Physical and Optical Properties of Atmospheric Aerosols in Summer at a Suburban Site in North China

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ABSTRACT

The physical and optical properties of atmospheric aerosols at a suburban site in North China were continuously measured from July 20, 2014 to August 30, 2014. The particle number concentration (N), mass concentration (M), geometric mean diameter (GMD), scattering coefficient (σsc), and Angström exponent (α) were calculated. The potential source contribution was also analyzed. The results revealed that the average N, M, GMD, σsc, and α values reached 19653.2 cm–3, 17.7 µg m–3, 44.38 nm, 186.7 Mm –1, and 1.77, respectively, in non-rainy days and 14323.1 cm –3, 15.3 µg m –3, 44.98 nm, 226.9 Mm –1, and 1.87, respectively, in rainy days. Small-sized aerosols (< 100 nm) dominated the total aerosol numbers under clear conditions. The diurnal variation of N showed one peak, usually appearing at 12:00, which could be correlated with new particle formation (NPF) events. Most NPF events began at 08:00–10:00 and continued until 12:00–14:00. The average particle formation rate (FR) and particle growth rate (GR) were 1.93 cm –3 s–1 and 7.24 nm h –1, respectively. The diurnal variation of M showed two peaks, at 7:00 and 21:00, which were caused by local or regional transport of urban plumes. A potential source contribution function (PSCF) analysis indicated that aerosol potential sources in Xinzhou were mainly concentrated in the relatively developed, densely populated areas, particularly in some areas to the east and southeast of Shanxi, and the PSCF values of these areas were higher than 0.6.

Keywords: Atmospheric aerosol; Size distribution; Scattering coefficient; NPF event.

INTRODUCTION

Atmospheric aerosols play crucial roles in environmental quality (Liu et al., 2008; Han et al., 2014, 2015) and sometimes cause serious environmental problems such as endangering human health and reducing visibility (Zhang et al., 2010; Liu et al., 2012, 2013). Furthermore, aerosols directly affect the earth’s radiation balance through scattering and absorbing solar radiation, and they indirectly influence the properties and lifetimes of clouds by acting as a condensation nucleus or an ice nucleus in cloud formation (Li et al., 2011b), eventually influencing the global climate change (Li et al., 2011a; Liu et al., 2012; Sun et al., 2015). The physical, chemical, and optical properties of aerosols determine their environmental and climatological effects (Liu et al., 2008; Laing et al., 2016). Aerosols have varying properties in different geographical and temporal distributions because of various factors such as different emission sources, transformations, and removal processes. This further results in large uncertainties in the evaluation of the effects of aerosols on both the environment and climate. To comprehensively and objectively assess the effect of aerosols on the environment and climate, more observational studies should be conducted in different regions.

Many cities in China are affected by air pollution. Emissions of anthropogenic pollutants have increased considerably in recent decades because of the rapid population and economic growth. In particular, serious atmospheric pollution events occurred more frequently in North China, which resulted in more complicated aerosol properties (Yan et al., 2008; Li et al., 2012a, 2013). Therefore, many
observational studies have investigated the physical, chemical, and optical properties of aerosols in different areas such as Beijing (Li et al., 2007; He et al., 2009), Tianjin (Deng et al., 2011; Ma et al., 2011), Shanghai (Xu et al., 2012; Han et al., 2015), Guangzhou (Andreae et al., 2008; Garland et al., 2008; Chen et al., 2016), Chengdu (Tao et al., 2014), Anhui (Fan et al., 2010; Wang et al., 2014, 2015b), Lanzhou (Pu et al., 2015; Wang et al., 2015a), and other areas (Yin et al., 2010; Li et al., 2011; Shen et al., 2011; Cao et al., 2012; Li et al., 2012b; Dai et al., 2016; Yuan et al., 2016).

Shanxi Province is located in the eastern part of the Loess Plateau in North China. Coal, chemical, and other heavy industries are the major industries in this region; these industries have emitted complicated types of aerosols in this region. Because of such a special geographical position and the heavy industrial background, issues such as local air quality, atmospheric particle distribution, and their effect on weather and climate are increasingly prominent and receive increasing public attention with the process of urbanization and the development of social economy. However, until now, few studies have examined the aerosol properties in this area. Thus, observational studies should be urgently conducted to examine the role of aerosols in environment and climate change in this region.

An integrated observational experiment (Aerosol-CCN-Cloud Closure Experiment, AC`Exp) including airborne measurements and ground observations was conducted in the summer of 2013 and 2014 in Shanxi, North China, and a few results were reported for the first time (Li et al., 2014a, 2015a, b, c; Wang et al., 2016; Zhang et al., 2016). This present study investigated the physical and optical properties of atmospheric aerosols including the aerosol particle number concentration (N_a), mass concentration (M_a), geometric mean diameter (GMD), spectrum distribution, scattering coefficient (σ_sc), and Ångström exponent (α). The details of this field campaign are described in Section 2. The frequency distribution features, diurnal variations, and average spectral features of aerosol properties, as well as the potential source contributions, are discussed in Section 3. The conclusions are provided in Section 4.

DESCRIPTION OF THE FIELD CAMPAIGN

Location of Measurements
Field measurements were conducted from July 20 to August 30, 2014, at the meteorological station (112.12°E, 38.07°N, 800 m ASL) in Xinzhou. This site is located southwest of Beijing (a metropolitan region of China) at a distance of approximately 360 km and northeast of Taiyuan City (the capital of Shanxi Province) at a distance of 60 km. The observatory is surrounded by a land of agricultural crops. Because of no presence of high buildings in the surrounding areas, the observatory area has better air diffusion conditions. Fig. 1 shows the average distribution of aerosol optical depth over Shanxi Province during the experimental period, in addition to the locations of Taiyuan and Xinzhou. The measured aerosol optical depth over

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**Fig. 1.** Map of Shanxi Province in North China. The location of the observation site is marked with a white circle, and Taiyuan City is marked with a white star. The shaded contour represents the mean distribution of aerosol optical depth during 201–242 days (July 20–August 30) in 2014 obtained from moderate resolution imaging spectroradiometer data. The inset map shows the location of the observation area in China. The yellow-, red-, and purple-shaded areas show the China Loess Plateau, Shanxi Province, and the North China Plain, respectively.
Shanxi Province decreased gradually from south to north. The relatively low values of the observed aerosol optical depth around Xinzhou indicate that the pollution in this site was lower than that in surrounding regions. Thus, Xinzhou can be taken as a suburban background site.

**Instruments and Measurements**

All instruments were placed in a measurement container with air-conditioner, and the sampling height was approximately 5 m. Atmospheric aerosol particles were collected from a sampling inlet that was installed ~1.5 m above the roof of the container. Particles' number concentration values associated with particle diameters of 10–600 nm were recorded using a scanning mobility particle sizer (SMPS, Model 3936, TSI, USA) in 109 bins (Zhang et al., 2016). The SMPS is comprised of a 3080 electric classifier, a 3022A condensation particle counter (CPC), and a microcomputer, and the SMPS was calibrated by using polystyrene latex spheres (PSL) of Particle Metrics Inc. (PMI) before the measurements took place (Li et al., 2014b; Li et al., 2017). The particles were passed through a drying tube before entering the differential mobility analyzer (DMA), and the relative humidity (RH) was below 30%. Relative deviations in particle diameter should be lower than 1%. The sample flow was set at 0.31 pm for the CPC, and the time resolution for the SMPS was set at 5 minutes. The number concentrations from SMPS measurements were converted to mass concentrations by using the composition dependent density that was estimated with the measured submicron aerosol composition (Wang et al., 2016) with the particle size distribution, and the details of the method developed by these studies (Salcedo et al., 2006; Aiken et al., 2009; Yin et al., 2015; Wang et al., 2016; Zhao et al., 2017). The GMD was also used to describe the aerosol size distribution, which can be defined as presented in Eq. (1):

$$GMD = \exp\left(\frac{\sum_i N_i \ln(D_i)}{\sum_i N_i}\right)$$  

where $N_i$ is the number concentration for a specific bin $i$ and $D_i$ is the average diameter of bin $i$.

An integrated nephelometer (Model 3563, TSI, USA) with three wavelengths (450, 550, and 700 nm) was used to measure $\sigma_{sc}$. The nephelometer was calibrated with filtered zero air as the low span gas and CO$_2$ as the high span gas before the experiment (Anderson and Ogren, 1998; Li et al., 2015). The inlet flow rate of ambient air was set to 10 L min$^{-1}$, and the average time interval was 5 minutes. A diffusion dryer was installed in the position before the sampling gas entered into the nephelometer, and the mean RH in the nephelometer chamber was below 40%.

The parameter $\alpha$ was calculated as the complement of $\sigma_{sc}$ measurements. This parameter ($\alpha$) depends on the size distribution of particles, and it can be used to estimate the aerosol type. For most atmospheric aerosols, the value of $\alpha$ is generally in the range of 0 to 2.5, and the value increases with a decrease in the particle size (Seinfeld and Pandis, 1998; Li et al., 2015). For example, in a typical polluted area where aerosols are mainly composed of fine particles, the $\alpha$ value is usually in the range of 1 to 2.5; however, in an area where aerosols are mainly composed of coarse particles, the $\alpha$ value tends to be lower than 1 or even close to 0 (Seinfeld and Pandis, 1998). The $\alpha$ value can be calculated using $\sigma_{sc}$ under different wavelengths, according to Eq. (2):

$$\alpha = -\log\left(\frac{\sigma_{sc}(\lambda_1)}{\sigma_{sc}(\lambda_2)}\right)$$

$$\log(\lambda_1 / \lambda_2)$$

The experiments in this study were conducted in China Standard Time.

**RESULTS AND DISCUSSION**

**Meteorological Parameters**

Meteorological parameters such as RH, temperature (T), precipitation, wind speed (WS) and wind direction (WD), were continuously measured at the station. During the measurement period, the temperature ranged from 12°C to 35°C, with an average of 21.9°C ± 4.7°C, and the RH ranged from 25% to 94%, with an average of 67.5% ± 17.2%. It rained for 13 days during the observation period, and the maximum rainfall intensity was 14.5 mm h$^{-1}$ (July 29, 2014). The rainfall intensity was mostly less than 1 mm h$^{-1}$ (light rain or drizzle; Fig. 2). The WS was generally below 4 m s$^{-1}$, with an average of 1.03 m s$^{-1}$ in a state of weak wind or a breeze. The prevailing winds were northeastly and southwestly. The

![Fig. 2. Time series of hourly averaged T, RH, and hourly rainfall intensity at the observation station from July 20 to August 30.](image-url)
southwest winds might have brought an urban plume from Taiyuan (Fig. 1) to the Xinzhou station.

**Statistical Characteristics of Aerosol Properties**

The temporal variations of \( N_a \) and \( M_a \) are illustrated in Fig. 3, and the time series of \( \sigma_{sc}(450, 550, \text{and} 700 \text{ nm}) \) are shown in Fig. 4. The maximum \( N_a \) reached 80,000 cm\(^{-3}\), with an average magnitude of 10\(^4\) cm\(^{-3}\). The maximum \( M_a \) was higher than 100 µg m\(^{-3}\), with an average magnitude of 10\(^1\) µg m\(^{-3}\).

The trend of \( \sigma_{sc} \) at different wavelengths (450, 550, and 700 nm) was consistent. The maximum value of \( \sigma_{sc}(550 \text{ nm}) \) was nearly 1000 M m\(^{-1}\), with an average magnitude of 10\(^2\) Mm\(^{-1}\).

The statistical values of the particle \( N_a, M_a, GMD, \text{and} \sigma_{sc} \) in non-rainy, rainy, and total observation days are presented in Table 1.

In non-rainy days during the field campaign, the maximum values of \( N_a, M_a, GMD, \sigma_{sc}, \text{and} \alpha \) were 82378.5 cm\(^{-3}\), 114.1 µg m\(^{-3}\), 99.22 nm, 970.0 Mm\(^{-1}\), and 2.64, respectively, and the corresponding average (standard deviation) values were 19653.2 ± 10445.1 cm\(^{-3}\), 17.7 ± 9.8 µg m\(^{-3}\), 44.38 ± 13.61 nm, 186.7 ± 164.2 Mm\(^{-1}\), and 1.77 ± 0.37, respectively.

In rainy days, the maximum values of \( N_a, M_a, GMD, \sigma_{sc}, \text{and} \alpha \) were 46880.3 cm\(^{-3}\), 59.3 µg m\(^{-3}\), 99.9 nm, 988.9 Mm\(^{-1}\), and 2.38, respectively, and the average (standard deviation) values were 14323.1 ± 7408.7 cm\(^{-3}\), 15.3 ± 12.5 µg m\(^{-3}\), 44.98 ± 17.95 nm, 226.9 ± 213.8 Mm\(^{-1}\), and 1.87 ± 0.21, respectively.

The maximum and average values of \( N_a \) and \( M_a \) were lower in rainy days than in the non-rainy days; in particular, the maximum \( N_a \) and \( M_a \) values in rainy days were nearly half of those in non-rainy days. However, the maximum and average values of \( GMD \) and \( \sigma_{sc} \) in rainy days were higher than those in the non-rainy days; this might be due to the heterogeneous chemical reaction occurred more frequently under high RH and low temperature conditions in rainy days, which was advantageous to the nitrate accumulation in the surface of aerosol particles especially particles with size larger than 300 nm and leads to particles size increasing. And also, the nitrate might decompose under the weather conditions of high temperature and low RH in the non-rainy days (Bergin et al., 2001; Cheng et al., 2008; Yin et al., 2010). The average values of \( \alpha \) in rainy days were lower than those in the non-rainy days. In the total observational days, the average values of \( N_a, M_a, GMD, \sigma_{sc}, \text{and} \alpha \) were 18571.9 cm\(^{-3}\), 17.1 µg m\(^{-3}\), 45.2 nm, 192.1 Mm\(^{-1}\), and 1.79, respectively. The average \( M_a \) and \( \sigma_{sc} \) values were relatively low, but both \( N_a \) and \( \alpha \) values were high, indicating that small particles dominated in the region during the field campaign.

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**Fig. 3.** Time series of 5-minute \( N_a \) and \( M_a \) at the observation station from July 20 to August 30.

**Fig. 4.** Time series of 5-minute \( \sigma_{sc}(450, 550, \text{and} 700 \text{ nm}) \) at the observation station from July 20 to August 30.
Table 1. Statistical summary of $N_a$, $M_a$, $GMD$, $\sigma_{sc}(550\text{nm})$, and $\alpha$ during the field experiment.

<table>
<thead>
<tr>
<th>Data type</th>
<th>$N_a$ (cm$^{-3}$)</th>
<th>$M_a$ (µg m$^{-3}$)</th>
<th>GMD (nm)</th>
<th>$\sigma_{sc}(550\text{nm})$ (Mm$^{-1}$)</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-rainy days</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max.</td>
<td>82378.5</td>
<td>114.1</td>
<td>99.22</td>
<td>970.0</td>
<td>2.64</td>
</tr>
<tr>
<td>Min.</td>
<td>1132.3</td>
<td>1.4</td>
<td>12.26</td>
<td>12.9</td>
<td>0.17</td>
</tr>
<tr>
<td>Ave.</td>
<td>19653.2</td>
<td>17.7</td>
<td>44.38</td>
<td>186.7</td>
<td>1.77</td>
</tr>
<tr>
<td>S.D.</td>
<td>10445.1</td>
<td>9.8</td>
<td>13.61</td>
<td>164.2</td>
<td>0.37</td>
</tr>
<tr>
<td>Rainy days</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max.</td>
<td>46880.3</td>
<td>59.3</td>
<td>99.99</td>
<td>988.9</td>
<td>2.38</td>
</tr>
<tr>
<td>Min.</td>
<td>1456.8</td>
<td>1.2</td>
<td>13.72</td>
<td>12.1</td>
<td>0.91</td>
</tr>
<tr>
<td>Ave.</td>
<td>14323.1</td>
<td>15.3</td>
<td>44.98</td>
<td>226.9</td>
<td>1.87</td>
</tr>
<tr>
<td>S.D.</td>
<td>7408.7</td>
<td>12.5</td>
<td>17.95</td>
<td>213.8</td>
<td>0.21</td>
</tr>
<tr>
<td>Total days</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max.</td>
<td>82378.5</td>
<td>114.1</td>
<td>99.99</td>
<td>988.9</td>
<td>2.64</td>
</tr>
<tr>
<td>Min.</td>
<td>98.2</td>
<td>1.2</td>
<td>12.26</td>
<td>12.1</td>
<td>0.17</td>
</tr>
<tr>
<td>Ave.</td>
<td>18571.9</td>
<td>17.1</td>
<td>45.19</td>
<td>192.1</td>
<td>1.79</td>
</tr>
<tr>
<td>S.D.</td>
<td>10182.9</td>
<td>10.3</td>
<td>14.85</td>
<td>173.7</td>
<td>0.35</td>
</tr>
</tbody>
</table>

The average $\sigma_{sc}$ value measured in Xinzhou was compared with results derived in other sites in China after the year 2000 (Table 2). The average $\sigma_{sc}$ value observed in this study is lower than those of most other sites listed in Table 2. For example, the $\sigma_{sc}$ value obtained in this study is lower than those recorded in Beijing (Li et al., 2007; He et al., 2009), Wuqing (Ma et al., 2011), Xingke (Chen et al., 2008), Guangzhou City (Andreae et al., 2008), Shouxian (Fan et al., 2010), Xi’an (Cao et al., 2012), Chengdu (Tao et al., 2014), and Shanghai (Han et al., 2015); comparable to those recorded in Yulin (Xu et al., 2004), SDZ (Yan et al., 2008), Lanzhou (Pu et al., 2015), and a rural site in Guangzhou (Garland et al., 2008); and higher than that recorded in Mt. Huang (Yuan et al., 2016).

Frequency Distribution Features

Fig. 5 shows the frequency distribution histograms for hourly averages of $N_a$, $M_a$, $\sigma_{sc}$, and $\alpha$. $N_a$ in the range of 12500–22500 cm$^{-3}$ most frequently appeared with a magnitude of 0.26. $N_a$ of less than 30000 cm$^{-3}$ accounted for

Table 2. Measurements of aerosol scattering properties at some other sites in China after the year 2000.

<table>
<thead>
<tr>
<th>Site</th>
<th>Period</th>
<th>$\sigma_{sc}$ (Mm$^{-1}$)</th>
<th>Instrument</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yulin (desert)</td>
<td>2001.04</td>
<td>158 (530nm)</td>
<td>Nephelometer M903</td>
<td>Xu et al., 2004</td>
</tr>
<tr>
<td>Lanzhou (urban)</td>
<td>2001–2002,</td>
<td>307 (450nm)</td>
<td>Nephelometer M3563</td>
<td>Zhang et al., 2004</td>
</tr>
<tr>
<td></td>
<td>winter</td>
<td>226 (550nm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>131 (700nm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDZ (rural)</td>
<td>2003–2005</td>
<td>174.6 (525nm)</td>
<td>Nephelometer M9003</td>
<td>Yan et al., 2008</td>
</tr>
<tr>
<td>Beijing, (rural)</td>
<td>2005.03</td>
<td>468 (550nm)</td>
<td>Nephelometer M9003</td>
<td>Li et al., 2007</td>
</tr>
<tr>
<td>Wuqing, Tianjin (suburban)</td>
<td>2009.3.6–4.5</td>
<td>280 (550nm)</td>
<td>Nephelometer TSI3563</td>
<td>Ma et al., 2011</td>
</tr>
<tr>
<td></td>
<td>7.12–8.14</td>
<td>379 (550nm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xianghe (suburban)</td>
<td>2005.3</td>
<td>468 (550nm)</td>
<td>Nephelometer TSI3563</td>
<td>Li et al., 2007</td>
</tr>
<tr>
<td>Xinken, Pearl River Delta (suburban)</td>
<td>2004.10–11</td>
<td>333 (550nm)</td>
<td>Nephelometer TSI3563</td>
<td>Cheng et al., 2008</td>
</tr>
<tr>
<td>Guangzhou (urban)</td>
<td>2004.10–11</td>
<td>463 (530nm)</td>
<td>Nephelometer M903</td>
<td>Andreae et al., 2008</td>
</tr>
<tr>
<td>Guangzhou (rural)</td>
<td>2006.7</td>
<td>200 (450nm)</td>
<td>Nephelometer M3563</td>
<td>Garland et al., 2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td>151 (550nm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>104 (700nm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PKU, Beijing (urban)</td>
<td>2005–2006</td>
<td>288 (525nm)</td>
<td>Nephelometer M9003</td>
<td>He et al., 2009</td>
</tr>
<tr>
<td>Shouxian, Anhui(rural)</td>
<td>2008.5–12</td>
<td>401 (550nm)</td>
<td>Nephelometer TSI3563</td>
<td>Fan et al., 2010</td>
</tr>
<tr>
<td>Shanghai</td>
<td>2010.12–2011.3</td>
<td>293 (532nm)</td>
<td>Nephelometer M9003</td>
<td>Xu et al., 2012</td>
</tr>
<tr>
<td>Xi’an (urban)</td>
<td>2009</td>
<td>525 (520nm)</td>
<td>Nephelometer, Aurora1000</td>
<td>Cao et al., 2012</td>
</tr>
<tr>
<td>Chengdu (urban)</td>
<td>2011</td>
<td>456 (520nm)</td>
<td>Nephelometer, Aurora1000</td>
<td>Tao et al., 2014</td>
</tr>
<tr>
<td>Taiyuan (urban)</td>
<td>2013.8</td>
<td>189 (550nm)</td>
<td>Nephelometer TSI3563</td>
<td>Li et al., 2015b</td>
</tr>
<tr>
<td>Lanzhou</td>
<td>2007.3–2010.12</td>
<td>155 (520 nm)</td>
<td>Nephelometer M9003</td>
<td>Pu et al., 2015</td>
</tr>
<tr>
<td>Shanghai (urban)</td>
<td>2012.12</td>
<td>288.7 (550nm)</td>
<td>Nephelometer Aurora3000</td>
<td>Han et al., 2015</td>
</tr>
<tr>
<td>Mt. Huang</td>
<td>2012.9.30–10.8</td>
<td>103.1 (550nm)</td>
<td>Nephelometer TSI3563</td>
<td>Yuan et al., 2016</td>
</tr>
<tr>
<td>Xinzhou (rural)</td>
<td>2014.07–08</td>
<td>192.1 (550nm)</td>
<td>Nephelometer TSI3563</td>
<td>This study</td>
</tr>
</tbody>
</table>
89% of the total $N_a$. Aerosols with an $M_a$ value of 12.5 µg m$^{-3}$ frequently appeared with a frequency of 0.28. Aerosols with an $M_a$ value of less than 25 µg m$^{-3}$ contributed to 84% of the total $M_a$, indicating that the station was located under relatively clear conditions in this field campaign. The peak frequency of $\sigma_{sc}$ appeared at 75 Mm$^{-1}$, and the peak value frequency was 0.27. Most of the hourly $\sigma_{sc}$ values were less than 300 Mm$^{-1}$ with a total frequency of 0.83. The total probability of hourly averaged $\alpha$ with values higher than 1.5 was 0.84. Overall, during the observation period, the average $N_a$, $M_a$, and $\sigma_{sc}$ values were generally less than 30000 cm$^{-3}$, 25 µg m$^{-3}$, and 300 Mm$^{-1}$, respectively, and the $\alpha$ value was generally higher than 1.5, signifying that the majority of aerosols in the observed region were small particles.

Diurnal Variations of $N_a$, $M_a$, $\sigma_{sc}$, and $\alpha$

Fig. 6 presents the diurnal variations of $N_a$, $M_a$, $\sigma_{sc}$, and $\alpha$. The diurnal variation of $N_a$ (Fig. 6(a)) showed a single-peak pattern. The $N_a$ value began to increase at 9:00, peaked at 12:00, and then decreased gradually and dropped to the lowest value at 16:00. Compared with $N_a$, $M_a$ exhibited a two-peak pattern (Fig. 6(b)), which occurred at 7:00 and 21:00, and the lowest value occurred at 16:00. Fig. 6(c) displays the diurnal cycle for $\sigma_{sc}$. The curve shape for $\sigma_{sc}$ is analogous to the diurnal variation of $M_a$ but relatively smoother. The higher value of $\sigma_{sc}$ appeared in early time from 7:00 to 10:00, and the $\sigma_{sc}$ decreased from 11:00 to 18:00, reached the lowest value at 18:00, and then increased slightly again at night with no obvious peak value. The diurnal variation of $\alpha$ (Fig. 6(d)) showed a negative correlation with the daily variation of $\sigma_{sc}$, and the $\alpha$ value fluctuated within a small scope.

New particle formation (NPF) events were closely related to diurnal variation patterns of $N_a$. NPF events can be defined as the bursts of the nucleation-mode $N_a$ for a period (hours) followed by the growth of newly formed particles to larger sizes (Birmili and Wiedensohler, 2000; Zhang et al., 2017). In the 42-day field campaign (29 clear days), 14 NPF events were observed. Table 3 lists the statistical values associated with six typical NPF events including the initial time, end time, duration time, growth of the total $N_a$ value ($\Delta N_{\text{Total}}$), growth of the $N_a$ value with GMD ranging from 10 to 20 nm ($\Delta N_{10-20}$), proportion of $\Delta N_{10-20}$ to $\Delta N_{\text{Total}}$ ($P_{\Delta N_{10-20}/\Delta N_{\text{Total}}}$, $P$), particle growth rate (GR), and particle formation rate (FR). The particle GR and FR were calculated using Eqs. (3) and (4) (Kulmala et al., 2004; Zhang et al., 2017).

$$GR = \frac{\Delta D}{\Delta t}$$

(3)

where $D_m$ is the particle size range $[D, D_{\text{max}}]$, $\Delta t$ is the duration time of the particle formation event, and the unit of GR is nm h$^{-1}$.  

Fig. 5. Frequency distribution for hourly averages of $N_a$ (a), $M_a$ (b), $\sigma_{sc}$ (c), and $\alpha$ (d).
Table 3. Case statistics of aerosol particle formation and growth during observation.

<table>
<thead>
<tr>
<th>Date</th>
<th>Initial time</th>
<th>End time</th>
<th>Duration</th>
<th>$\Delta N_{total}$</th>
<th>$\Delta N_{10-20}$</th>
<th>$P$</th>
<th>$D_{\text{max}}$ (nm)</th>
<th>$J_{10}$ (cm$^{-3}$s$^{-1}$)</th>
<th>GR (nm h$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/24</td>
<td>8:29</td>
<td>12:29</td>
<td>4:00</td>
<td>72701</td>
<td>43829</td>
<td>0.6</td>
<td>34</td>
<td>3.04</td>
<td>6.00</td>
</tr>
<tr>
<td>7/25</td>
<td>8:15</td>
<td>12:45</td>
<td>4:30</td>
<td>29401</td>
<td>25145</td>
<td>0.86</td>
<td>38</td>
<td>1.55</td>
<td>6.22</td>
</tr>
<tr>
<td>7/28</td>
<td>8:02</td>
<td>11:47</td>
<td>3:45</td>
<td>52249</td>
<td>33817</td>
<td>0.65</td>
<td>41</td>
<td>2.56</td>
<td>8.27</td>
</tr>
<tr>
<td>8/8</td>
<td>9:48</td>
<td>13:18</td>
<td>3:30</td>
<td>40892</td>
<td>21391</td>
<td>0.52</td>
<td>42</td>
<td>1.70</td>
<td>9.14</td>
</tr>
<tr>
<td>8/24</td>
<td>9:03</td>
<td>14:03</td>
<td>5:00</td>
<td>48767</td>
<td>29114</td>
<td>0.6</td>
<td>42</td>
<td>1.62</td>
<td>6.40</td>
</tr>
<tr>
<td>8/25</td>
<td>8:04</td>
<td>12:55</td>
<td>4:51</td>
<td>26524</td>
<td>18822</td>
<td>0.71</td>
<td>46</td>
<td>1.08</td>
<td>7.42</td>
</tr>
<tr>
<td>Aveg.</td>
<td>8:36</td>
<td>13:18</td>
<td>4:16</td>
<td>45089</td>
<td>28686</td>
<td>0.66</td>
<td>40.5</td>
<td>1.93</td>
<td>7.24</td>
</tr>
</tbody>
</table>

Eq. (4) was $N_{10,20}$ mm$^{-1}$.

All NPF events on sunny days and most NPF events here were initiated approximately between 08:00 and 10:00 when the solar radiation rapidly increased and continued until 12:00 or even after 14:00, lasting for approximately 3–5 hours. The average duration was 4.3 hours, with the

$$ R = \frac{\Delta N_{D_{\text{max}}, \text{max}}}{\Delta t} $$

where $\Delta N_{D_{\text{max}}, \text{max}}$ is $N_{a}$ in the size range $[D_{\text{min}}, D_{\text{max}}]$ and $\Delta t$ is the duration time of the particle formation event; the unit of FR is cm$^{-3}$ s$^{-1}$. In this study, an NPF event was defined as $N_{a}$ falling within the first 16 size bins of the SMPS (diameter midpoint range from 11.8 to 20.2 nm) bumped up; the FR was considered as the particle FR at 10 nm ($J_{10}$), and $\Delta N_{D_{\text{max}}, \text{max}}$ in Eq. (4) was $N_{10,20}$ mm$^{-1}$.
minimum and maximum durations being 3.5 and 5 hours, respectively. Both $\Delta N_{\text{Total}}$ and $\Delta N_{10-20}$ increased during NPF events. The maximum and minimum values of $\Delta N_{\text{Total}}$ were 72701 and 26524 cm$^{-3}$, respectively, with an average value of 45089 cm$^{-3}$. The maximum and minimum values of $\Delta N_{10-20}$ were 43829 and 18822 cm$^{-3}$, respectively, with an average value of 28686 cm$^{-3}$. The proportion of $\Delta N_{10-20}$ to $\Delta N_{\text{Total}}$ was 0.52 to 0.86, with an average of 0.66, suggesting that the proportion of nucleation particles with GMD ranging from 10 to 20 nm considerably contribute to the total number concentration. The size of newly formed particles was mainly between 10 and 50 nm (particles with a size smaller than 10 nm cannot be observed by the SMPS used in this field experiment), and the corresponding particle size range with high number concentration values was generally from 10 to 30 nm. The particle FR ranged from 1.08 to 3.04 cm$^{-3}$ s$^{-1}$, with an average value of 1.93 cm$^{-3}$ s$^{-1}$, and the particle GR varied from 6.0 to 9.14 nm h$^{-1}$, with an average value of 7.24 nm h$^{-1}$. The FR and GR values obtained in this study were compared with those reported for other places in North China. The average FR value obtained in this study is lower than that recorded in Shangdianzi (SDZ) in the North China Plain (8.0 cm$^{-3}$ s$^{-1}$) (Shen et al., 2011); furthermore, the average GR value obtained in this study is higher than those obtained in SDZ (4.3 nm h$^{-1}$) (Shen et al., 2011) and Xi’an (5.0 ± 1.9 nm h$^{-1}$) (Peng et al., 2017).

In this case study, an NPF event that occurred on August 24, 2014, was selected. Figs. 7(a), 7(b), 7(c), 7(d), and 7(e) illustrate the diurnal variations of the contour plots of the average particle number-size distribution, $\Delta N_{\text{Total}}$ and $\Delta N_{10-20}$, particle GMD and $M_a$, WS and WD, and temperature and RH, respectively. August 23 was a rainy day, with the daily accumulated rainfall being 10.1 mm. Thus, an NPF event occurred on the following day, August 24. The NPF event started when the WS decreased from 2.3 to 0.8 m s$^{-1}$, nearly in a state of breeze, and remained at a low value (approximately 1 m s$^{-1}$), which benefited the accumulation of newly formed particles (Zhang et al., 2017). The RH remained below 40% and the temperature was higher than 24°C when the NPF event occurred. During the NPF.

![Fig. 7. Diurnal variations of contour plots of average particle number-size distribution (a), $\Delta N_{\text{Total}}$ and $\Delta N_{10-20}$ (b), particle GMD and $M_a$ (c), wind speed and wind direction (d), and temperature and relative humidity (e).](image-url)
duration, both the total $N_a$ and the nucleation-mode $N_a$ (10–20 nm) increased, revealing a good positive correlation. The average $GMD$ of total particles and the $M_a$ decreased to the lowest values before the start of the NPF event and then further increased slowly during the NPF duration. Both the average $GMD$ and $M_a$ also showed a satisfactory positive correlation.

To further investigate the contribution of NPF effects on diurnal variation of $N_a$, the diurnal variation curves of $N_a$ in total days, NPF days and non-NPF days were displayed separately in Fig. 8. Compared the three diurnal variation curves, a peak value was obviously showed at 12:00 in the curve of NPF days, and the same feature was seen in the curve of total days, however there was no peaks at the same time in the curve of non-NPF days, indicating that NPF events contributed a lot to the diurnal variation of $N_a$ during the experiment period.

From Table 3, Figs. 7 and 8, the reason for the diurnal variation of $N_a$ distribution can be nearly explained. As shown in Fig. 6(a), the $N_a$ value increased from 09:00 and peaked at 12:00. Table 3 and Fig. 7 indicate that the time range when the NPF event normally occurred was from 09:00 to 12:00, which is in accordance with the time range of the increase in $N_a$. From 9:00, solar radiation began to enhance gradually. Thus, NPF events occurred frequently because of the photochemical effect, leading to the generation and accumulation of fine particles, especially those with a nanoscale size. This further caused an increase in $N_a$ which peaked at 12:00. By contrast, the NPF had only a little influence on diurnal variation of particle mass concentration because the size of these newly formed particles was very small.

The diurnal variation of aerosol $M_a$ (Fig. 6(b)) showed two peaks at time intervals between 7:00–8:00 in the morning and 18:00–21:00 in the evening, which correspond to the local daily rush hours in summer that involve intensive human activities. Strong pollutants emitted from human activities, such as transportation and cooking, during the morning and evening rush hours may enhance the peak pollutant levels in the corresponding time, which affected the diurnal variation of aerosol $M_a$.

Combined the meteorological data from the Global Data Assimilation System (GDAS) (NECP, $1° \times 1°$) of the American Meteorological Environment Prediction Center and the Hybrid of Single Particle Lagrangian Integrated Trajectory (Hysplit 4) model (Draxler and Hess, 1997) from the Atmosphere Research Laboratory (ARL) of the National Oceanic and Atmospheric Administration (NOAA) and the Australian Bureau of Meteorology, the Boundary Layer Heights (BLH) during the experiment period of the observation site (112.12°E, 38.07°N) were calculated to detect the effects of the BLH on diurnal variation of aerosol scattering features over the observation region. Fig. 9 shows the diurnal variation of average BLH from July 20 to August 30, 2014. The average values of BLH were lower in night time. From earlier time around 6:00 in the morning, the BLH began to develop and reached the maximum height at around 14:00, and decreased slowly. On the contrary, the average values of $\sigma_{sc}$ were relatively higher in time of 7:00–9:00, decreased after 10:00 and reached the lowest at 18:00, and then increased slowly during night time, which were partly attributed to the enhanced emissions in the morning and the turbulent dilution with the PBL development after noon. This results were as same as the studies of Wuqing in the North China Plain (Ma et al., 2011), Guangzhou in the Pearl River Delta (Garland et al., 2008), and Nanjing, in the Yangtze River Delta (Yu et al., 2016).

Additionally, the relationship between $M_a$ and $\sigma_{sc}$ was positive, with the linear correlation coefficient being 0.95 (Fig. 10), thus resulting in similar diurnal variation curves for both parameters.

**Average Aerosol Size Distribution**

Fig. 11 shows the average aerosol number-size and mass-size spectral distribution curves on rainy, non-rainy, and total observation days. Figs. 11(a) and 11(c) present a bimodal spectrum of the average particle number-size distribution. As indicated in this figure, the main peak value

![Fig. 8. Diurnal variation characteristics of $N_a$ in in total days, NPF days and non-NPF days, the vertical lines are the standard deviations.](image-url)
Fig. 9. Diurnal variations of scattering coefficients as well as the average Boundary Layer Height (PBL) during the experiment period.

Fig. 10. Correlation of $M_a$ with $\sigma_{sc}$.

of $N_a$ appeared in the particle size range of 10–20 nm and the secondary peak value appeared in the particle size range of 50–70 nm. A unimodal distribution could be clearly seen in the aerosol mass spectrum curve (Figs. 11(b) and 11(d)), with a high $M_a$ appearing in the particle size range of 100–400 nm and the peak value appearing at 300 nm. The $N_a$ value of particles with diameters of 10–300 nm was lower on rainy days than on non-rainy days; by contrast, the $N_a$ value of particles with diameters larger than 300 nm was higher on rainy days than on non-rainy days. The particle mass-size distribution curves for rainy and non-rainy days could be observed to nearly overlap at diameters of 10–300 nm; however, the average $M_a$ line on rainy days showed an increasing trend, and the average $M_a$ line on non-rainy days decreased. Both of the shapes of the particle number-size and mass-size distribution curves on rainy and non-rainy days were similar, indicating that rainy weather with high RH had effects on particle size distribution especially particles with size larger than 300 nm, and the same features were showed in observational studies in Beijing (Bergin et al., 2001), Mt Huang (Yin et al., 2010), and the Pearl River Delta (Cheng et al., 2008) of China. An average aerosol $M_a$ with higher values generally appeared in particles larger than 100 nm (Fig. 11(d)), which is in contrast to the aerosol number-size distribution (Fig. 11(c)). Therefore, particles smaller than 100 nm contributed the majority of the total $N_a$ and particles larger than 100 nm contributed to the total aerosol $M_a$ during the field measurements.

**Potential Source Contribution Analysis**

Potential source contribution function (PSCF) is the probability that an air parcel with a given or a higher concentration of a pollutant arrives at a receptor site after having been passed through a specific geographical area (Gao et al., 1993; Brankov et al., 1998; Cape et al., 2000; Backer, 2010). PSCF analysis is a method used to determine pollution potential sources by combining the air mass trajectory (NOAA, the Hysplit) (Draxler and Rolph, 2003; Dan et al., 2016) and the corresponding element values based on the conditional probability function.

PSCF is defined as the conditional probability of a particular parameter (such as the number concentration, $M_a$, and optical properties) of an air mass coming from some specific area and reaching the observation station, which is larger than the corresponding set threshold value (Gao et al., 1993). If the air mass transportation track stops over a grid point $(i, j)$, where $i$ and $j$ represent the longitude and latitude, respectively, the emissions belonging to the grid will arrive at the final receptor through the air mass. Thus, the probable places of aerosol sources, which can lead to a high value of certain parameters in the receptor site, can be determined through the PSCF method.

In this study, the experimental area was divided into a $0.2^\circ \times 0.2^\circ$ grid. A threshold value was set for the elements, when the element value of the trajectory was higher than the threshold. The trajectory was considered as pollution; $m_{ij}$ is the number of pollution trajectories whose endpoints fall within the grid $(i, j)$, whereas $n_{ij}$ is the number of regular trajectories whose endpoints fall within the grid $(i, j)$.

PSCF can be expressed by Eq. (5). PSCF is a type of conditional probability, and the error of PSCF increases with an increase in the distance between the grid and sample points. When $n_{ij}$ is low, a larger uncertainty is generated. To reduce the uncertainty, the weighting function $W(n_{ij})$ is introduced in Eq. (6) (Hopke et al., 1995; Polissar et al., 1999; Xu and Akhtar, 2010).

When an $n_{ij}$ value in a certain grid is lower than three times the average number of trajectory endpoints ($n_{ave}$) within
Fig. 11. Particle number-size and mass-size distribution characteristics during the observation days. From (a) to (d), the parameters are: (a) particle number-size distribution on rainy and non-rainy days; (b) particle mass-size distribution on rainy and non-rainy days; (c) average values of the particle number-size distribution curve over all observation days; and (d) average values of the aerosol mass-size distribution curve over all observation days. In (c) and (d), the colored dotted lines show the daily average spectral distribution curve, and the vertical blue or red lines show the standard deviation.

Each grid of the research area, $W(n_{ij})$, should be used to reduce the uncertainty of the PSCF analysis. A higher PSCF value indicates higher contribution of this grid interval to the particle concentration of the observation station.

$$PSCF_{ij} = \frac{n_i}{n_j} \times W(n_{ij})$$  \hspace{1cm} (5)

$$W(n_{ij}) = \begin{cases} 1.0, & 3n_{ave} < n_{ij} \\ 0.7, & 1.5n_{ave} < n_{ij} \leq 3n_{ave} \\ 0.4, & n_{ave} < n_{ij} \leq 1.5n_{ave} \\ 0.17, & n_{ij} \leq n_{ave} \end{cases}$$  \hspace{1cm} (6)

In this study, the potential sources of aerosol contributing to aerosol scattering characteristics were analyzed along with the backward trajectories of air masses and aerosol $\sigma_{sc}$. The grid area corresponding to high PSCF values was the potential aerosol source area for the central region of Shanxi, and the trajectories passing by this receptor area were the conveying paths, which affected aerosols. Fig. 12 presents the results of the PSCF analysis based on aerosol $\sigma_{sc}$ as the characteristic parameters, with the Xinzhou station (112.70°E, 112.70°N) of Shanxi serving as the receptor. Fig. 12 shows that aerosols of central Shanxi in the summer of the observation period mainly came from local emission or regional transmission, and most of the transmission distances were in the short range. Aerosol potential sources were mainly concentrated in the severely polluted areas of North China with high population density and serious industrial and traffic pollution, such as Hebei Province, southwest area of Shandong Province, north and northeast area of Henan Province, and north area of Hubei Province. The PSCF values of Hebei and Shandong were the highest, and the contribution values were between 0.7 and 0.9. The PSCF values of southern Shanxi and Henan Province were between 0.6 and 0.9.

Some aerosols were delivered through long-distance transportation. Examples include particles transported from the Xinjiang region of northwest China through Gansu, Inner Mongolia, Ningxia and Shaanxi; particles transported from outer Mongolia through northern Shanxi; and some particles transported from southeast of China. The PSCF value of these remote areas was approximately 0.1–0.2. Overall, the central Shanxi area was highly affected by its east, south, and southeast air masses in the summer of 2004, with a relatively high PSCF value of 0.6 or higher. Particles from long-distance transmission were less, with a PSCF value of less than 0.3.
CONCLUSIONS

Field measurements of atmospheric aerosol characteristics at a suburban site in Shanxi Province, North China, were conducted from July 20 to August 30, 2014.

The majority of aerosols in this region were small particles. The average values of \(N_a\), \(M_a\), GMD, \(\sigma_{sc}\), and \(\alpha\) were 19653.2 cm\(^{-3}\), 17.7 \(\mu\text{g m}^{-3}\), 44.38 nm, 186.7 Mm\(^{-1}\), and 1.77, respectively, in non-rainy days and 14323.1 cm\(^{-3}\), 15.3 \(\mu\text{g m}^{-3}\), 44.98 nm, 226.9 Mm\(^{-1}\), and 1.87, respectively, in rainy days. The maximum and average values of \(N_a\) and \(M_a\) were lower in rainy days, but the maximum and average values of GMD and \(\sigma_{sc}\) were higher in rainy days than in the non-rainy days. The frequency distribution features showed that the average \(N_a\), \(M_a\), and \(\sigma_{sc}\) values were less than 30000 cm\(^{-3}\), 25 \(\mu\text{g m}^{-3}\), and 300 Mm\(^{-1}\), and the \(\alpha\) value was higher than 1.5.

The diurnal variation of \(N_a\) showed a one-peak distribution, and the peak value usually occurred at 12:00; that of \(M_a\) showed two peaks, which occurred at 7:00 and 21:00; that of \(\sigma_{sc}\) was analogous to the diurnal variation of \(M_a\); and that of \(\alpha\) showed a negative correlation with the daily variation of \(\sigma_{sc}\). NPF events generally began at 08:00–10:00 and continued until 12:00 or even after 14:00. The proportion of nucleation particles with GMD of 10–20 nm contributed majorly to the total \(N_a\). The average FR and GR were 1.93 cm\(^{-1}\) s\(^{-1}\) and 7.24 nm h\(^{-1}\), respectively. NPF events were the main reason for the higher value and diurnal variation of \(N_a\), whereas the diurnal variation of the aerosol \(M_a\) was mainly influenced by pollutant emissions from local human activities.

The average aerosol number-size distribution had a bimodal spectrum, and the average mass-size spectral distribution curves showed a unimodal distribution. The \(N_a\) and \(M_a\) values of particles with diameters of 10–300 nm were lower on rainy days than on non-rainy days; however, the average \(M_a\) curve on rainy days showed an increasing trend when the particle diameters were larger than 300 nm. Overall, particles smaller than 100 nm contributed the majority of the total \(N_a\), whereas particles larger than 100 nm contributed considerably to the total aerosol \(M_a\) during the field measurements in Shanxi in the summer of 2014.

The potential sources of aerosols for the central area of Shanxi were analyzed in combination with the backward trajectories of air masses and aerosol \(\sigma_{sc}\). Aerosol potential sources were mainly concentrated in Hebei Province, the southwest area of Shandong Province, the north and northeast area of Henan Province, and the north area of Hubei Province. The PSCF values of these areas were above 0.6.

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