Spatial and temporal variations of the concentrations of PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ in China

Y. Q. Wang$^1$, X. Y. Zhang$^1$, J. Y. Sun$^1$, X. C. Zhang$^2$, H. Z. Che$^1$, and Y. Li$^1$

$^1$Laboratory of Atmospheric Chemistry, Chinese Academy of Meteorological Sciences, Beijing, China
$^2$Meteorological Observation Center, Beijing, China

Received: 26 March 2015 – Accepted: 25 April 2015 – Published: 8 June 2015

Correspondence to: Y. Q. Wang (yaqiang.wang@gmail.com)

Published by Copernicus Publications on behalf of the European Geosciences Union.
Abstract

Concentrations of PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ were monitored at 24 stations of CAWNET (China Atmosphere Watch Network) from 2006 to 2014 using GRIMM 180 dust monitors. The highest particulate matter (PM) concentrations were observed at the stations of Xian, Zhengzhou and Gucheng, in Guanzhong and the Hua Bei Plain (HBP). The second highest PM concentrations were observed in northeast China, followed by southern China. According to the latest air quality standards of China, 14 stations reached the PM$_{10}$ standard and only 7 stations, mainly rural and remote stations, reached the PM$_{2.5}$ standard. The PM$_{2.5}$ and PM$_{10}$ ratios showed a clear increasing trend from northern to southern China, because of the substantial contribution of coarse mineral aerosol in northern China. The PM$_{1}$ and PM$_{2.5}$ ratios were higher than 80% at most stations. PM concentrations tended to be highest in winter and lowest in summer at most stations, and mineral dust impacts influenced the results in spring. A decreasing interannual trend was observed in the HBP and southern China from 2006 to 2014, but an increasing trend occurred at some stations in northeast China. Also diurnal variations of PM concentrations and meteorological factors effects were investigated.

1 Introduction

Tropospheric aerosols are important because of their strong influence on the climate system through both direct and indirect effects. These include the direct effect of scattering and absorbing radiant energy and the indirect effect of modifying the microphysical properties of clouds, and hence their radiative properties and lifetime (Haywood and Boucher, 2000). They also attract attention because of their effects on visibility impairment (Watson, 2002) and human health (Delfino et al., 2005; Pope III and Dockery, 2006). Therefore, the spatial and temporal variation of aerosols is essential to
understand, but remains a complex subject because of the relatively short lifetime and complexity of aerosol physical and chemical properties (Ramanathan et al., 2001).

Particle size is considered a key parameter to define the impact of particulate matter (PM) on human health; fine PM (PM_{2.5} and PM_{1}) poses a greater health risk than coarse PM (PM_{10}) (Oberdörster et al., 2005). There have been numerous network-based observation studies of the PM_{2.5} concentration and chemical composition in North America and Europe. For example, based on a dataset across 19 Canadian sites, most of the PM_{2.5} concentrations were found to be below 26 \mu gm^{-3}, and PM_{2.5} accounted for 49% of the measured PM_{10} (Brook et al., 1997). PM_{2.5} and PM_{10} particle concentrations measured at 42 sites in the Interagency Monitoring of Protected Visual Environments (IMPROVE) network over the 1993 seasonal year (March 1993 to February 1994) showed the PM_{2.5} concentration had a large gradient from west to east in the US, averaging 3 \mu gm^{-3} in most of the west compared with 13 \mu gm^{-3} in the Appalachian region (Eldred et al., 1997). Another study based on 143 sites of IMPROVE in the year 2001 showed that sulfates, carbon and crustal material were responsible for most of the measured PM_{2.5} at the majority of sites in the US (Malm et al., 2004). The temporal variation and spatial distribution of PM_{2.5} concentrations have also been reported in Switzerland (Gehrig and Buchmann, 2003), Austria (Gomiscek et al., 2004) and six central and eastern European countries (Houthuijs et al., 2001).

As a country with a rapidly developing economy, China has suffered from a serious air pollution problem in recent years due to substantial increases in energy consumption and other related production of large amounts of aerosols and precursor gas emissions (Zhang et al., 2009). The spatial distribution and interannual variation of PM_{10} concentrations was studied using a dataset accumulated from 86 Chinese cites (Qu et al., 2010). The chemical compositions of PM_{10} samples were investigated at 16 sites over China, and the result indicated a dominant scattering feature of aerosols in China (Zhang et al., 2012). Existing studies of network PM_{2.5} observations have been limited to certain seasons in a single year (Cao et al., 2012), and most other research
has focused on one or more of the largest cities (He et al., 2001; Wang et al., 2002, 2006; Wei et al., 1999; Yao et al., 2002; Zhao et al., 2009; Zheng et al., 2005).

The heavy haze problem encourages the Chinese government to pay more attention to PM$_{2.5}$ monitoring and air quality standards. The Ministry of Environmental Protection of China issued new ambient air quality standards in 2012, among which the PM$_{2.5}$ concentration was the first to be included. Subsequently, construction of a national environmental PM$_{2.5}$ monitoring station network began in 2013.

In this paper, we firstly present a long-term PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ monitoring dataset from 2006 to 2014, based on 24 stations of CAWNET (China Atmosphere Watch Network), operated by the China Meteorological Administration (CMA). The spatial pattern of average PM concentration levels and the relationships among them are reported. In addition, their seasonal, interannual and diurnal variations and meteorological factors effects are presented.

2 The near real-time PM dataset

The PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ concentrations were monitored at 24 stations of CAWNET from 2006 to 2014 using GRIMM dust monitor EDM 180 instruments with 31 different size channels at a flow rate of 1.2 L min$^{-1}$. The instrument was designed to measure particle size distribution and particulate mass, based on a light scattering measurement of individual particles in the sampled air. GRIMM developed protocols were used to convert the measured size number distribution to a mass concentration consistent with U.S. Environmental Protection Agency protocols for measuring particulate matter based on aerodynamic diameter. A Nafion dryer was equipped at the inlet to exclude fine particulate water, but the nonvolatile and semi-volatile components are included in the measurement result (Grimm and Eatough, 2009). The GRIMM instruments were calibrated annually using a calibration tower that permitted powder injection (on demand) of aerosol particles in a wide size range of 0.2–30 µm. The operation was fully computer controlled and permitted access to one to three spectrometers in comparison
to one reference “mother unit”. The 5 min averaged PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ concentrations were recorded at each station and transported to the CMA information center hourly in near real-time.

The PM concentration data results from GRIMM instrument were compared to the results from tapered element oscillating microbalances (TEOM) instrument in some studies (Grimm and Eatough, 2009; Hansen et al., 2010). The instruments were in good agreement, e.g. linear regression of the Grimm vs. the FDMS TEOM data in Rubidoux yielded a slope of 1.10 $\pm$ 0.05 with an intercept of $-3.9 \pm 4.2 \ \mu g m^{-3}$, and the uncertainty was 9.9 % (Grimm and Eatough, 2009).

The 24 PM observation stations are described in Table 1, and a map of their distribution is given in Fig. 1. Most stations were located in East China, an area of high population density and fast economic development; therefore, PM emitted from human activities was mainly recorded. The stations were classified as urban/suburban, rural and remote stations according to their location. Unlike rural stations, remote stations were located in areas far away from regions of strong anthropogenic emissions, and thus natural emissions and long-range transport of anthropogenic air pollution were the main sources of PM at these stations.

3 Results and discussion

3.1 Average PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ levels in China

The averaged PM concentration values are presented in Table 2. A distribution bar chart map of the averaged PM concentrations is presented in Fig. 2. The highest PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ concentrations were observed at the stations of Xian (135.4, 93.6 and 77.0 $\mu g m^{-3}$, respectively), Zhengzhou (131.7, 84.8 and 71.0 $\mu g m^{-3}$, respectively) and Gucheng (127.8, 89.7 and 79.4 $\mu g m^{-3}$, respectively), which are located in the most polluted areas of the Hua Bei Plain (HBP) and Guanzhong Plain. Although Gucheng is a suburban site, it is located in the rapidly urbanizing area around Beijing, and is
therefore subject to associated large quantities of air pollution emissions. These areas were also identified by Zhang et al. (2012) as Region II with similar visibility change and large visibility loss in the past 40 years. The stations all recorded very high coarse and fine PM concentrations, implying high emissions of both primary emitted mineral particles and secondary formatted particles in these areas. Qingdao is a coastal city with relatively low PM concentrations compared with inland cities in the HBP.

The PM concentrations were also high in northeast China, which is an established industrial base area. The ensemble average values of the five urban stations of Ansan, Shenyang, Benxi, Fushun and Shiping were 88.8, 58.4 and 49.8 µg m\(^{-3}\), for PM\(_{10}\), PM\(_{2.5}\) and PM\(_1\) respectively. Dandong is a rural station with relatively low PM concentrations.

The similarity among the PM values for Chifeng, Erlianhaote and Yulin is due to their location, far from regions of intensive economic development, and is also strongly affected by sand and dust storms, given the stations are located adjacent to dust source areas. Thus, the average PM\(_{10}\) concentrations were much higher than the PM\(_{2.5}\) and PM\(_1\) concentrations at these sites. For example, the average PM concentrations were 88.0, 42.4 and 32.6 µg m\(^{-3}\) at Chifeng, which is surrounded by Horqin Sandy Land and Onqin Daga Sandy Land.

Chengdu, the capital of Sichuan Province, is located in the Sichuan Basin, which is also a highly polluted area with high aerosol optical depth and low visibility (Li et al., 2003; Luo et al., 2001; Zhang et al., 2012), due to the poor dispersion conditions and heavy local industrial emissions. The average PM\(_{10}\), PM\(_{2.5}\) and PM\(_1\) concentrations were 78.0, 59.5 and 52.7 µg m\(^{-3}\), respectively.

There are three stations in the South China area: Panyu, located in Guangzhou City, the capital of Guangdong Province, which is the center of the Pearl River Delta region; Nanning, the capital of Guangxi Province; and Guilin, a famous tourist city, also located in Guangxi Province. The ensemble average PM concentrations of the three sites were 55.8, 43.1 and 38.8 µg m\(^{-3}\) for PM\(_{10}\), PM\(_{2.5}\) and PM\(_1\), respectively.
Significant visibility loss and relatively high PM$_{10}$ concentrations have been observed over the middle and lower reaches of the Yangtze River after the 1980s due to the rapid economic development in the region (Qu et al., 2010; Zhang et al., 2012). Although there was no urban site available in this study to characterize the high PM concentrations in this region, the background conditions and temporal variance could be determined from the rural site data. Dongtan, near Shanghai City, is located on Chongming Island with low PM concentrations (31.9, 27.4 and 24.8 µg m$^{-3}$ for PM$_{10}$, PM$_{2.5}$ and PM$_{1}$, respectively) due to the substantial influence of clean sea air mass. The ensemble average PM concentrations of Lushan, Changde and Jinsha were 44.3, 37.2 and 33.6 µg m$^{-3}$ for PM$_{10}$, PM$_{2.5}$ and PM$_{1}$, respectively.

Lhasa, the capital of Tibet Autonomous Region, is located in the center of the Tibetan Plateau at a very high altitude of 3663 m. The PM$_{2.5}$ and PM$_{1}$ concentrations in Lhasa were low, with average values of 14.0 and 9.6 µg m$^{-3}$, respectively, because of its relatively small population and few industrial emissions. However, the average PM$_{10}$ concentration was 37.7 µg m$^{-3}$, mainly due to the high amounts of fugitive dust from dry and bare land and the impacts of regional dust storm events (Chen et al., 2013). As a result, minerals represent the major component of aerosol samples in this area (Zhang et al., 2012).

The lowest PM concentration values were observed in the two remote sites of Akadala and Shangri-La. The lower altitude and stronger contribution of soil dust at Akadala (Qu et al., 2009), located in a dry region, leads to higher PM concentrations than at the Shangri-La site.

According to the latest air quality standards of China (annual averaged PM$_{10}$ and PM$_{2.5}$ concentrations of 70 and 35 µg m$^{-3}$), 14 stations reached the PM$_{10}$ standard and only 7 stations, mainly rural and remote stations, reached the PM$_{2.5}$ standard. The ratio of substandard (daily averaged PM$_{10}$ or PM$_{2.5}$ concentrations that exceed the standard values) days to total observation days at each station was calculated using the standard daily averaged PM$_{10}$ and PM$_{2.5}$ concentrations of 150 and 75 µg m$^{-3}$ (Table 2). Substandard days of PM$_{10}$ and PM$_{2.5}$ represented more than 30 and 50 % of
Spatial and temporal variations of the concentrations of PM\(_{10}\), PM\(_{2.5}\) and PM\(_{1}\) in China

Y. Q. Wang et al.

3.2 Relationships between PM\(_{10}\), PM\(_{2.5}\) and PM\(_{1}\) concentrations

The squared correlation coefficient ($R^2$) values of the linear fit between PM\(_{10}\) and PM\(_{2.5}\) and between PM\(_{1}\) and PM\(_{2.5}\) are given in Table 2. Higher values indicate that two PM size bins may have more identical-source characteristics. At most stations, the $R^2$ values between PM\(_{1}\) and PM\(_{2.5}\) were higher than the values between PM\(_{2.5}\) and PM\(_{10}\), because PM\(_{1}\) and PM\(_{2.5}\) both belong to fine particle size bins, which are normally...
emitted from the same sources. For example, the $R^2$ values were 0.7857 between PM$_{2.5}$ and PM$_{10}$, and 0.9689 between PM$_1$ and PM$_{2.5}$, at Gucheng (Fig. 3). Correlation coefficient analysis is sensitive to outliers, and thus sand storm events may impact the result considerably, due to abnormally high concentration values. There were four strong dust storm event days at Akdala in 2012, on 21 April and 22, and 9 May and 20, which resulted in the four outlier points shown in Fig. 4a, and the low $R^2$ value of 0.5346 between PM$_1$ and PM$_{2.5}$. The value increased to 0.9406 when the four outlier points were removed (Fig. 4b). Similar results were also observed at Yulin and Erlianhaote around dust storm source regions (Table 2).

The average values of the daily PM$_{2.5}$/PM$_{10}$ and PM$_1$/PM$_{2.5}$ ratios are listed in Table 2. The spatial distribution map of the average PM$_{2.5}$/PM$_{10}$ ratios (Fig. 5) shows lower ratio values in northern China, influenced by Asian sand and dust storms (Wang et al., 2008; Zhang et al., 2003). The values were also influenced by fugitive dust due to the low precipitation amounts in northern China, especially at Lhasa, Erlianhaote, Yulin and Chifeng, with ratio values of less than 0.6. The ratio values at the stations in northeast China were between 0.6 and 0.7, except at Dandong where the value was 0.71. The values were also low at Zhengzhou and Akdala, at 0.68 and 0.67, respectively. The highest ratio value was 0.9 at Dongtan, and the other stations with ratio values higher than 0.8 were Chengdu, Changde, Guilin, Jinsha and Lushan. The values were between 0.7 and 0.8 at other stations. The PM$_1$/PM$_{2.5}$ ratios showed a similar spatial distribution, but the values were higher than PM$_{2.5}$/PM$_{10}$. The lowest ratio value of 0.6 was also observed at Lhasa, and the values at most stations in southern China were greater than or equal to 0.9.

### 3.3 Seasonal variations

The seasonal variations of PM$_{10}$ concentrations (Fig. 6a) show that winter and spring were the most polluted seasons at all sites except Lushan, where the highest value was observed in autumn. This result is consistent with a previous study of PM$_{10}$ variation.
across China from 2000 to 2006 (Qu et al., 2010). The higher winter concentrations were caused by higher emissions during the cold season from heating, and more stagnant weather conditions with a lower planetary boundary layer. The opposite conditions and more precipitation due to the summer monsoon resulted in the lowest PM$_{10}$ concentration values in summer. Spring is the dust storm season in East Asia (Qian et al., 2004; Wang et al., 2008; Zhou and Zhang, 2003), which leads to high PM$_{10}$ concentrations in dust source regions and downwind areas in northern China. For example, the PM$_{10}$ concentrations in spring were much higher than other seasons at the dust source sites of Yulin and Erlianhaote.

For PM$_{2.5}$, winter was still the most polluted season at most sites, while the contribution of spring decreased substantially in northern China (Fig. 6b). This trend can be further observed from the PM$_{1}$ distribution (Fig. 6c); hence, the average PM$_{1}$ concentration of spring was lowest at Yulin, Xian, Zhengzhou, Gucheng and Benxi. The seasonal variation patterns were very similar for PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ at the sites in southern China.

A spatial distribution map of the seasonal average PM$_{2.5}$/PM$_{10}$ ratios is given in Fig. 6d. For the reasons given above, lower PM$_{2.5}$/PM$_{10}$ ratios were observed in spring at the northern China sites, while the seasonal variation was not significant at the southern China sites.

### 3.4 Interannual variations

The interannual variations of PM$_{2.5}$ at various stations are presented in Fig. 7. Significant decreasing trends were observed at the HBP stations of Zhengzhou and Gucheng (Fig. 7a). The annual averaged PM$_{2.5}$ concentrations decreased from 123.4 to 65.2 µg m$^{-3}$ at Zhengzhou, and from 101.0 to 69.1 µg m$^{-3}$ at Gucheng, during 2006–2014. At Zhengzhou, the lowest value of 63.7 µg m$^{-3}$ occurred in 2012, and this level was maintained in subsequent years; however, at Gucheng, the value increased suddenly in 2012 to 95.1 µg m$^{-3}$ and then declined rapidly during 2013 and 2014. At Xian,
the annual averaged PM$_{2.5}$ concentrations decreased from 2006 to 2009, increased until 2011, and then decreased again until 2014 (Fig. 7a).

For the stations in northeast China, a significant increasing trend of PM$_{2.5}$ concentrations was observed at Shenyang and Benxi from 2006 to 2013, followed by a decrease in 2014 (Fig. 7b). The peak value at Shenyang was especially high in 2013 at 123.1 µgm$^{-3}$, while the values were less than 60 µgm$^{-3}$ in the other years. The highest values were observed in 2009 at Anshan and Dandong, but the lowest value was in 2014 at Anshan and 2010 at Dandong. A general decreasing trend was observed at Siping, with a few fluctuations. At Fushun, the value decreased from 2006 to 2011 and then increased to 2013, followed by a slight decrease in 2014.

For the stations along the middle and lower reaches of the Yangtze River, a common trend was a clearly lower PM$_{2.5}$ value in 2014 than in 2013, but the general variation trend was not significant (Fig. 7c). A peak value of 33.7 µgm$^{-3}$ was observed in 2012 at Dongtan, followed by a decrease to 24.12 µgm$^{-3}$ over the subsequent two years. At Jinsha and Changde, the highest value was in 2013, while it was in 2009 at Lushan.

For the stations in southern China, a general decreasing trend was observed, with obvious fluctuations (Fig. 7d). Panyu is a typical station in the centre of the Pearl River Delta economic area of China. The PM$_{2.5}$ value decreased from 64.6 µgm$^{-3}$ in 2006 to 41.6 µgm$^{-3}$ in 2014, and the lowest value was 36.4 µgm$^{-3}$ in 2010. A similar trend was observed in Gulin, with a stronger fluctuation from 2010 to 2012. At Nanning, a peak value occurred in 2010 and the lowest value of 28.5 µgm$^{-3}$ was observed in 2012.

The general observations of the PM$_{10}$ and PM$_{1}$ interannual variation trend were similar to the PM$_{2.5}$ at most stations. For example, a similar trend and fluctuations were observed at the stations presented in Figs. 8 and 7a. A difference in the trend was observed at Zhengzhou from 2013 to 2014, with a significant increasing trend of PM$_{10}$ and decreasing trend of PM$_{1}$. 
3.5 Diurnal variations

The average diurnal variations of PM$_{2.5}$ at various stations are presented in Fig. 9. Pronounced diurnal variations of PM$_{2.5}$ were observed in most urban sites with obvious morning peak around 7:00 to 8:00 a.m. and afternoon valley between 2:00 and 4:00 p.m. At some stations, evening peak can be recognized around 7:00 to 9:00 p.m. (Siping, Benxi, Fushun, Anshan, Guilin and Panyu) or midnight (Gucheng, Xian). This bimodal pattern was also observed in Beijing city (Zhao et al., 2009). The unimodal pattern without evening peak can be identified at some other stations (Zhengzhou, Shenyang and Nanning). In urban areas, the morning and evening peaks are contributed by enhanced anthropogenic activity during rush hour, and the afternoon valley is mainly due to higher atmospheric mixing layer which is benefit for air pollution diffusion. Panyu station is on top of a 140 m hill at the edge of Guangzhou city, so aged and mixing aerosols were observed with weakly urban diurnal variation pattern. Similar with Panyu station, the rural stations along the middle and lower reaches of the Yangtze River have no typical urban diurnal variation pattern (Fig. 9c).

3.6 Meteorological influences

Central-eastern China experienced severe haze events in January 2013 with regional stable planetary boundary layer and low mixing height (Wang et al., 2014). The daily averaged PM$_{2.5}$ concentrations and the meteorological factors of wind speed and relative humidity data in this period at Zhengzhou, Shenyang and Nanning were plotted in Fig. 10. Zhengzhou is located in this haze region with very high PM$_{2.5}$ concentrations especially from 6 to 15 January. The wind speed variation was negative related with PM$_{2.5}$ concentrations. The rapid increasing of PM$_{2.5}$ concentrations from 1 to 6 January was corresponding with the rapid decreasing of wind speed at same period. Also the big wind speed in 24 January resulted in low PM$_{2.5}$ concentration. Shenyang and Nanning are not located in this severe haze region, but still suffered some fine particle pollutant days in this month. The negative correlation between PM$_{2.5}$ and wind speed
were also observed at Shenyang and Nanning. In general, relative humidity (RH) variation was positive related with PM$_{2.5}$ concentrations if no precipitation occurred. Otherwise the high RH with precipitation correspondences low PM concentrations due to wet deposition.

For interannual variation, the negative correlation between PM$_{2.5}$ concentrations and wind speed and positive correlation between PM$_{2.5}$ concentrations and relative humidity cannot be well identified (Fig. 11). It reveals the emission variation possibly dominates the long-term PM concentration trend; meanwhile meteorological factors play a leading role during a short period.

4 Conclusions

Spatial and temporal trends in PM pollution were examined using PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ concentration data at 24 stations from 2006 to 2014. Relatively high PM concentrations were observed at most stations. There were 14 stations that reached the PM$_{10}$ annual air quality standard, but only 7 stations, mostly rural and remote stations, reached the PM$_{2.5}$ annual air quality standard of China. The highest PM concentrations were observed at the stations in the HBP and Guanzhong Plain. In addition, the percentage value of substandard days of PM$_{2.5}$ was greater than 50%, indicating very serious air pollution in these regions. PM pollutants are also a serious problem in the industrial regions of northeast China and the Sichuan basin. The PM concentrations were relatively lower in the southern areas of China, but the averaged PM$_{2.5}$ concentration was still higher than the national standard.

As they are both fine particles, PM$_{1}$ and PM$_{2.5}$ were more correlated than PM$_{2.5}$ and PM$_{10}$. The correlations were sensitive to the effect of outlier data at those stations heavily impacted by dust storm events. More dust aerosol was observed in northern China, and thus the PM$_{2.5}$/PM$_{10}$ ratios increased from less than 0.6 to around 0.9 when moving from north to south China.
Pronounced seasonal variations were observed at most stations, with the highest concentrations in winter and lowest concentrations in summer. PM$_{10}$ concentrations were also high in spring, due to the contribution of dust storm events, especially at those stations near to dust source regions. For PM$_{2.5}$ and PM$_{1}$, spring was a relatively low concentration season, especially at the stations in northern China. Also, low PM$_{2.5}$/PM$_{10}$ ratios were observed in spring in northern China.

An interannual decreasing trend was observed in the HBP and southern China from 2006 to 2014, but an increasing trend occurred at some stations in northeast China, and no significant trend could be found over the middle and lower reaches of the Yangtze River. Annual-averaged PM concentrations were lower in 2014 than 2013 at most stations, which may indicate an improvement in air quality following the “Action Plan for the Control of Air Pollution” document issued by the Chinese government in September 2013.

Bimodal and unimodal diurnal variation patterns were identified at urban stations. The negative correlation between PM concentrations and wind speed was found in a short period, but emission variation must to be considered for long-term trend analysis especially in rapid developing countries.

This network observation dataset provides the longest continuous record of fine particle concentrations in China, but it features a limited number of stations and an uneven spatial distribution. Importantly, there is no representative city site in the Yangtze River delta region, which is considered an important haze area in China. The emission sources and meteorological factors influencing PM spatial and temporal patterns in China still require further study.

Acknowledgements. This work was supported by grants from the National Key Project of Basic Research (2014CB441201), the National Natural Science Foundation of China (41275167) and the Chinese Academy of Meteorological Sciences (2013Z007). It was also supported by the Climate Change Collaborative Innovation Center and the CMA Innovation Team of Haze-fog Observation and Forecasts.
References

Brook, J. R., Dann, T. F., and Burnett, R. T.: The relationship among TSP, PM$_{10}$, PM$_{2.5}$, and inorganic constituents of atmospheric particulate matter at multiple Canadian locations, J. Air Waste Manage. Assoc., 47, 2–19, 1997.


### Table 1. Description of the PM stations.

<table>
<thead>
<tr>
<th>Stations</th>
<th>Latitude (° N)</th>
<th>Longitude (° E)</th>
<th>Altitude (m)</th>
<th>Start Time</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zhengzhou</td>
<td>34.78</td>
<td>113.68</td>
<td>99.0</td>
<td>1/2006</td>
<td>Urban, in the center of Zhengzhou city, 56 m building.</td>
</tr>
<tr>
<td>Chengdu</td>
<td>30.65</td>
<td>104.04</td>
<td>496.0</td>
<td>3/2006</td>
<td>Urban, in the center of Chengdu city, 91 m building.</td>
</tr>
<tr>
<td>Xian</td>
<td>34.43</td>
<td>108.97</td>
<td>363.0</td>
<td>1/2006</td>
<td>Urban, in northern margin of Xian city, 20 km north of center of Xian city, 4 m sampling container.</td>
</tr>
<tr>
<td>Nanning</td>
<td>22.82</td>
<td>106.35</td>
<td>84.0</td>
<td>1/2006</td>
<td>Urban, in Nanning city, 140 m hill.</td>
</tr>
<tr>
<td>Anshan</td>
<td>41.05</td>
<td>123.00</td>
<td>78.3</td>
<td>10/2007</td>
<td>Urban, in Anshan city, 10 m building.</td>
</tr>
<tr>
<td>Shenyang</td>
<td>41.76</td>
<td>123.41</td>
<td>110.0</td>
<td>10/2007</td>
<td>Urban, in Shenyang city, 15 m building.</td>
</tr>
<tr>
<td>Benxi</td>
<td>41.19</td>
<td>123.47</td>
<td>185.4</td>
<td>10/2007</td>
<td>Urban, in Benxi city, 12 m building.</td>
</tr>
<tr>
<td>Fushun</td>
<td>41.88</td>
<td>123.95</td>
<td>163.0</td>
<td>10/2007</td>
<td>Urban, in Fushun city, 10 m building.</td>
</tr>
<tr>
<td>Qingdao</td>
<td>36.07</td>
<td>120.33</td>
<td>77.2</td>
<td>3/2007</td>
<td>Urban, in Qingdao city, top of Fulongshan hill.</td>
</tr>
<tr>
<td>Lhasa</td>
<td>29.67</td>
<td>91.13</td>
<td>3630.0</td>
<td>1/2006</td>
<td>Urban, in Lhasa city, 7 m building.</td>
</tr>
<tr>
<td>Siping</td>
<td>43.18</td>
<td>124.33</td>
<td>165.4</td>
<td>3/2007</td>
<td>Urban, in Siping city, 4 m sampling container.</td>
</tr>
<tr>
<td>Panyu</td>
<td>23.00</td>
<td>113.35</td>
<td>5.0</td>
<td>1/2006</td>
<td>Suburban, in Panyu district of Guangzhou city, 140 m hill.</td>
</tr>
<tr>
<td>Gucheng</td>
<td>39.13</td>
<td>115.80</td>
<td>5.2</td>
<td>1/2006</td>
<td>Suburban, 38 km southwest of Baoding city, within area of rapid urbanization, 8 m building.</td>
</tr>
<tr>
<td>Chifeng</td>
<td>42.27</td>
<td>118.97</td>
<td>568.0</td>
<td>3/2007</td>
<td>Rural, suburbs of Chifeng city, 4 m sampling container.</td>
</tr>
<tr>
<td>Dandong</td>
<td>40.05</td>
<td>124.33</td>
<td>13.9</td>
<td>3/2007</td>
<td>Rural, suburbs of Dandong city, 4 m sampling container.</td>
</tr>
<tr>
<td>Erlainhaote</td>
<td>43.65</td>
<td>111.97</td>
<td>965.9</td>
<td>3/2007</td>
<td>Rural, suburbs of Erlainhaote city, 4 m sampling container.</td>
</tr>
<tr>
<td>Yulin</td>
<td>38.43</td>
<td>109.20</td>
<td>1135.0</td>
<td>1/2006</td>
<td>Rural, 10 km north of Yulin city, at the southeastern edge of Mu Us desert.</td>
</tr>
<tr>
<td>Jinsa</td>
<td>29.63</td>
<td>114.20</td>
<td>416.0</td>
<td>4/2006</td>
<td>Rural, 105 km north of Wuhan city, 8 m building.</td>
</tr>
<tr>
<td>Gulin</td>
<td>25.32</td>
<td>110.30</td>
<td>164.4</td>
<td>1/2006</td>
<td>Rural, north margin of Gulin city, meteorological observation field.</td>
</tr>
<tr>
<td>Lushan</td>
<td>29.57</td>
<td>115.99</td>
<td>1165.0</td>
<td>1/2006</td>
<td>Rural, Kunlun peak of Mount Lu.</td>
</tr>
<tr>
<td>Changde</td>
<td>29.17</td>
<td>111.71</td>
<td>563.0</td>
<td>1/2006</td>
<td>Rural, 18 km northwest from Changde city, 8 m building.</td>
</tr>
<tr>
<td>Dongtan</td>
<td>31.50</td>
<td>121.80</td>
<td>10.0</td>
<td>5/2009</td>
<td>Rural, east of Chongming island near Shanghai.</td>
</tr>
<tr>
<td>Akxala</td>
<td>47.12</td>
<td>87.97</td>
<td>562.0</td>
<td>3/2006</td>
<td>Remote, 55 km west of Fuhai county, 10 m building.</td>
</tr>
<tr>
<td>Shangri-La</td>
<td>28.02</td>
<td>99.73</td>
<td>3580.0</td>
<td>10/2006</td>
<td>Remote, 12 km northeast of Shangri-La county.</td>
</tr>
</tbody>
</table>
Table 2. Averaged PM\textsubscript{10}, PM\textsubscript{2.5} and PM\textsubscript{1} concentrations and their interrelationships at each station.

<table>
<thead>
<tr>
<th>Stations</th>
<th>Averaged PM concentrations (µg m\textsuperscript{-3})</th>
<th>SB ratio (PM\textsubscript{10})</th>
<th>SB ratio (PM\textsubscript{2.5})</th>
<th>PM\textsubscript{2.5}/PM\textsubscript{10}</th>
<th>PM\textsubscript{1}/PM\textsubscript{2.5}</th>
<th>R\textsuperscript{2} (PM\textsubscript{2.5} to PM\textsubscript{10})</th>
<th>R\textsuperscript{2} (PM\textsubscript{1} to PM\textsubscript{2.5})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zhengzhou</td>
<td>131.7 (84.4) 84.8 (47.4) 71.0 (40.5)</td>
<td>0.31</td>
<td>0.51</td>
<td>0.68</td>
<td>0.84</td>
<td>0.68</td>
<td>0.91</td>
</tr>
<tr>
<td>Chengdu</td>
<td>76.0 (75.2) 59.5 (42.2) 52.7 (35.4)</td>
<td>0.11</td>
<td>0.27</td>
<td>0.83</td>
<td>0.91</td>
<td>0.76</td>
<td>0.94</td>
</tr>
<tr>
<td>Xian</td>
<td>135.4 (97.3) 93.6 (67.3) 77.0 (55.6)</td>
<td>0.34</td>
<td>0.52</td>
<td>0.73</td>
<td>0.83</td>
<td>0.77</td>
<td>0.93</td>
</tr>
<tr>
<td>Nanning</td>
<td>51.2 (56.3) 38.4 (24.7) 34.9 (22.2)</td>
<td>0.01</td>
<td>0.08</td>
<td>0.77</td>
<td>0.91</td>
<td>0.52</td>
<td>0.97</td>
</tr>
<tr>
<td>Anshan</td>
<td>97.8 (62.9) 60.9 (42.9) 52.3 (39.0)</td>
<td>0.17</td>
<td>0.25</td>
<td>0.65</td>
<td>0.85</td>
<td>0.72</td>
<td>0.98</td>
</tr>
<tr>
<td>Shenyang</td>
<td>85.0 (58.2) 59.1 (42.7) 50.8 (36.7)</td>
<td>0.11</td>
<td>0.25</td>
<td>0.69</td>
<td>0.85</td>
<td>0.88</td>
<td>0.97</td>
</tr>
<tr>
<td>Benxi</td>
<td>97.6 (57.4) 66.7 (45.0) 54.8 (36.4)</td>
<td>0.13</td>
<td>0.30</td>
<td>0.69</td>
<td>0.82</td>
<td>0.81</td>
<td>0.94</td>
</tr>
<tr>
<td>Fushun</td>
<td>80.3 (54.2) 50.1 (31.7) 42.8 (28.3)</td>
<td>0.07</td>
<td>0.17</td>
<td>0.60</td>
<td>0.85</td>
<td>0.64</td>
<td>0.97</td>
</tr>
<tr>
<td>Qingdao</td>
<td>64.8 (52.1) 47.3 (34.0) 41.1 (30.5)</td>
<td>0.05</td>
<td>0.17</td>
<td>0.76</td>
<td>0.86</td>
<td>0.76</td>
<td>0.95</td>
</tr>
<tr>
<td>Lhasa</td>
<td>37.7 (30.8) 14.0 (10.7) 9.6 (8.6)</td>
<td>0.01</td>
<td>0.00</td>
<td>0.40</td>
<td>0.66</td>
<td>0.72</td>
<td>0.94</td>
</tr>
<tr>
<td>Panyu</td>
<td>58.7 (33.1) 44.5 (24.4) 39.7 (22.1)</td>
<td>0.02</td>
<td>0.12</td>
<td>0.77</td>
<td>0.89</td>
<td>0.95</td>
<td>0.98</td>
</tr>
<tr>
<td>Gucheng</td>
<td>127.8 (75.1) 89.7 (53.0) 79.4 (48.8)</td>
<td>0.31</td>
<td>0.54</td>
<td>0.71</td>
<td>0.87</td>
<td>0.79</td>
<td>0.97</td>
</tr>
<tr>
<td>Siping</td>
<td>83.3 (54.3) 55.4 (35.2) 48.5 (32.5)</td>
<td>0.10</td>
<td>0.22</td>
<td>0.68</td>
<td>0.86</td>
<td>0.71</td>
<td>0.96</td>
</tr>
<tr>
<td>Chiling</td>
<td>88.0 (66.9) 42.4 (33.1) 32.6 (27.8)</td>
<td>0.17</td>
<td>0.14</td>
<td>0.51</td>
<td>0.75</td>
<td>0.72</td>
<td>0.92</td>
</tr>
<tr>
<td>Dandong</td>
<td>66.8 (44.0) 45.6 (24.8) 39.3 (21.3)</td>
<td>0.03</td>
<td>0.11</td>
<td>0.71</td>
<td>0.86</td>
<td>0.64</td>
<td>0.90</td>
</tr>
<tr>
<td>Erlanhaote</td>
<td>49.1 (68.0) 22.0 (60.9) 15.9 (66.9)</td>
<td>0.03</td>
<td>0.03</td>
<td>0.51</td>
<td>0.72</td>
<td>0.71</td>
<td>0.91</td>
</tr>
<tr>
<td>Goling</td>
<td>49.1 (58.0) 22.0 (26.2) 15.9 (14.7)</td>
<td>0.03</td>
<td>0.03</td>
<td>0.51</td>
<td>0.72</td>
<td>0.71</td>
<td>0.91</td>
</tr>
<tr>
<td>Yulin</td>
<td>66.6 (67.1) 31.2 (21.0) 22.4 (15.9)</td>
<td>0.06</td>
<td>0.03</td>
<td>0.54</td>
<td>0.72</td>
<td>0.54</td>
<td>0.61</td>
</tr>
<tr>
<td>Jinshu</td>
<td>42.0 (38.6) 33.6 (24.1) 30.5 (21.9)</td>
<td>0.01</td>
<td>0.06</td>
<td>0.85</td>
<td>0.90</td>
<td>0.63</td>
<td>0.89</td>
</tr>
<tr>
<td>Guilin</td>
<td>57.6 (55.5) 46.5 (36.8) 41.7 (27.1)</td>
<td>0.04</td>
<td>0.15</td>
<td>0.85</td>
<td>0.90</td>
<td>0.70</td>
<td>0.96</td>
</tr>
<tr>
<td>Lushan</td>
<td>45.4 (32.7) 37.8 (27.9) 33.2 (26.7)</td>
<td>0.01</td>
<td>0.09</td>
<td>0.85</td>
<td>0.86</td>
<td>0.91</td>
<td>0.95</td>
</tr>
<tr>
<td>Changde</td>
<td>45.7 (33.8) 40.3 (29.1) 37.0 (27.5)</td>
<td>0.01</td>
<td>0.12</td>
<td>0.89</td>
<td>0.91</td>
<td>0.93</td>
<td>0.96</td>
</tr>
<tr>
<td>Dongtan</td>
<td>31.9 (34.0) 27.4 (25.9) 24.8 (23.8)</td>
<td>0.01</td>
<td>0.06</td>
<td>0.90</td>
<td>0.90</td>
<td>0.92</td>
<td>0.96</td>
</tr>
<tr>
<td>Akdala</td>
<td>17.1 (57.6) 9.8 (13.7) 7.7 (6.9)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.67</td>
<td>0.79</td>
<td>0.80</td>
<td>0.95</td>
</tr>
<tr>
<td>Shangri-La</td>
<td>6.8 (6.3) 5.2 (5.3) 4.5 (5.0)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.76</td>
<td>0.81</td>
<td>0.94</td>
<td>0.99</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Arithmetic mean value with standard deviation in parentheses.

\textsuperscript{b} The ratio of substandard days (daily averaged PM\textsubscript{10} or PM\textsubscript{2.5} concentrations that exceed the standard values) to total observation days.
Figure 1. Distribution of the PM observation stations used in this study.
Figure 2. Map showing bar charts of average PM$_{10}$, PM$_{2.5}$ and PM$_1$ concentration (µg m$^{-3}$) distributions at the observation stations.
Figure 3. Scatterplots of (a) PM$_{2.5}$ vs. PM$_{10}$ and (b) PM$_1$ vs. PM$_{2.5}$ at Gucheng.
Figure 4. Scatterplots of PM$_1$ vs. PM$_{2.5}$ (a) with and (b) without data from the strong sand and dust storm at Akdala.
Figure 5. Spatial distribution of the average ratios of PM$_{2.5}$/PM$_{10}$. 
Figure 6.
Figure 6. Spatial distribution of the seasonal average concentrations (µg m⁻³) of (a) PM₁₀, (b) PM₂.₅, (c) PM₁, and (d) ratios of PM₂.₅/PM₁₀.
Spatial and temporal variations of the concentrations of PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ in China

Y. Q. Wang et al.

Figure 7.
Figure 7. Interannual variations of PM$_{2.5}$ concentrations at (a) the stations in the HBP and Guanzhong Plain, (b) the stations in northeast China, (c) the stations along the middle and lower reaches of the Yangtze River, and (d) the stations in southern China.
Figure 8. Interannual variations of (a) PM$_{10}$ concentrations and (b) PM$_{1}$ concentrations at Zhengzhou, Xian and Gucheng.
Spatial and temporal variations of the concentrations of PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ in China

Y. Q. Wang et al.

Figure 9.

PM$_{2.5}$ concentration ($\mu$g m$^{-3}$)
Hour (Beijing time)
Figure 9. Diurnal variations of PM$_{2.5}$ concentrations at (a) the stations in the HBP and Guanzhong Plain, (b) the stations in northeast China, (c) the stations along the middle and lower reaches of the Yangtze River, and (d) the stations in southern China.
Spatial and temporal variations of the concentrations of PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ in China

Y. Q. Wang et al.

Figure 10.
Figure 10. Daily averaged PM$_{2.5}$ concentrations vs. wind speed and relative humidity data at Zhengzhou, Shenyang and Nanning in January 2013.
Figure 11.
Figure 11. Interannual variations of PM$_{10}$, PM$_{2.5}$ and PM$_{1}$ vs. wind speed and relative humidity at Zhengzhou and Nanning.