) to the south; and the Luoxiao Mountain Range (900–1600 m.a.s.l.) to the southeast. The plain extends to the northeast along the wide Yangtze River valley.

The climate in the study area is controlled by the monsoon related circulation which induces dry cold air masses from the north in winter and hot and humid air from the south in summer (120–200 mm monthly rainfall).

According to Wuhan emission inventories (Wuhan Environmental Protection Bureau data) the main SO\textsubscript{2} emissions arise from coal fired power plants (63%) and iron and steel works (27%); PM stack emissions are mainly caused by power generation (82%) and the iron and the steel industry (16%); PM fugitive emissions mainly result from the iron and the steel industry (89%) and cement factories (10%). Other industries, such as petrochemical and other chemical-based plants (e.g., fertilizer and sulphuric acid), construction activities and paper mills, and urban activities (e.g., road traffic and domestic boilers using coal for heating and cooking) also contribute to PM, NO\textsubscript{2} and SO\textsubscript{2} levels. No detailed emission inventory data were available for NO\textsubscript{2}.

In addition to the local and regional PM emissions, long range transport of mineral dust in spring and carbonaceous aerosols due to widespread biomass firing in South-eastern Asia may contribute to PM levels in Wuhan.

**Sampling Sites and Methods**

PM\textsubscript{10} sampling was simultaneously performed at two sites, urban and industrial, belonging to the Wuhan Environment Protection Bureau. These two stations are located at a distance of 17 km from each other.

Changqian is an industrial air quality monitoring station (114°25′38″E, 30°36′37″N, 38 m.a.s.l.) located in the NE of Wuhan. Most of the aforementioned industrial activities operate in this area. It should be noted that the PM\textsubscript{10} sampler was moved to a 100 m distant site in the middle of the campaign, due to technical reasons.

The Hankou urban air quality monitoring station (114°17′1″E, 30°37′11″N, 23 m.a.s.l.) is situated on the roof of a 5-storey building in the N of Wuhan. Urban emissions, such as the ones stated above, prevail in this area.

A 24h PM\textsubscript{10} sampling was simultaneously performed at the industrial and urban sites from September 2003 to September 2004 (with an interruption between November...
2003 and February 2004) with a frequency of 2 days out of each 9 days. Furthermore, 6 samples of PM$_{10}$ were collected at the Mulanhu regional background air quality station (40 km N from Wuhan; Mulanhu Lake) during March and September 2004. Particles were collected on 20.3 × 25.4 cm quartz micro-fibre filters (QF20 Schleicher and Schuell), using Wuhan Tianhong high volume samplers (Th-1000CII, 63 m$^3$/hr) equipped with PM$_{10}$ impactors. The 60 samples collected at each site were conditioned after sampling in a dessicator at 20–25°C for 48 h prior to the gravimetric determination of the PM$_{10}$ levels.

Moreover, levels of PM$_{10}$, SO$_2$ and NO$_2$ were monitored in real time with standard DASIBY instrumentation (beta attenuation for PM$_{10}$) at Changqian and Hankou by the Wuhan Environment Protection Bureau.

**Meteorological Interpretations**

Back-trajectories were calculated daily for the sampling periods with the HYSPLIT-4 model (Draxler and Rolph, 2003) to interpret the different source regions of the air masses reaching the study area. Back-trajectories were computed by modelling vertical velocity at midday for 5 back day periods at 500, 1500 and 2500 m.a.s.l., with a 6 hour step for every day.

To study the transport of dust from the Gobi desert and of carbonaceous aerosols due to biomass burning in Southeastern Asia, the results of the back-trajectory interpretations were coupled with the outputs of the NAAPs model for mineral dust and smoke (http://www.nrlmry.navy.mil/aerosol).

**RESULTS AND DISCUSSION**

**PM$_{10}$ Levels: Automatic vs. Filter Sampling**

The differences between PM$_{10}$ levels registered by means of automatic measurements and those measured with the gravimetric method were evaluated. The automatic PM$_{10}$ measurements underestimated levels by 26% at Hankou and by 38% at Changqian (Fig. 2) with respect to gravimetric measurements.

The aforementioned differences are due to the operation mode of automatic samplers. These instruments heat the aerosol sample in order to minimise condensed water. This gives rise to the volatilization of semi-volatile species and a consequent underestimation in PM$_{10}$ levels with respect to filter based PM$_{10}$ determination (Allen et al., 1997). In EU, the automatic PM$_{10}$ measurements must be corrected by means of an experimentally determined ‘filter/automatic measurements’ ratio (European Commission, 2001). If not available, automatic PM$_{10}$ measurements must be corrected by a factor ranging from 1.3 to 1.5. It is essential to establish a methodology that allows us to compare the results obtained in different countries, as the correction of the automatic measurements is performed in a different manner in different countries, as reported recently by the European Topic Center (ETC, Alastuey et al., 2011). This will be extremely useful for the evaluation and comparison of PM data between different countries, as well as for the use of these data as input for Chinese and foreign epidemiological and climate studies.

**PM$_{10}$ SO$_2$ and NO$_2$ Levels**

Mean PM$_{10}$, NO$_2$ and SO$_2$ levels in the study period measured with the real time automatic instrumentation (without correction for PM$_{10}$), were 152, 49 and 80 µg/m$^3$ and 134, 62 and 39 µg/m$^3$ at the Changqian-industrial and Hankou-urban sites, respectively. Mean PM$_{10}$ NO$_2$ and SO$_2$ levels in the study period recorded by automatic instrumentation during the 24h PM$_{10}$ sampling days were 127, 44 and 74 µg/m$^3$ at the Changqian-industrial site, and 117, 60 and 38 µg/m$^3$ at the Hankou-urban site (Table 1). The differences between the average levels obtained in the whole period with respect to those obtained for the sampling days were small at the urban site, but significant at the industrial hotspot. This is due to the more episodic character of the industrial pollution.

The urban site exhibited slightly lower PM$_{10}$ levels, much lower SO$_2$ levels and higher NO$_2$ levels than the industrial site due to the lower industrial (SO$_2$) and higher road traffic (NO$_2$) influence.

Although SO$_2$ levels were significantly lower at the urban site, a number of events exceeding 100 µg/m$^3$ were recorded (Fig. 3). At the industrial site, daily mean concentrations > 200 and > 500 µg/m$^3$ occurred a number of times (Fig. 3). The intense SO$_2$ episodes (daily means > 500 µg/m$^3$) recorded at Changqian may be related to sulphide roasting, smelting or combustion of high sulphur coals.
located at a distance of 17 km from each other, daily mean levels of PM10 at the Changqian-industrial site and at the Hankou-urban site, the correlation between the three pollutants (PM10-NO2-SO2) is relatively high ($R^2 = 0.37–0.6$), which indicates the heavy industrial influence. The simultaneous NO2, SO2 and PM10 peaks during pollution events at both sites (Fig. 3) corroborates the expected influence of common industrial and urban sources in the day-to-day temporal variation. The SO2/NO2 ratio at the Changqian site (0.2 to 8 with a mean value of 1.5) is higher than at Hankou (0.2 to 1.3 with a mean value of 0.6), which indicates the heavy industrial influence.

In order to evaluate the industrial and urban nature of the monitoring sites, the correlation between the three major pollutants measured in this study (PM10, NO2, SO2) were analysed. Despite the fact that the two selected sites are located at a distance of 17 km from each other, daily mean levels of PM10 at the Changqian-industrial site and at the Hankou-urban site exhibit a high correlation during the whole year (Fig. 4). This indicates that PM10 events have a regional nature owing to the meteorology and to the wide spatial dispersion of the pollution plume.

At the Changqian-industrial site, the correlation of PM10 with SO2 ($R^2 = 0.08$) is lower than that of PM10 with NO2 ($R^2 = 0.28$) given that the proximity to large SO2 emissions results in relatively fresh SO2 fumigations (Fig. 3). At the Hankou-urban site, the correlation between the three pollutants (PM10-NO2-SO2) is relatively high ($R^2 = 0.37–0.51$). The simultaneous NO2, SO2 and PM10 peaks during pollution events at both sites (Fig. 3) corroborates the expected influence of common industrial and urban sources in the day-to-day temporal variation. The SO2/NO2 ratio at the Changqian site (0.2 to 8 with a mean value of 1.5) is higher than at Hankou (0.2 to 1.3 with a mean value of 0.6), which indicates the heavy industrial influence.

At the industrial site, mean PM10 obtained by gravimetric methods was 197 µg/m³, with typical daily values between 67 and 413 µg/m³. At the urban site, an annual mean PM10 of 156 µg/m³ was recorded by gravimetry, with daily values ranging from 46 to 379 µg/m³. These concentrations are similar to those found by Wei et al. (1999) in this city, and exceed by 3 to 4 times the PM10 US and EU annual limit values (US-EPA, 1996; EU Directive 2008/50/EC).

PM10 concentrations at Wuhan are similar to levels in other Asian mega-cities, such as Shangai, higher than levels in Hong Kong, and lower than those in Beijing and Nanjing (Wang et al., 2003; Ho et al., 2003; Kim and Kim, 2003; Zheng et al., 2004; Sun et al., 2004; Table 2). Compared with other mega-cities, PM10 levels at Wuhan are similar to those in Calcutta (Karar and Gupta, 2007), lower than those in New Delhi (Balachandran et al., 2000; Mönkkönen et al., 2004) and higher that those in American mega-cities such as Santiago de Chile, Buenos Aires, Sao Paulo and Mexico City (Rojas-Bracho et al., 2002; Bogo et al., 2003; Querol et al., 2008).

### Table 1. Mean daily levels of SO2, NO2 and PM10 obtained by the gravimetric and automatic (beta attenuation) instruments at Hankou, Changqian and Mulanhu stations during the PM10 sampling days from September 2003 to September 2004. SD: standard deviation.

<table>
<thead>
<tr>
<th>Day/month/year</th>
<th>Station 1 (Changqian)</th>
<th>Station 4 (Hankou)</th>
<th>Mulanhu</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PM10</td>
<td>PM10</td>
<td>SO2</td>
</tr>
<tr>
<td></td>
<td>gravimetry</td>
<td>beta</td>
<td>gravimetry</td>
</tr>
<tr>
<td>Mean levels</td>
<td>197</td>
<td>128</td>
<td>74</td>
</tr>
<tr>
<td>Max</td>
<td>413</td>
<td>239</td>
<td>569</td>
</tr>
<tr>
<td>Min</td>
<td>67</td>
<td>32</td>
<td>5</td>
</tr>
<tr>
<td>n</td>
<td>59</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td>SD</td>
<td>72</td>
<td>45</td>
<td>100</td>
</tr>
</tbody>
</table>

**Fig. 3.** Daily levels of PM10, SO2 and NO2 measured at Hankou and Changqian.

**Fig. 4.** Cross correlation plots between PM10 levels measured with automatic beta monitors at Changqian and Hankou stations.
The six additional PM$_{10}$ samples collected at the Mulanhu regional background site resulted in a mean PM$_{10}$ concentration of 118 µg/m$^3$ (ranging between 72 and 159 µg/m$^3$), only 29% lower than that recorded simultaneously at the Hankou-urban site (Table 1). These results were quite unexpected given that Mulanhu was considered a regional background site, and they indicate that PM levels at this site must be influenced by the pollution plume from Wuhan. Consequently, it is possible to conclude that the PM emissions from the Wuhan area have a minimum reach of at least 40 km (distance between Wuhan and Mulanhu). These results are comparable to those obtained by Querol et al. (2008) for the Mexico City pollution plume, which was detected over at least 60 km.

**Table 2. Comparison of PM$_{10}$ levels from Wuhan with data reported for selected Asian Cities.**

<table>
<thead>
<tr>
<th></th>
<th>Dec–Feb</th>
<th>Mar–May</th>
<th>Jun–Aug</th>
<th>Sep–Nov</th>
<th>Whole year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wuhan, industrial hotspot</td>
<td>206</td>
<td>182</td>
<td>226</td>
<td>158</td>
<td>179</td>
</tr>
<tr>
<td>Wuhan, urban site</td>
<td>169</td>
<td>175</td>
<td>133</td>
<td>94</td>
<td>157</td>
</tr>
<tr>
<td>Wuhan, Mulanhu lake</td>
<td>116</td>
<td>120</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shanghai$^a$ Nov–01 to Jan–02</td>
<td></td>
<td>148</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beijing$^b$, 2002–2003</td>
<td>252</td>
<td></td>
<td></td>
<td>164</td>
<td></td>
</tr>
<tr>
<td>Nanjing$^c$ 2001</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hongkong$^d$ Nov–00 to Feb–01</td>
<td>79</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Korea, Seoul city$^e$ March–May 2001</td>
<td></td>
<td></td>
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</tbody>
</table>

Gr: Gravimetry, Aut-D: Automatic-dashby monitor. $^a$Zheng et al. (2004); $^b$Sun et al. (2004); $^c$Wang et al. (2003); $^d$Ho et al. (2003); $^e$Kim and Kim (2003).

**Relationship between PM and Meteorology**

**Seasonal Evolution**

Levels of PM$_{10}$ underwent a seasonal evolution with lower levels in summer than in winter. Daily mean values of PM$_{10}$ at both sites are typically within the ranges 75–130 µg/m$^3$ from June to September and 100–200 µg/m$^3$ from October to February (Fig. 4 and Fig. 5(A)). Levels of NO$_2$ and SO$_2$ experienced a similar seasonal evolution. Fig. 5 shows the basic meteorological parameters which account for the seasonal evolution of PM$_{10}$ at Wuhan. In autumn-winter, the mean surface pressure charts show that the meteorological conditions are, on average, dominated by the presence of a high pressure system over China and Mongolia (Fig. 5(E)). This north-western dry subsidence (see pressure at ground level in Fig. 5(B)) results in a strong stability and stratification of the low troposphere and in minimal precipitation rates (Figs. 5(B) and (C)). The minima in the “1000–925 hPa layer” thickness in winter corroborate the stagnation of pollutants at ground level (Fig. 5(B)). In contrast, the typical summer meteorology is mainly dominated by low pressures in the South of China (Fig. 5(F)), resulting in SE humid air masses i.e. the monsoon season (Fig. 5(D)). Note in Fig. 5(D) how NW and SE are the most important airflows in the western and eastern hemispheres, respectively. This shows how the seasonal evolution of PM$_{10}$ at Wuhan (and probably in the other cities of Central China) is driven by an anticyclonic North-western dry-subsidence resulting in a PM$_{10}$ maximum in winter and a south-eastern humid airflow which gives rise to PM$_{10}$ minimum in summer (Fig. 5(A)).

**Day-to-Day Variations: PM Events**

A total of 32 PM$_{10}$ episodes exceeding 100 µg/m$^3$ (daily mean) were identified at the Hankou urban background site. These episodes lasted a mean of 5 days per episode with a range of 1 to 21 days, but in most cases (25 out of 32) from 2 to 7 days. Most of these high episodes were caused by local or regional pollution, but at least in 13 of them there was also a clear contribution of dust transport from the Gobi desert (10 events in March–June). Moreover, some events could be attributed to the contribution of biomass burning from SE Asia.

(a) Local/Regional Pollution versus Low PM$_{10}$ Episodes

In winter, the concatenation of high and low PM$_{10}$ episodes was mainly caused by the alternation between high pressure systems over China (Fig. 5) and strong winds prompted by southward transport of air masses. Thus, within the period 1st to 17th of January 2004 (Fig. 6), the anticyclone located over Central China (Fig. 6(A)) resulted in a strong inversion layer near the ground (Fig. 6(D)) and in high PM$_{10}$ and NO$_2$ concentrations from the 2nd to the 6th of January 2004 (Fig. 6(C)). From 8th to 11th a NE advection resulted in clean air conditions over the city (Fig. 6(E)). In summer, low PM$_{10}$ levels were mostly induced by the entry of southern depressions over Central China resulting in the heavy rainfall typical of the monsoon season. A large number of these depressions reached central China from the warm sea in the south before moving away towards the east. The summer PM$_{10}$ events usually occurred between two consecutive rainy episodes, whereas other PM$_{10}$ events were reinforced by high pressures over this part of the continent.

(b) Asian Dust Events

Mineral dust events were mostly induced by strong north-west winds over the Gobi desert. In most cases, these winds resulted from a strong gradient pressure between the North-Asian anticyclone (displaced toward western China) and a depression at the NE of this anticyclone. The event on March 29–30th is a typical case (Fig. 7). As observed in the NAAP model simulations, these scenarios result in a transport of dust towards central and NE China. Fig. 7 also highlights the impact of these dust events in the daily mean
PM$_{10}$ time series at Wuhan during March and May 2004.

During strong Asian dust events, the NAAPs model often forecasts mineral dust concentrations between 100 and 600µg/m$^3$ in TSP, the PM$_{10}$ levels at Wuhan being between 150 and 300 µg/m$^3$.

The impact of these natural contributions on daily PM levels is evidenced in Fig. 7. However, their magnitude cannot be easily quantified based on local PM data, given that natural (mineral) dust contributions are added onto local anthropogenic contributions. In Southern Europe, where African dust outbreaks are frequently registered, this issue is solved by applying a methodology based on

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**Fig. 5.** (A) PM$_{10}$ daily means at the two monitoring sites of Wuhan. (B–C) Meteorological parameters. (D) Number of days with air back-trajectories proceeding from several sectors. (E–F) Mean 1000 hPa geopotential charts for autumn-winter (Sept. 2003–Feb. 2004) and summer (Jun.–Sep. 2004).

**Fig. 6.** 1000 hPa charts, daily mean PM$_{10}$ and NO$_2$ levels and vertical profiles of temperature showing the scenarios of local-urban (2–6 of Dec. 2004) and clean air (7–10 of Dec. 2004) episodes.
the comparison of simultaneous PM levels at urban and regional background locations during days with African dust contributions (Escudero et al., 2007). Because of the limited regional background data available in this study, it is not possible to perform this kind of analysis and therefore only an approximate estimate of the natural dust contributions is presented.

Days under the influence of dust outbreaks were identified by means of back-trajectory and aerosol map analysis, and PM$_{10}$ levels and increments were then evaluated for these days. During the study period, the influence of mineral dust (mainly from the Taklimakan desert, West of Gobi) was registered on average on 20% of the days/year (a total of 82 days), and mean daily PM$_{10}$ levels were on average 60–70 µg/m$^3$ higher during these days than during days when no dust outbreaks were detected (daily mean of 190–200 µg/m$^3$ during days with dust outbreaks vs. 120–140 µg/m$^3$ during days without dust outbreaks, for both monitoring sites). As a result, it may be concluded that natural dust contributions are an important source of PM$_{10}$ aerosols in Wuhan during dust outbreaks, which are also a relatively frequent phenomenon in the area. Therefore, this type of natural contributions should be taken into account for the evaluation of air quality in the area, the application of daily or annual limit values and the potential assessment of the data from an epidemiological point of view.

(c) Biomass Burning Events

Contributions from regional-scale open burning of biomass were also identified in three of the 32 high PM$_{10}$ events. Open fires (agricultural residues, natural wildfires and/or open-air cooking, among others) are frequent in South-eastern Asia and they may have a high impact on ambient air PM levels in Southern and Middle China. These emissions also have a high impact on visibility (Husar et al., 2000; Deng et al., 2008). These events were relatively scarce during the study period, thus making it difficult to assess their impact on PM levels. However, back-trajectory interpretations using Hysplit model coupled with NAAPS aerosol maps (Fig. 8) allowed us to detect biomass burning contributions from the south to PM$_{10}$ levels at Wuhan for

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**Fig. 7.** Daily mean PM$_{10}$ levels at the two monitoring sites of Wuhan, backtrajectories and synoptic chart and NAAP model simulation for the Asian dust events on 29 and 30 of March 2004.

**Fig. 8.** Smoke transport (due to biomass burning) from South Asia to Central China. Hysplit back trajectories, NAAPS maps of surface smoke and daily PM$_{10}$ levels at both monitoring sites.
the 10th March 2004. During this day ~200 µg/m³ of PM$_{10}$ were recorded at Wuhan, the contribution of smoke being estimated at ~60 µg/m³ of PM$_{10}$ according to NAAPs simulations. These episodes may influence PM levels and composition on approximately 10% of the peak PM episodes, on average, based on the data from the study period.

CONCLUSIONS

Levels of PM$_{10}$ at Wuhan (annual means of 130 to 160 µg/m³ across the city) were much higher than those typically recorded in Europe or the US, but within the ranges of typical concentrations in other Chinese cities. The comparison of real time automatic PM$_{10}$ measurements with standard gravimetric measurements allowed the establishment of a correction method for the automatic measurements following European guidelines, and revealed that the automatic PM$_{10}$ measurements were underestimated by 26–38%. These corrected PM$_{10}$ values can therefore be compared to other measurements around the world.

The PM sources across the city are widely dispersed. This fact together with the influence of the prevailing meteorology resulted in relatively homogeneous PM concentrations across the city, as shown by the high correlation ($r^2 = 0.76$) between PM$_{10}$ concentrations at the two sampling sites within the city. The variability and ratios between PM$_{10}$, NO$_2$ and SO$_2$ are clearly influenced by the industrial and the urban sources. Moreover, there is a high regional background of PM$_{10}$, as evidenced by the high PM$_{10}$ concentrations recorded at the rural site (72 to 159 µg/m³), which can be influenced by the Wuhan pollution plume.

Regarding PM$_{10}$ temporal variability, meteorology exerts a significant influence, both seasonally and on a daily basis. Higher winter PM$_{10}$ concentrations are favoured by northern-dry subsidence conditions that hinder the dilution and dispersion of pollutants (with the frequent formation of an inversion layer near the ground), whereas the lower summer PM$_{10}$ levels are linked to the arrival of southern moist air masses typical of the monsoon season. In addition to the local urban-industrial sources, mineral dust transported from the Gobi desert and carbonaceous aerosols derived from open biomass burning resulted in high PM$_{10}$ episodes. Mineral dust episodes were registered on 20% of the days during the study period, and resulted in PM$_{10}$ increments of approximately 60–70 µg/m³ on the daily means. Biomass burning episodes were more scarce (10% of the peak PM episodes), with estimated contributions of approx. 60 µg/m³ (according to model simulations).

Our results evidence that detailed knowledge of PM episodes and sources may be obtained by means of relatively straightforward and economic routine measurements generally available at air quality monitoring networks, which can be extremely useful to obtain information for air quality policy design.

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REFERENCES


in PM$_{2.5}$ and PM$_{10}$ Aerosols in Hong Kong. Atmos. Environ. 37: 31–39.


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