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Characteristics of visibility and particulate matter (PM) in an urban area of Northeast China

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ABSTRACT

The visibility data from 2010 to 2012 were obtained at Shenyang in Northeast China and the relations between visibility, PM mass concentration and meteorological variables were statistically analyzed. These results demonstrate that the monthly–averaged visibility over Shenyang was higher in March and September with values of approximately 19.0±4.3 km and 17.1±4.3 km, respectively. Low visibility over Shenyang occurred in January at approximately 11.0±4.7 km. Among the meteorological variables considered, wind speed was the main meteorological factor that influenced visibility and PM mass concentrations. The relation between visibility and PM indicates that fine particles are already a main source of pollutants, the existence of which is the most important factor in the deterioration of visibility in an urban area of Northeast China. The study also shows an obvious diurnal variation and weekend effects of visibility and PM, which are mainly caused by human activities. Results of this study highlight the significant impact of fine particles on air pollution and visibility in an urban area of Northeast China.

Keywords: *Visibility, particulate matter, Shenyang, Northeast China*

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1. Introduction

Visibility is defined as the greatest distance in a given direction at which an object can be visually identified with unaided eyesight (Wark et al., 1998). The impairment of visibility is primarily attributed to the scattering and absorption of visible light by suspended particles (Chan et al., 1999).

Fine particles, generally characterized as $PM_{2.5}$, are believed to be primarily responsible for the scattering of visible light and a cause of the degradation of visibility (Sloane et al., 1991). Fine particulate matter is the principal pollutant in most urban areas in China (Zhang et al., 2009; Zhang et al., 2013) and has acquired worldwide attention for its adverse impacts on visibility (Ghim et al., 2005) and public health (Hong et al., 2002).

Due to economic growth and increasing emissions in China, degradation of visibility has become an environmental issue of public concern in most metropolitan areas in China (Chang et al., 2009; Che et al., 2009). There were some studies about fine particle characteristic in sub–urban region of Northeast China (Zhang et al., 2008; Shen et al., 2011; Zhang et al., 2012a). However, there are few studies about fine particle characteristic in urban area of this region. As the capital of Liaoning Province and the largest city of Northeast China, Shenyang is a rapidly developing and industrialized city, and the air quality in Shenyang is a major environmental concern (Liu et al., 2010) for the public.

This study characterized the visibility from 2010 to 2012 and investigated the potential relation between visibility and relevant factors, including PM_{10}, $PM_{2.5}$ and $PM_{1.0}$, relative humidity (RH), temperature and wind speed. The primary objectives of this study are to (1) examine monthly and annual variations of PM and visibility in urban region of Northeast China, (2) confirm the relation between fine airborne particles (especially $PM_{1.0}$ which has not been mentioned in the most researches) and the deterioration of visibility in an urban region of Northeast China, (3) show that the information obtained in this study will allow evaluation of the changes in air quality in Shenyang and help to determine source emission control strategies for particulate matter reduction. Such data may also have a bearing on the model simulations. Accordingly, this study aimed not only to investigate the temporal and spatial variations of visibility in metropolitan Shenyang, but also to identify the main causes of visibility impairment by fine airborne particles.

2. Instruments and Data

A FD12 Visibility Automatic Observation Instrument and a GRIMM180 Particle Instrument at the Shenyang site were installed on the roof of the Northeast Regional Meteorological Observation Centre (E 123.50°, N 41.77°, 60 m). The instrument performance indicators are shown in Table 1. Daily and monthly mean values of visibility and PM were investigated using statistical analysis to characterize their properties. The data, including continuous hourly visibility, PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ data and meteorological variables

(RH, temperature, wind speed and precipitation) from 2010 to 2012, were collected at the Shenyang station. This station is located in the centre of the city which is frequently affected by the pollutants emitted by both industrial and residential activities. This site may be representative of the variations in visibility that are affected by the anthropogenic factors in the large cities of northeast China.

Table 1. *Performance parameters of FD12 and GRIMM180*

Instrument	GRIMM180 Particle Instrument	FD12 Visibility Instrument
Working Principle	90° laser scattering	33° Infrared forward scattering
Observation elements	Aerosol number concentration of 31 channels and mass concentration of PM_{10}, $PM_{2.5}$, $PM_{1.0}$	Visibility
Measuring time	1~60 min	15 s
Measuring range	Particle size distribution of 0.25~32 μm, Mass concentration of 1~1 500 μg m^{-3}	10~50 000 m
Accuracy	Range ±2%	10~10 000 m ±10%, 10 000~50 000 m±20%

3. Results and Discussion

3.1. Variations of monthly–averaged visibility and PM mass concentration

Figure 1a shows the variation of the monthly–averaged visibility over Shenyang. There are two peaks in the visibility distribution. The maximum visibility values over Shenyang occur in March and September with values of approximately 19.0±4.3 km and 17.1±4.3 km, respectively. The minimum visibility over Shenyang occurs in January at approximately 11.0±4.7 km. In contrast, there is an inverse correlation between AOD (aerosol optical depth) and visibility. As Figure 1b shows, high AOD occurs in February and July with values of approximately 1.0±0.4 and 1.0±0.5 at 500 nm, respectively. Low AOD occurs in March and September with values of approximately 0.6±0.3 and 0.5±0.3 at 500 nm, respectively. Analysis of the relation between AOD and the measured horizontal visibility indicates that the high aerosol concentration in the atmosphere is the major reason for the decreased visibility level.

There are two peaks in the PM concentration distributions for Shenyang, as shown in Figure 1c. The high concentrations of PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ occurred in January with values of approximately 88.0±23.5 μg m^{-3}, 69.5±19.9 μg m^{-3} and 63.8±19.3 μg m^{-3}, respectively. The low values occurred in March at approximately 56.8±11.5 μg m^{-3}, 40.3±8.9 μg m^{-3} and 34.4±8.5 μg m^{-3}, respectively.

As shown in Figure 1, the changes in visibility and PM mass concentration show close correspondence; specifically, high PM mass concentration corresponds to low visibility. The variations in visibility and PM concentration at Shenyang may be related to weather patterns and long–range transported pollution. In summer, the air contains more water vapor, so that aerosol hygroscopic growth causes an increase in PM which produces poorer visibility. In addition, because of the intense summer sunlight, motor vehicle emissions of hydrocarbons can more readily form secondary particles through a series of photochemical reactions. The new particles suspended in the air increase the concentration of pollutants and decrease the summer visibility. The main reason for lower visibility in the winter is the burning of coal, which produces large numbers of particles. In addition, the inversion temperature phenomenon in winter induces slower

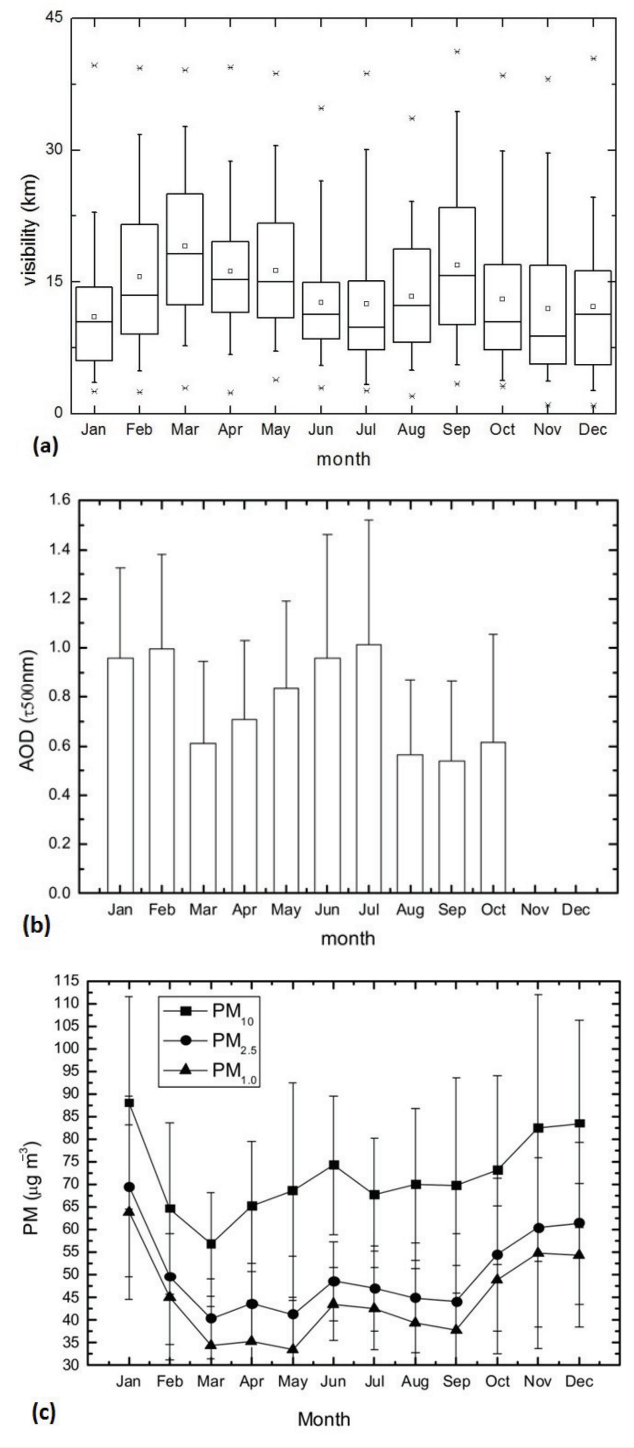

Figure 1. (a) *Monthly–averaged visibility,* ***(b)*** *PM concentration and* ***(c)*** *ratio of $PM_{2.5}$/PM_{10}.*

pollutant diffusion, thus the PM concentration is higher in January and February and this cannot be ignored as a cause of lower visibility (Zhao et al., 2009; Deng et al., 2011; Tiwari et al., 2013). The air in spring is dry and windy along with lower humidity, and the frequent high winds strengthen the convective activity in the atmosphere, thus more readily destroying the lower atmosphere inversion layer. Wang et al. (2011) analyzed the air pollution during a sandy dust weather event in 2010 in Liaoning Province, involving long–distance transport of dust particles from north and northwest China. Cheng et al. (2008) suggest that, in spring, the aerosol consists of many coarse particles most likely because of the long–distance transport of dust particles from

Northern China. Ma et al. (2012) studied an intense and wide–ranging dusty weather event on 11–12 May, 2011, steered by the Mongolian low pressure cell over Liaoning Province. Thus, the low PM in spring could contribute to the transportation and diffusion of pollutants. Guinot et al. (2007) indicated that, in the spring, greater dispersion and strong spring winds are likely to contribute to lower $PM_{2.5}$ concentrations. The autumn weather in Northern China lies to the South of a subtropical high pressure cell that retreats at this time and, given the sinking airflow and sunny conditions, there are fewer impurities in the air. Diminished rainfall leads to lower moisture in the air, resulting in increasing visibility compared to visibility in the summer.

The correlations between visibility, PM and meteorological conditions, including temperature, RH and wind speed, were analyzed in this study. The results show that visibility has higher correlation coefficients with wind speed (r=0.60) and relative humidity (r=–0.50), while PM has a higher correlation coefficient with wind speed and temperature as shown in Table 2. Thus, wind speed was the main meteorological factor influencing both visibility and particle mass concentration. Low wind speeds combined with temperature inversions indicated stable meteorological conditions during the pollutant process, which limited the dispersion of pollutants and can induce higher PM concentration and lower visibility. High temperatures, especially in summer, may lead to intense vertical dispersion of pollutants which induce an inverse relation between temperature and PM, especially in the fine particle categories ($PM_{2.5}$ and $PM_{1.0}$). When the relative humidity is high, aerosol hygroscopic increase is significant, which can induce the increasing of PM concentration and scattering capability (Li et al., 2010). Finally the visibility is low. However, when the relative humidity is low, the aerosol hygroscopicity increase is weak which can induce the aerosol scattering capability decreasing and the visibility raising.

***Table 2.** Correlation between visibility, PM and meteorological conditions*

Correlation coefficient	Visibility	PM_{10}	$PM_{2.5}$	$PM_{1.0}$
Wind speed	0.60	–0.50	–0.43	–0.49
RH	–0.50	0.29	0.13	0.20
Temperature	0.15	–0.40	–0.66	–0.64

3.2. Annual variations of visibility and PM mass concentration

Table 3 shows the annual variation in visibility and PM concentration from 2010 to 2012 in different seasons at the Shenyang station. The annual concentration values of $PM_{2.5}$ in Shenyang from 2010 to 2012 were approximately 42.1±21.0 µg m^{-3}, 51.3±27.2 µg m^{-3} and 58.6±29.5 µg m^{-3}, respectively, with a total annual value of 50.7 µg m^{-3}, which exceeds the annual limit of the National Ambient Air Quality Standard (15.0 µg m^{-3}) for $PM_{2.5}$ (U.S. EPA, 1997). The annual concentrations of $PM_{2.5}$ are listed in Table 4 along with results from other studies. Compared with the $PM_{2.5}$ concentrations in other cities, the mean annual $PM_{2.5}$ concentration in Shenyang was higher than those in urban areas of China such as Fuzhou (44.3 µg m^{-3}) (Xu et al., 2012) and Hong Kong (34.1 µg m^{-3}) (Louie et al., 2005), as well as some metropolitan cities abroad such as Seoul in Korea (43.0 µg m^{-3}) (Kim et al., 2007), but lower than in many other cities, as shown in Table 4. These results suggest that $PM_{2.5}$ pollution is not significantly high in the atmosphere in Shenyang, although it should remain as a concern.

***Table 3.** Annual variation of visibility and PM*

		Spring	Summer	Autumn	Winter	Annual
Visibility (km)	2010	13.9±5.6	11.4±6.3	14.6±9.1	11.6±5.8	12.9±7.0
	2011	18.6±7.7	12.2±6.2	14.7±8.7	12.9±7.0	14.6±7.8
	2012	18.8±8.3	15.1±8.0	12.6±7.8	14.0±9.8	15.1±8.8
	Annual	17.0±1.8	12.7±0.6	14.0±2.7	12.5±1.9	14.2±7.9
PM_{10} (µg m^{-3})	2010	53.8±24.7	59.8±29.9	66.3±42.2	68.2±30.2	62.0±32.7
	2011	52.0±35.9	73.0±27.0	94.4±47.4	77.7±34.0	74.5±40.2
	2012	84.6±31.6	75.5±28.8	65.8±35.4	92.7±43.2	80.0±36.4
	Annual	63.6±6.1	70.7±3.3	75.2±6.6	78.7±12.4	72.2±36.4
$PM_{2.5}$ (µg m^{-3})	2010	35.8±14.1	37.5±16.3	44.4±23.2	50.9±25.3	42.1±21.0
	2011	33.3±16.1	45.6±19.3	64.0±30.8	60.5±27.0	51.3±27.2
	2012	56.2±22.4	56.6±23.7	50.2±30.4	71.0±35.9	58.6±29.5
	Annual	41.8±1.7	46.8±1.9	53.0±8.3	60.2±10.0	50.7±25.9
$PM_{1.0}$ (µg m^{-3})	2010	29.0±12.8	31.9±15.1	37.5±21.8	44.5±24.3	35.7±19.9
	2011	25.1±12.5	39.8±18.0	56.9±30.0	55.8±25.6	44.8±26.3
	2012	49.4±21.5	53.3±23.2	46.6±29.8	64.8±33.4	53.6±28.1
	Annual	34.4±0.9	41.8±2.2	47.2±8.6	54.4±9.4	44.7±24.8

***Table 4.** Summary of $PM_{2.5}$ measurements in the literature*

Site	$PM_{2.5}$ (µg m^{-3})	Period	Reference
Shenyang, China mainland	50.7	2010–2012	This study
Shandong University, China mainland	148.7	2006–2007	Yang et al. (2012)
Chengdu, China mainland	165.1	2009–2010	Tao et al. (2013)
Hong Kong	34.1	2000–2001	Louie et al. (2005)
Seoul, Korea	43.0	2003–2005	Kim et al. (2007)
Taiyuan, China mainland	193.4	2005–2006	Meng et al. (2007)
Fuzhou, China mainland	44.33	2007–2008	Xu et al. (2012)
Chegongzhuang, Beijing, China mainland	96.5	2001–2002	Duan et al. (2006)
Agra, India	104.9	2006–2008	Kulshrestha et al. (2009)
Xiamen, China mainland	86.16	2009–2010	Zhang et al. (2012b)

The seasonal changes in PM mass concentrations are increasing year by year, for which there may be several reasons. The combination of increased emissions from heating sources and low boundary layer height (BLH) (Sun et al., 2004; Guinot et al., 2007) during winter may cause air quality deterioration. The peak PM in summer may also result from the high water vapor content in the atmosphere in this period, when RH can reach about 80.6%. Pollutants can easily absorb moisture and so grow. The increase in mean grain size of hygroscopic aerosol is susceptible to atmospheric gas–particle transformation reactions, which enhance the formation of aerosols. In addition, local particles may be re–suspended in the atmosphere due to strong winds in spring and autumn, which can also increase the particle concentration.

Table 3 shows that, although the PM mass concentration increases in spring, summer and winter on a yearly basis, a significant reduction occurred in the autumn of 2012. The reason for this phenomenon may be the fact that the autumn rainfall in 2012 (60.0 mm) was more than twice the total received in the autumn of 2011 (29.0 mm); therefore, the significantly lower PM mass concentration may have resulted from the wet deposition effect.

Although the PM mass concentration increases year by year, the visibility diminishes only in autumn, while increasing in the three other seasons. This result is obviously not consistent with the changes in PM mass concentration. Accordingly, we attempt to explain this outcome in the following section by reference to the annual changes in visibility.

3.3. Annual variations in extreme visibility and PM levels

Gomez and Smith (1987) used a statistical method to represent variation in visibility by applying the definition of "very good visibility" for a visual range exceeding 19.0 km. Extremes in visibility values were explored right across China (Fu et al., 2013) as a means of determining the features of consecutive extreme visibility events.

Table 5 shows the days with visibility >19.0 km often appear during the spring and autumn, while days with visibility <10.0 km occur in summer and winter. The spring and autumn occurrence of "very good visibility" may be explained by the frequent presence of synoptic systems that yield a northerly continental wind component capable of transporting relatively clean air masses into the region.

The number of days with visibility >19.0 km in Shenyang was 59, 123 and 145 in 2010 through to 2012, and the number of days with visibility <10.0 km was 132, 119 and 121 in the same three years. These results indicate that the number of days with low visibility did not show the same significant changes as those with good visibility. Therefore, although the PM mass concentration increased year after year, the annual visibility has significantly increased.

There seem to be obvious trends among the variations in $PM_{2.5}$ and $PM_{1.0}$ levels in Shenyang as shown in Figure 1c. Figure 2 shows that the highest ratios of $PM_{2.5}/PM_{10}$ and $PM_{1.0}/PM_{10}$ appeared in winter with values of approximately 0.76 and 0.69, respectively. The lowest ratios occurred in spring with values of approximately 0.66 and 0.54, respectively. Residential heating in winter may be the main cause of the increases in $PM_{2.5}/PM_{10}$ and $PM_{1.0}/PM_{10}$ ratios, while the strong winds in spring increase the concentration of coarse particles in the air, which decreases the ratios of $PM_{2.5}/PM_{10}$ and $PM_{1.0}/PM_{10}$. There is an obvious inverse correlation trend between visibility and PM ratios; these indicate that fine particles constitute an important component of the yearly particle mass concentrations, which are the main pollutants that affect the Shenyang area.

The annual ratio of $PM_{2.5}/PM_{10}$ was calculated for the three years from 2010 to 2012 and was found to be approximately 69.2%, 69.1% and 72.6%, respectively. In order to capture possible changes in $PM_{2.5}/PM_{10}$ levels in Shenyang, we compared our results (a total annual value of approximately 70.3%) with those from other studies. Our measured approximate $PM_{2.5}/PM_{10}$ levels in Shenyang are obviously lower than the values in Shenzhen (73.3%) and Zhuhai (70.8%) (Cao et al., 2003) but higher than those in Xi'an (51.9%) (Wei et al., 1999), Beijing (64%) (He et al., 2001), Tianjin (57.9 %) (Gu et al., 2010) and Guangzhou (68.0%) (Wang et al., 2006). The results also indicate that fine particles are the main component of PM_{10} in the Shenyang atmosphere.

3.4. Relation between visibility and PM mass concentration

The correlation between visibility and PM mass concentration including PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ was analyzed (Figure 3). The results show that $PM_{2.5}$ and $PM_{1.0}$ have higher correlation coefficients with visibilities of approximately r=0.51 and r=0.50, respectively. However, there was no apparent correlation between visibility and PM_{10} (r=0.38).

Atmospheric visibility is constrained by the atmospheric extinction effect on the scattering and absorption of sunlight, particularly because of the fine particles and gaseous pollutants which seriously weaken the light signals from objects. These results clearly indicate the seriousness of fine particle pollution in the Shenyang area.

3.5. Diurnal variations and weekend effects of visibility and $PM_{2.5}$ mass concentration

Figure 4 depicts the diurnal patterns of visibility and PM mass concentration in Shenyang. We divided the variations into different seasons because diurnal variation is related to boundary layers, solar radiation and temperature.

Table 5. *Seasonal and annual days of visibility >19.0 km and <10.0 km*

Level	Visibility<10 km					Visibility>19 km				
2010 Season (days)	Spring (81)	Summer (87)	Autumn (91)	Winter (83)	Total	Spring (81)	Summer (87)	Autumn (91)	Winter (83)	Total
Days (%)	21 (25.9)	44 (50.6)	36 (39.6)	31 (37.3)	132	15 (18.5)	12 (13.8)	23 (25.3)	9 (10.8)	59
Visibility (km)	7.8±2.3	6.9±2.3	7.0±1.9	5.4±1.8	6.8±2.1	23.3±2.2	24.3±4.0	27.8±6.6	22.1±2.1	24.4±3.7
2011 Season (days)	Spring (88)	Summer (86)	Autumn (90)	Winter (90)	Total	Spring (88)	Summer (86)	Autumn (90)	Winter (90)	Total
Days (%)	11 (12.5)	36 (41.9)	33 (36.7)	39 (43.3)	119	35 (39.8)	13 (15.1)	25 (27.8)	15 (16.7)	123
Visibility (km)	7.8±1.9	6.9±2.2	6.3±2.0	7.3±1.7	7.1±2.0	26.4±4.8	23.0±4.7	26.4±4.6	25.2±6.2	25.3±5.1
2012 Season (days)	Spring (92)	Summer (81)	Autumn (89)	Winter (88)	Total	Spring (92)	Summer (81)	Autumn (89)	Winter (88)	Total
Days (%)	16 (17.4)	26 (32.1)	39 (43.8)	40 (45.5)	121	40 (43.5)	22 (27.2)	17 (19.1)	26 (29.5)	145
Visibility (km)	7.7±1.7	7.2±1.5	5.8±2.0	5.5±2.5	6.55±1.9	26.5±5.4	25.8±5.7	24.8±5.5	26.9±5.8	26.0±5.6

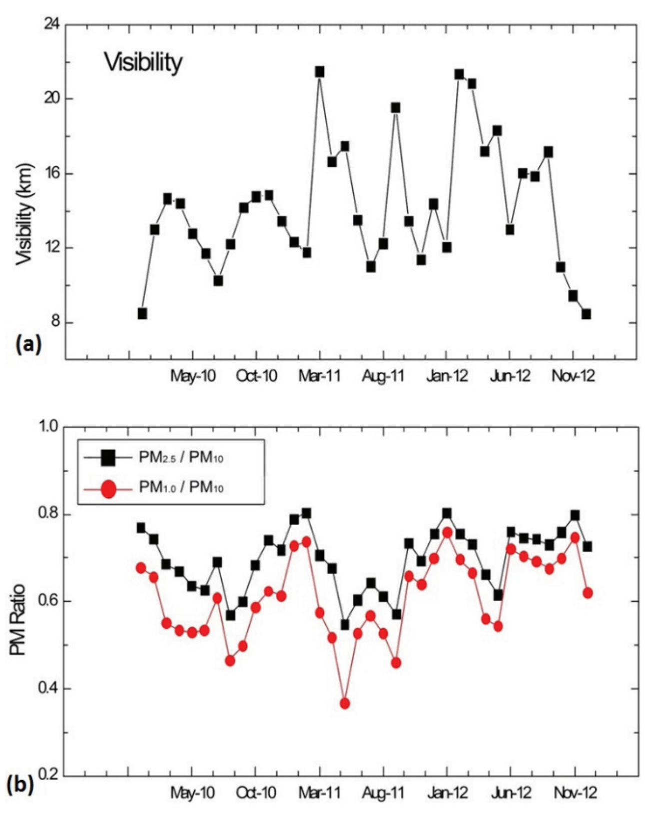

***Figure 2. (a)** Monthly–averaged visibility and **(b)** ratio of $PM_{2.5}/PM_{10}$ and $PM_{1.0}/PM_{10}$.*

Visibility shows obvious diurnal variations in all seasons, with a peak value occurring in the early morning at approximately 07:00 hr (local time) and then decreasing until 14:00 hr. This is maintained for a period of time and then continues to decrease in the late afternoon until approximately 18:00 hr; in summer, the morning peak value decreases continuously until 21:00 hr. After approximately 07:00 hr, visibility gradually decreases due to enhanced anthropogenic activity during the rush hour. Starting at approximately 12:00 hr, the visibility maintains a consistent value until 18:00 hr. When the evening rush hour occurs, visibility begins to decrease even further. Visibility in summer declines from 07:00 hr to 21:00 hr, which is different from other seasons. This variation arises because the longer and stronger solar irradiation during summer favors the photochemical formation of secondary aerosol particles, which are the major constituents of $PM_{2.5}$ (Wang et al., 2008). Unlike the longer periods of summer sunshine, winter periods are shorter, especially in northern China. Sunset occurs before 16:00 hr, which sharply decreases the photochemical formation of secondary aerosol particles. Therefore, visibility in winter appears to increase at approximately 17:00 hr. Following the pollutant emissions caused by the evening rush hour and heating of buildings in the winter, visibility begins to decline after 22:00 hr.

The average diurnal variations in $PM_{2.5}$ concentration at Shenyang are shown in Figure 4b. Pronounced diurnal variations of $PM_{2.5}$ are observed in this area but with different seasonal patterns. $PM_{2.5}$ concentration generally decreases from midnight to 07:00 hr. Concentrations then increase until 12:00 hr, after which they are steady until 20:00 hr when they increase again. The seasons of spring, autumn and winter, therefore, display a bimodal pattern with peaks between 12:00 hr and 20:00 hr (corresponding to the morning and evening rush hours). The change of $PM_{2.5}$ mass concentration at night is greater in winter and smaller in summer. This phenomenon is attributed to the diurnal patterns of the meteorological conditions in summer and winter. During the night, $PM_{2.5}$ concentrations decrease because of reduction in source activities and the removal of particles by dry deposition, a mechanism for hygroscopic particles that is enhanced by the increase in relative humidity. The wind speed at night is higher in winter than in summer, and the temperature difference between day and night is also higher in these two seasons, which may account for the greater changes observed in winter.

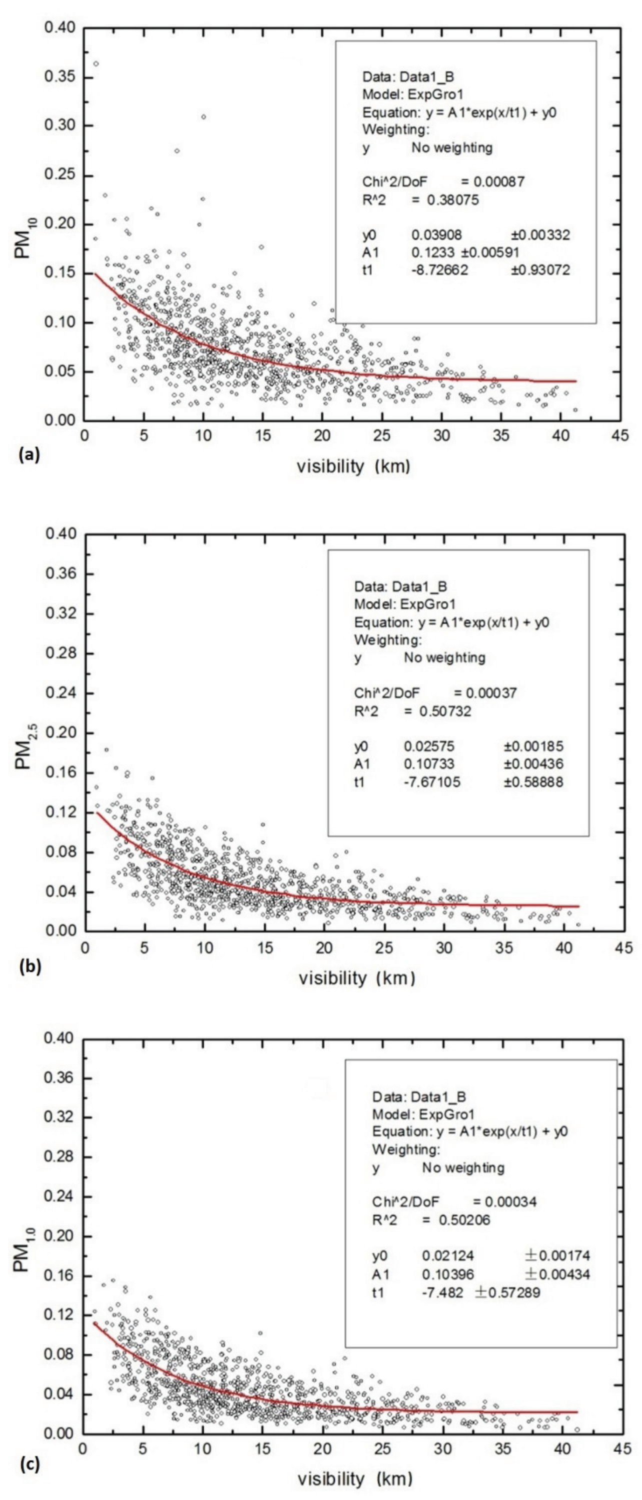

***Figure 3.** Correlation between visibility and particle concentration including **(a)** PM_{10}, **(b)** $PM_{2.5}$ and **(c)** $PM_{1.0}$.*

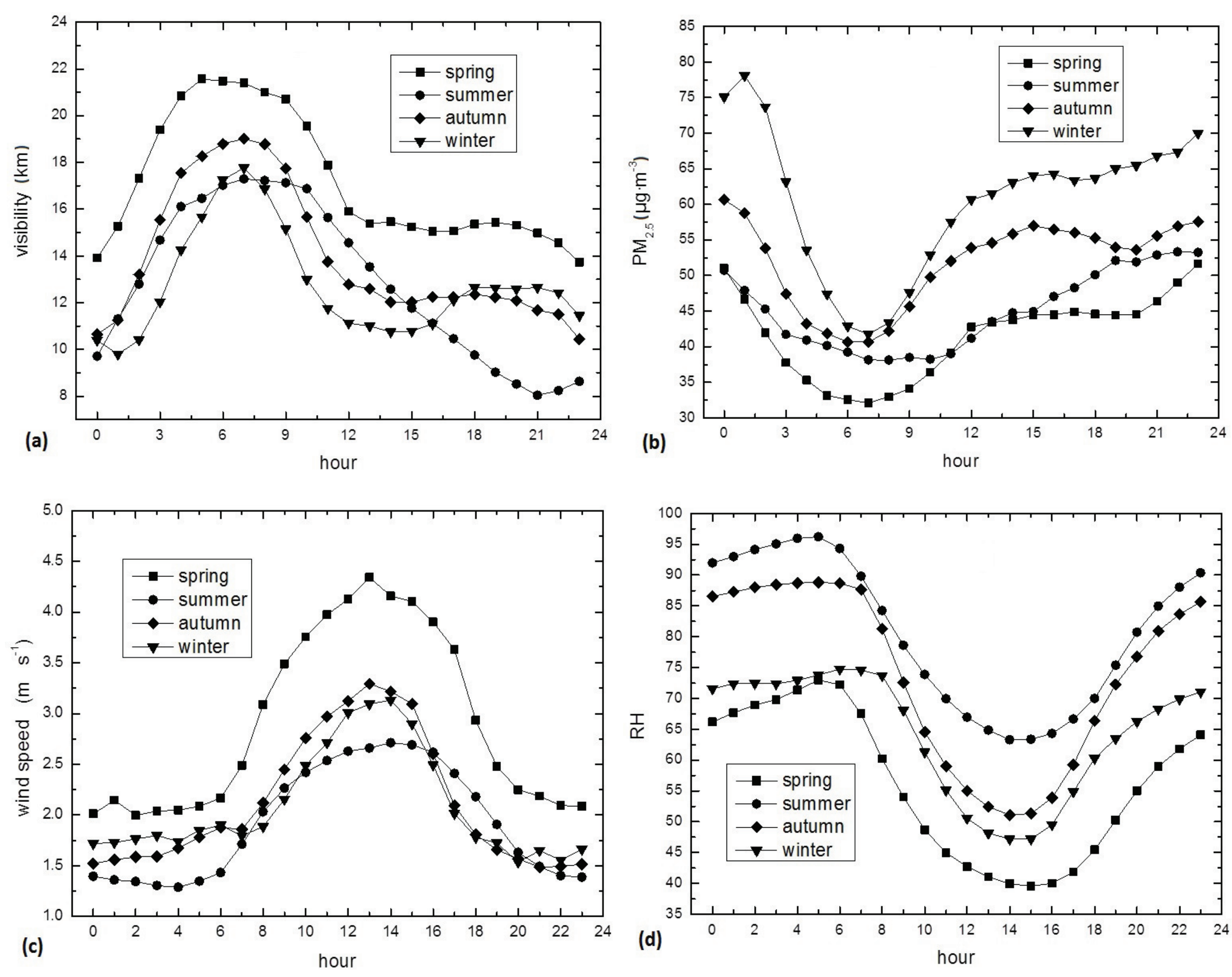

***Figure 4. (a)** Diurnal variation in visibility, **(b)** $PM_{2.5}$ concentration, **(c)** wind speed and **(d)** RH.*

As observed in the daily variations of visibility and PM concentration, human activities are one of the main factors affecting the Shenyang area. The weekend effect on visibility was reported in Taiwan by Tsai et al. (2007), who found higher visibility on weekend days. The potential weekend effect on Shenyang was also investigated in this study, but for different reasons. Visibility gradually decreases from Monday to Friday (Figure 5a), but it increases during the weekend. The gradual decrease during weekdays is most likely a response to the greater anthropogenic activity during rush hours.

There is also an obvious weekend effect on the emission of air pollutants, including PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ (Figure 5b). The weekend effect on particles suggests that PM concentration gradually increases from Monday to Friday and then decreases during the weekend. However, PM_{10} concentrations show a moderate increase on Sunday, which may be due to the local traffic conditions associated with holiday travel, thus bearing an important influence on the concentration patterns during weekends.

4. Summary and Discussion

Visibility and PM concentration variations were analyzed in Shenyang from 2010 to 2012. The monthly–averaged visibility over Shenyang is higher in March and September with values of approximately 19.0±4.3 km and 17.1±4.3 km, respectively. Low visibility over Shenyang occurs in January at approximately 11.0±4.7 km. There is a negative correlation between visibility and PM concentration. In addition, wind speed is the main meteorological factor that influences PM mass concentration, which then influences visibility.

The number of days with visibility >19.0 km and <10.0 km in Shenyang are 59, 123, 145 and 132, 119, 121 in the three year period from 2010 to 2012, respectively. The number of days with poor visibility undergoes smaller changes compared to the number of days with good visibility. Thus, although PM concentration is increasing year on year, annual visibility continues to increase.

The levels of PM indicate that human activities are already the main source of pollutants, and the relation between visibility and PM means that fine particles are the most important factor affecting visibility. Visibility and PM concentration show obvious diurnal variations and weekend effects, mainly due to human activities.

In general, visibility in Shenyang is mostly affected by anthropogenic activity. However, the effect of pollutant emissions and meteorological factors on visibility still requires in–depth investigation.

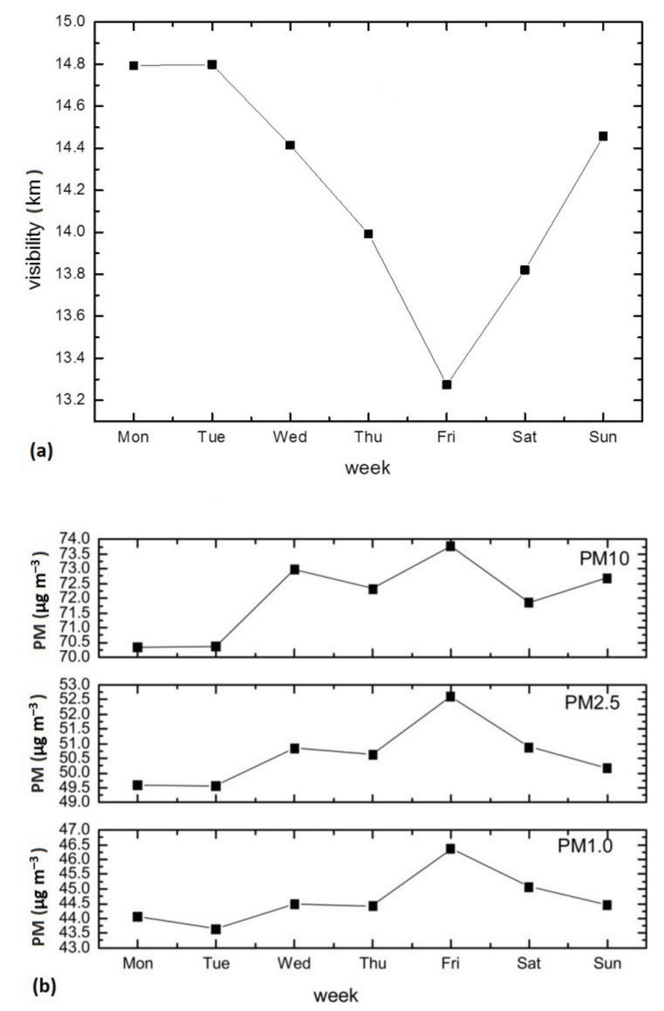

***Figure 5. (a)** Weekend effects of visibility and **(b)** PM concentration.*

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References

Cao, J.J., Lee, S.C., Ho, K.F., Zhang, X.Y., Zou, S.C., Fung, K., Chow, J.C., Watson, J.G., 2003. Characteristics of carbonaceous aerosol in Pearl River Delta Region, China during 2001 winter period. *Atmospheric Environment* 37, 1451–1460.

Chan, Y.C., Simpson, R.W., Mctainsh, G.H., Vowles, P.D., Cohen, D.D., Bailey, G.M., 1999. Source apportionment of visibility degradation problems in Brisbane (Australia) using the multiple linear regression techniques. *Atmospheric Environment* 33, 3237–3250.

Chang, D., Song, Y., Liu, B., 2009. Visibility trends in six megacities in China 1973–2007. *Atmospheric Research* 94, 161–167.

Che, H.Z., Zhang, X.Y., Li, Y., Zhou, Z.J., Qu, J.J., Hao, X.J., 2009. Haze trends over the capital cities of 31 provinces in China, 1981–2005. *Theoretical and Applied Climatology* 97, 235–242.

Cheng, T.T., Zhang, R.J., Han, Z.W., Fang, W., 2008. Relationship between ground–based particle component and column aerosol optical property in dusty days over Beijing. *Geophysical Research Letters* 35, art. no. L20808.

Deng, J.J., Wang, T.J., Jiang, Z.Q., Xie, M., Zhang, R.J., Huang, X.X., Zhu, J.L., 2011. Characterization of visibility and its affecting factors over Nanjing, China. *Atmospheric Research* 101, 681–691.

Duan, F.K., He, K.B., Ma, Y.L., Yang, F.M., Yu, X.C., Cadle, S.H., Chan, T., Mulawa, P.A., 2006. Concentration and chemical characteristics of $PM_{2.5}$ in Beijing, China: 2001–2002. *Science of the Total Environment* 355, 264–275.

Fu, C.B., Wu, J., Gao, Y.C., Zhao, D.M., Han, Z.W., 2013. Consecutive extreme visibility events in China during 1960–2009. *Atmospheric Environment* 68, 1–7.

Ghim, Y.S., Moon, K.C., Lee, S.Y., Kim, Y.P., 2005. Visibility trends in Korea during the past two decades. *Journal of the Air & Waste Management Association* 55, 73–82.

Gomez, B., Smith, C.G., 1987. Visibility at Oxford, 1926–1985. *Weather* 42, 98–106.

Gu, J.X., Bai, Z.P., Liu, A.X., Wu, L.P., Xie, Y.Y., Li, W.F., Dong, H.Y., Zhang, X., 2010. Characterization of atmospheric organic carbon and element carbon of $PM_{2.5}$ and PM_{10} at Tianjin, China. *Aerosol and Air Quality Research* 10, 167–176.

Guinot, B., Cachier, H., Sciare, J., Tong, Y., Xin, W., Jianhua, Y., 2007. Beijing aerosol: atmospheric interactions and new trends. *Journal of Geophysical Research – Atmospheres* 112, art. no. D14314.

He, K.B., Yang, F.M., Ma, Y.L., Zhang, Q., Yao, X.H., Chan, C.K., Cadle, S., Chan, T., Mulawa, P., 2001. The characteristics of $PM_{2.5}$ in Beijing, China. *Atmospheric Environment* 35, 4959–4970.

Hong, Y.C., Lee, J.T., Kim, H., Ha, E.H., Schwartz, J., Christiani, D.C., 2002. Effects of air pollutants on acute stroke mortality. *Environmental Health Perspectives* 110, 187–191.

Kim, H.S., Huh, J.B., Hopke, P.K., Holsen, T.M., Yi; S.M., 2007. Characteristics of the major chemical constituents of $PM_{2.5}$ and smog events in Seoul, Korea in 2003 and 2004. *Atmospheric Environment* 41, 6762–6770.

Kulshrestha, A., Satsangi, P.G., Masih, J., Taneja, A., 2009. Metal concentration of $PM_{2.5}$ and PM_{10} particles and seasonal variations in urban and rural environment of Agra, India. *Science of the Total Environment* 407, 6196–6204.

Li, W.J., Shao, L.Y., Buseck, P.R., 2010. Haze types in Beijing and the influence of agricultural biomass burning. *Atmospheric Chemistry and Physics* 10, 8119–8130.

Liu, N.W., Ma, Y.J., Wang, Y.F., Liu, X.M., 2010. Mass concentration variation of atmospheric particles and relationship with visibility in Dandong. *Research of Environmental Sciences* 23, 642–646 (in Chinese).

Louie, P.K.K., Chow, J.C., Chen, L.W.A., Watson, J.G., Leung, G., Sin, D.W.M., 2005. $PM_{2.5}$ chemical composition in Hong Kong: urban and regional variations. *Science of the Total Environment* 338, 267–281.

Ma, Y.J., Liu, N.W., Hong, Y., Wang, Y.F., Zhang, Y.H., 2012. The impacts on various particles sizes and the quality caused by a dust weather process in spring 2011 in Liaoning. *Acta Scientiae Circumstantiae* 32, 1160–1167 (in Chinese).

Meng, Z.Y., Jiang, X.M., Yan, P., Lin, W.L., Zhang, H.D., Wang, Y., 2007. Characteristics and sources of $PM_{2.5}$ and carbonaceous species during winter in Taiyuan, China. *Atmospheric Environment* 41, 6901–6908.

Shen, Z.X., Wang, X., Zhang, R.J., Ho, K.F., Cao, J.J., Zhang, M.G., 2011. Chemical composition of water–soluble ions and carbonate estimation in spring aerosol at a semi–arid site of Tongyu, China. *Aerosol and Air Quality Research* 11, 360–368.

Sloane, C.S., Watson, J., Chow, J., Pritchett, L., Willard Richards, L., 1991. Size–segregated fine particle measurements by chemical species and their impact on visibility impairment in Denver. *Atmospheric Environment Part A. General Topics* 25, 1013–1024.

Sun, Y.L., Zhuang, G.S., Ying, W., Han, L.H., Guo, J.H., Mo, D., Zhang, W.J., Wang, Z.F., Hao, Z.P., 2004. The air–borne particulate pollution in Beijing – concentration, composition, distribution and sources. *Atmospheric Environment* 38, 5991–6004.

Tao, J., Zhang, L.M., Engling, G., Zhang, R.J., Yang, Y.H., Cao, J.J., Zhu, C.S., Wang, Q.Y., Luo, L., 2013. Chemical composition of $PM_{2.5}$ in an urban environment in Chengdu, China: importance of springtime dust storms and biomass burning. *Atmospheric Research* 122, 270–283.

Tiwari, S., Srivastava, A.K., Bisht, D.S., Parmita, P., Srivastava, M.K., Attri, S.D., 2013. Diurnal and seasonal variations of black carbon and $PM_{2.5}$ over New Delhi, India: influence of meteorology. *Atmospheric Research* 125, 50–62.

Tsai, Y.I., Kuo, S.C., Lee, W.J., Chen, C.L., Chen, P.T., 2007. Long–term visibility trends in one highly urbanized, one highly industrialized, and two rural areas of Taiwan. *Science of the Total Environment* 382, 324–341.

U.S. EPA (U.S. Environmental Protection Agency), 1997. *40 CFR Part 50 National Ambient Air Quality Standards for Particulate Matter, Final Rule*. Federal Register, 62, pp. 38651–38701.

Wang, Y.F., Ma, Y.J., Lu, Z.Y., Hong, Y., 2011. Analysis of meteorological elements and the air pollution during a sand dust weather process in 2010 in Liaoning province. *Journal of Meteorology and Environment* 27, 27–31 (in Chinese).

Wang, H.L., Zhuang, Y.H., Wang, Y., Sun, Y.L., Yuan, H., Zhuang, G.S., Hao, Z.P., 2008. Long-term monitoring and source apportionment of PM2.5/PM10 in Beijing, China. *Journal of Environmental Science* 20, 1323-1327.

Wang, X.H., Bi, X.H., Sheng, G.Y., Fu, J.M., 2006. Chemical composition and sources of PM_{10} and $PM_{2.5}$ aerosols in Guangzhou, China. *Environmental Monitoring and Assessment* 119, 425–439.

Wark, K., Warner, C.F., Davis, W.T., 1998. *Air Pollution–Its Origin and Control*, 3rd edition, Addison–Wesley, MA, United States, 573 pages.

Wei, F., Teng, E., Wu, G., Hu, W., Wilson, W.E., Chapman, R.S., Pau, J.C., Zhang, J., 1999. Ambient concentrations and elemental compositions of PM_{10} and $PM_{2.5}$ in four Chinese cities. *Environmental Science & Technology* 33, 4188–4193.

Xu, L.L., Chen, X.Q., Chen, J.S., Zhang, F.W., He, C., Zhao, J.P., Yin, L.Q., 2012. Seasonal variations and chemical compositions of $PM_{2.5}$ aerosol in the urban area of Fuzhou, China. *Atmospheric Research* 104, 264–272.

Yang, L.X., Zhou, X.H., Wang, Z., Zhou, Y., Cheng, S.H., Xu, P.J., Gao, X.M., Nie, W., Wang, X.F., Wang, W.X., 2012. Airborne fine particulate pollution in Jinan, China: concentrations, chemical compositions and influence on visibility impairment. *Atmospheric Environment* 55, 506–514.

Zhang, R., Jing, J., Tao, J., Hsu, S.C., Wang, G., Cao, J., Lee, C.S.L., Zhu, L., Chen, Z., Zhao, Y., Shen, Z., 2013. Chemical characterization and source apportionment of $PM_{2.5}$ in Beijing: seasonal perspective. *Atmospheric Chemistry and Physics* 13, 7053–7074.

Zhang, R.J., Tao, J., Ho, K.F., Shen, Z.X., Wang, G.H., Cao, J.J., Liu, S.X., Zhang, L.M., Lee, S.C., 2012a. Characterization of atmospheric organic and elemental carbon of $PM_{2.5}$ in a typical semi–arid area of Northeastern China. *Aerosol and Air Quality Research* 12, 792–802.

Zhang, F.W., Xu, L.L., Chen, J.S., Yu, Y.K., Niu, Z.C., Yin, L.Q., 2012b. Chemical compositions and extinction coefficients of $PM_{2.5}$ in peri-urban of Xiamen, China, during June 2009–May 2010. *Atmospheric Research* 106, 150-158.

Zhang, Q., Streets, D.G., Carmichael, G.R., He, K.B., Huo, H., Kannari, A., Klimont, Z., Park, I.S., Reddy, S., Fu, J.S., Chen, D., Duan, L., Lei, Y., Wang, L.T., Yao, Z.L., 2009. Asian emissions in 2006 for the NASA INTEX–B mission. *Atmospheric Chemistry and Physics* 9, 5131–5153.

Zhang, R., Fu, C., Han, Z., Zhu, C., 2008. Characteristics of elemental composition of $PM_{2.5}$ in the spring period at Tongyu in the semi–arid region of Northeast China. *Advances in Atmospheric Sciences* 25, 922–931.

Zhao, X.J., Zhang, X.L., Xu, X.F., Xu, J., Meng, W., Pu, W.W., 2009. Seasonal and diurnal variations of ambient $PM_{2.5}$ concentration in urban and rural environments in Beijing. *Atmospheric Environment* 43, 2893–2900.