Seasonal and vertical variations in aerosol distribution over Shijiazhuang, China

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HIGHLIGHTS
- Surface aerosol concentration and aerosol vertical distribution were analyzed.
- We apply a four-modal log-normal size distribution to fit aerosol size distribution.
- Meteorological conditions are found to exert a major influence on the aerosol distributions.
- The aerosol vertical profiles under synoptic conditions can be categorized into three types.

ABSTRACT
To obtain a representative sampling of aerosol vertical profiles, we performed an extensive airborne characterization of aerosols under different environmental conditions over Shijiazhuang, China. Surface aerosol concentration and aerosol vertical distribution were analyzed using a set of 104 vertical profiles of aerosol number concentration and size distribution ranging from 0.1 to 3 μm observed by PCASP-100X. A four-modal lognormal size distribution with 10-based logarithm was applied to fit measured aerosol size distributions at different altitudes of three seasons (spring, summer and autumn). It was found that the surface aerosol number concentration had a negative correlation with wind speed. In addition to wet removal of aerosols owing to precipitation in summer, vertical transport of aerosols from the surface to high levels is strongly influenced by convective instability, which contributes to the seasonality of aerosol vertical profiles. The aerosol vertical profiles under a wide range of synoptic conditions can be categorized as “ED” (exhibiting an exponential declining tendency with altitude), “SAL” (aerosol layers existing near surface), and “BAL” (aerosol layers at the boundary layer height). The multi-lognormal fitting captures the total aerosol number size distribution at 0.1–3 μm reasonably well. The average scale height of aerosols during spring, summer and autumn is 1.0 km, 1.6 km and 1.0 km, respectively.

1. Introduction
Vertical variation of aerosol distribution has significance on aerosol–cloud–climate interactions from several aspects, including atmospheric transport, aerosol activation efficiency to cloud condensation nuclei, light scattering and absorption, wet and dry deposition fluxes, interaction between biological systems and aerosols (Maring et al., 2003). Numeric models should not neglect the contribution of aerosol vertical variations when assessing aerosol direct and indirect effects.

Globally, thermal-dynamic structure and turbulence in the boundary layer are responsible for aerosol transport from the ground to higher levels. Meteorological conditions are found to exert a major influence on the aerosol distributions (Birmili et al., 2001; Fuelberg et al., 1996; Tai et al., 2012). Atmospheric stability represents the extent to which thermal-dynamic structure impacts on turbulence generation, enhancement or suppression, and significantly influences aerosol transport. Convective available potential energy (CAPE) and the lifted index (LIFT) are two key parameters in quantifying the atmospheric stability. CAPE depicts the atmospheric convective energy, and elevated CAPE indicates an increase of atmospheric instability. LIFT is given by the temperature difference between the 500 hPa isobaric surface and parcels first arising from modified ground along the dry adiabatic, and then...
along the moist adiabatic after reaching the condensation level on the T-logp map, decreasing as the instability enhances (Rasmussen and Blanchard, 1998). Stratification of haze layers was observed on days when profiles of stability were neutral or weakly stable (Stein et al., 2003). Relatively few studies have been performed to quantify the impacts of meteorological parameters on aerosol variation over China. Aerosol transport is largely related to atmospheric vertical velocity and temperature inversions, in terms of horizontal and vertical aspects.

Understanding the impacts of synoptic situations on aerosol vertical variation has been the focus of many researches in the past, including exploration of synoptic patterns in highly polluted events over urban areas. Persistent atmospheric stability and pollution slow down the decrease rate of aerosol concentration with altitude. Zhang et al. (2009) analyzed the correlation between surface synoptic situations and aerosol distributions. Synoptic patterns also have regional significance in ozone episodes in Hong Kong (Huang et al., 2006). Cold front passages usually dominate over the North China Plain (NCP) and tend to bring gale to the region in 12–24 h behind the front. Mechanisms responsible for pollutant transport to upper troposphere in Asia are mainly caused by deep convection in cloud scale, and warm conveyor belts in front of cold frontal synoptic system. Further discussion of synoptics can be found in Mari et al. (2004).

To date, however, very little work has been done on statistical analysis of long term aerosol vertical variations over China. Well-documented observations of aerosol vertical variations are required for reliable modeling of aerosol radiative properties and their effects on cloud processes. Aerosols in the upper troposphere influence the earth radiation budget by modulating cirrus and heterogeneous chemical processes. Various intensive aircraft field measurements allowed us to study meteorological impacts on aerosols.

The objective of this work is to investigate how synoptic properties and meteorological parameters impact the aerosol vertical variations. Seasonal evolution of aerosol size distribution and aerosol scale height are also investigated over the NCP region. This work intends to contribute to the understanding of the aerosol seasonality and the role played by synoptic situations and meteorological properties over the urban regions in China. The main goal of this study is to draw up a set of representative aerosol vertical distributions for different types of synoptic patterns using statistical analysis of a large number of in situ airborne measurements.

2. Data and methodology

In situ airborne measurements of aerosol particles have been collected over Shijiazhuang (38.03° N, 114.26° E), China, during 2006–2010 excluding winters. The city is located about 264 km southwest of Beijing, the hinterland area in North China Plain with a high population density. The region is characterized by a warm temperate monsoon climate, dominated by the northern cyclones and cold fronts in the spring, resulting in strong wind, and precipitation by convection is mainly concentrated in summer.

The Cheyenne-III aircraft operated by the Weather Modification Office of Hebei Province was equipped with a suite of instruments made by the Particle Measuring System (PMS) Co., USA, including a passive cavity aerosol spectrometer probe (PCASP-100X) for aerosols, a FSSP-ER for droplet size distribution, a 2D-C probe for measurements of two dimension images. The PCASP-100X is an optical particle counter for measuring aerosol size distribution from 0.10 to 3.00 μm in diameter in 15 different size bins with a frequency of 1 Hz. The sample flow volume in the PCASP-100X was set to 1 cm³ s⁻¹. The sample inlet is designed to minimize aerosol losses. The inlet is on the front of the probe and enters a direct sample path without turns or corners. The intake tube cone provides a flow deceleration ratio of 10:1 to isokinetically match the inlet needle flow of 8–10 m s⁻¹. The sample inlet needle has an Inner Diameter of 0.5 mm which maintains into the sample inlet of the sample cavity. The total transit time in the inlet section is only a few hundredths of a second. The other onboard equipments, for example, pressure sensor, King LWC probe and the GPS device, permit meteorological properties, location and altitude observations. The calibration is conducted every year using polystyrene latex spheres (PSL) by Particle Metrics Inc. (PMI) in the United States before the measurements take place. Aerosols were sampled during descending or climbing up flight legs at different altitudes. The ground meteorological station has been continuously measuring air temperature, pressure and humidity.

Vertical distributions of aerosols are the mean values in 50 m, 100 m, 200 m intervals at altitude ranges from 0–600 m, 600–3000 m and 3000–7000 m, respectively, to minimize observational biases. In order to have a view of the meteorological properties impact on aerosol variation, the NCAR/NCEP daily reanalysis data was used, with a horizontal resolution of 1° × 1° and 26 vertical levels, involving horizontal and vertical velocity fields. Flight patterns typically consist of several vertical profiles up to maximum ~7 km combined with low altitude horizontal legs over the urban area in Shijiazhuang (~117 km²). All flights started and ended at Zhengding International Airport, Shijiazhuang.

Data obtained from 104 flights were used in this study, in which, 35 flights conducted in spring (March to May), 14 flights in summer (mainly June) and 55 flights in autumn (September to November). We used the multi-lognormal distribution function to fit the measured aerosol particle size distribution, which is defined as

$$\frac{dN(D)}{d(\log(D_p))} = \sum_{i=1}^{n} N_i \frac{\exp\left(-\frac{(\log(D_p) - \log(D_{i,fl})})^2}{2(\log(g_{i,fl})^2}\right)}{2\pi g_{i,fl}^2}$$

(1)

where n is the number of modes per size distribution for the best fit, $D_p$ is the particle diameter in μm, $N_i$ is the particle number in mode i, $D_{i,fl}$ is the geometric mean diameter of the mode i in μm and $g_{i,fl}$ is the standard deviation of mode i (Seinfeld and Pandis, 1998).

The scale height of aerosols where vertical profiles of aerosol concentration approximately satisfy an exponential decline function reflects aerosol characteristic properties in the boundary layer, defined as the equivalent thickness of the aerosol layer where aerosol number concentrations remain constant with height. Seasonality analysis of the scale height of aerosols over the North China Plain is performed, noting that the distribution of aerosol particle profiles is expressed by the exponential equation as follows:

$$N_z = N_0 e^{-z/H_p}$$

(2)

where $N_z$ denotes the aerosol number concentration at altitude $z$, $N_0$ represents aerosol number concentration at the surface, and $H_p$ is the scale height, which describes the slope of the profiles (Fernández-Gálvez et al., 2013).

3. Results and discussion

3.1. Seasonal variation of aerosol vertical distribution

Fig. 1 displays the seasonal evolution of the profiles of the number concentration of aerosol particles derived from 104 flights. It can be seen that the vertical variations of the concentration of aerosol particles below about 2.5 km are quite close, but when we compare the seasonal series of aerosol vertical variations with each other, considerable difference exists above the 1200 m level.
The total particle number concentration sized 0.1–3 μm of different altitudes in different seasons together with some meteorological parameters is presented in Table 1. Since precipitation can clean aerosols out of the atmosphere, the aerosol concentrations are the lowest in the summertime from surface to 600 m level due to moderate precipitation during June over the Shijiazhuang region. The maximum aerosol number concentration near surface was found during the autumn, dominated by relatively weak winds compared with the other two seasons, which then show a tendency of declining with altitudes. Biomass burning and industrial activities are considerable sources of anthropogenic aerosols. CCN concentrations are highest due to the burning of biomass in the late dry season (Ross et al., 2003). Agricultural biomass burning might contribute to the accumulation mode particles in autumn, which is the harvesting season in NCP (Wu et al., 2008).

The height of the atmospheric boundary layer (ABL) is a fundamental parameter characterizing the structure of the lower troposphere (Seibert et al., 2000). Normally, the boundary layer is capped by a temperature inversion or an absolutely stable layer, above which aerosol concentrations decrease sharply. The ABL also exhibits a clear seasonal variation, as can be seen in Table 1. The total aerosol number concentrations sized 0.1–3 μm show a relative maximum from 600 m to 1200 m level in springtime due to its highest ABL height (1120 m), within which a relatively uniform aerosol vertical distribution is observed. Intense convection can penetrate stable layers, thus transporting aerosols to a higher level. Stronger convective activity during summertime favors elevated aerosol concentrations above 1200 m. The results aforementioned highlight that seasonal variation of aerosol vertical distributions is linked to precipitation, surface wind, the ABL height and atmospheric convective intensity at different altitudes.

3.2. Variation of surface aerosol concentrations

Surface aerosols play an important role in human life, which is defined as particles within the layer of 0–500 m (≈950 hPa) in this work. To confirm the relationship between the meteorological characteristics and the surface aerosols, statistic analysis of synoptic patterns during 104 research flights was performed. The analysis identifies three categories of surface aerosols under a wide variety of weather conditions: Type I, Type II, and Type III, are defined when surface aerosol concentration is less than 5.0 × 10^3 cm^{-3}, 5.0–10^3 cm^{-3} and more than 1.0 × 10^4 cm^{-3}, respectively. Synoptic situations corresponding to each type are characterized.

Table 2 summarizes the surface aerosol concentrations in the three types of all the flights and the corresponding winds. Type I exhibits a high frequency as 67% among all the three surface aerosol distribution types, justifying it as the dominating surface aerosol features in this region. Average frequency of Type III, associated with heavy pollution episodes, recorded over the industrialized region is extremely low (3%). In order to characterize the effect of wind speed on aerosol concentrations, wind speed from 1000 hPa to 950 hPa was computed from the NCEP data. Optimum correlation was obtained between the aerosol concentrations and the surface wind speeds under 950 hPa level. Type I with relatively low aerosol concentrations is typically under strong wind speed, suggesting that there is a significant negative correlation between surface wind and aerosol concentrations at the sizes between 0.1 μm and 0.3 μm. Fig. 3 illustrates the seasonal distributions of the three surface aerosol types.

The maximum distribution frequency in spring, summer and autumn is observed in Type I, which is 0.63, 0.73 and 0.73, respectively, followed by that of Type II (Fig. 2). The frequency of Type III is the lowest in three seasons, which was observed in autumn only, mainly resulted from the weak surface winds and relatively lower boundary height.

Presence of considerable winds is generally associated with high surface atmospheric pressure after the frontal passage, an intermediate region of the high and the low, or the southerly ahead of the inverted trough and the low. These situations favor the advection of surface aerosols to the neighboring regions. In addition, large scale vertical motions are responsible for aerosol transport from the ground to the upper troposphere, with an average of 600 cm^{-3} for surface aerosol concentrations, in accordance with the results obtained in Beijing under the same synoptic conditions. Cyclonic low as well as the pre-frontal warm regions, are the favorable synoptic conditions of aerosol penetration high into the troposphere. When the surface is dominated with a weak low pressure system, ascending airflow due to convergence linked with wind shear at the 850 hPa level or ahead of the trough, could also result in cases of Type I.

Under these weather conditions, Type III is highly favored: windless conditions in the relatively low pressure zones ahead of the surface high, and sinking airflow in high pressure systems which can prohibit aerosol uplifting, thus facilitate the accumulation of surface aerosols. The capping inversion associated with the
3.3. Case study of typical aerosol vertical distributions

3.3.1. Classification of aerosol vertical distributions

The aerosol profiles under a wide range of synoptic conditions can be categorized as “ED” (exhibiting an exponential declining tendency with altitude), “SAL” (aerosol layers existing near surface), and “BAL” (aerosol layers at the boundary layer height).

Parallel to measuring aerosol vertical distributions, local meteorological data and synoptic patterns during corresponding flights have been analyzed. Considerable winds at upper levels and absence of inversion layers are favorable factors for aerosol vertical transport and advection, resulting in an exponential declining tendency of aerosol profiles. Westerly trough and cold frontal systems are the prevailing synoptic situations at high altitudes for ED. The region is dominated by the westerly ahead of the cold frontal trough. The long lasting cold frontal systems can increase the cloud cover before or after the frontal zones, by inducing cold air flowing southwards during its whirling moving. At the same time, ED is usually correlated with surface low pressure or cyclones. SAL refers to aerosol profiles with fairly constant aerosol concentrations in inversion layers and then exponentially decline with altitudes. The northwesterly behind the trough or ahead of the ridge with a higher frequency, or behind the vortex system is the prevailing conditions at upper levels associated with SAL. With surface high pressure systems, sunny days with inversion during night due to temperature falling are observed frequently among the SAL cases. BAL can be attributed to inversion in the atmosphere but with relatively weak convective activities near the ground, leading to a much less uniform aerosol distribution than that of SAL within the boundary layer, but only accumulate at the boundary layer altitude. The westnortherly also occurs among most BAL cases, but with surface low pressure systems. Sunny days with less cloud favor the formation of inversion, and at the same time, the surface lows are linked to wind divergence near ground.

As examples of the above mentioned classifications (Fig. 3), three specific cases will be discussed in the following sections to illustrate how different synoptic meteorological parameters lead to aerosol profiles measured over Shijiazhuang.

3.3.2. Meteorological conditions of three cases

Fig. 4 shows the synoptic systems for the 3 cases under different conditions. In case 2009-10-16, classified as ED, one can see that aerosols are mainly contained from the surface to the 500 m level with a mean concentration of $2205 \text{ cm}^{-3}$, and monotonically decreased to a mean concentration of $420 \text{ cm}^{-3}$ above 500 m, showing an exponential decrease tendency which has been the

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**Table 1**

<table>
<thead>
<tr>
<th>Altitude</th>
<th>Season</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–600 m</td>
<td></td>
<td>3.90 ± 0.95</td>
<td>2.97 ± 0.49</td>
<td>4.22 ± 0.69</td>
</tr>
<tr>
<td>600–1200 m</td>
<td></td>
<td>2.38 ± 0.47</td>
<td>1.96 ± 0.39</td>
<td>2.24 ± 0.33</td>
</tr>
<tr>
<td>Above 1200 m</td>
<td></td>
<td>0.39 ± 0.50</td>
<td>0.55 ± 0.46</td>
<td>0.83 ± 0.53</td>
</tr>
</tbody>
</table>

**Table 2**

<table>
<thead>
<tr>
<th>Types</th>
<th>Bins of surface aerosol number concentration ($\times 10^3 \text{ cm}^{-3}$)</th>
<th>Average aerosol number concentration ± standard deviation ($\times 10^3 \text{ cm}^{-3}$)</th>
<th>Wind speed near surface (m s$^{-1}$)</th>
<th>Sample number/ Sample ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>&lt;5</td>
<td>4.52 ± 1.25</td>
<td>3.52</td>
<td>70/67%</td>
</tr>
<tr>
<td>Type II</td>
<td>5–10</td>
<td>6.91 ± 1.28</td>
<td>3.40</td>
<td>28/30%</td>
</tr>
<tr>
<td>Type III</td>
<td>&gt;10</td>
<td>14.24 ± 3.73</td>
<td>2.15</td>
<td>6/3%</td>
</tr>
</tbody>
</table>

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Fig. 3. Aerosol vertical profiles of “ED” (2009-10-16, a), “SAL” (2007-09-23, b) and “BAL” (2010-10-18, c), respectively.
suggested distribution type in earlier literature (Liu et al., 2009). The synoptic situation on October 16, 2009 was characterized by a cold vortex at high altitudes at 08:00 local time (LT) at Shijiazhuang, located at eastern Inner Mongolia. The trough line was situated in the eastern loop, shifting eastwards with the cold vortex. The region was dominated by the westnortherly behind of the trough at 20:00, with a cold advection and strong winds due to the isotherms being significantly behind of the contour. Shijiazhuang was located before the surface high pressure system, with intensive isobar associated with strong winds (see Fig. 4). Wet deposition of aerosols over the upstream regions was efficient in aerosol removal from the atmosphere. Dissipated inversion at altitudes below 1 km (950–1000 hPa) due to cold air passages, together with the considerable strong winds, are the main factors contributing to aerosol diffusion. It is worth mentioning that the aerosol layer located at altitudes from 3 km to 5 km is negligible considering its relatively low concentrations.

As shown in Fig. 3, this case (2007-09-23) belongs to SAL, when aerosols over Shijiazhuang exhibited a relatively uniform distribution at altitudes below 2 km with an aerosol layer near surface. The average aerosol concentration within the aerosol layer was 2237 cm$^{-3}$, 42% higher than that at the same altitudes in ED cases (1570 cm$^{-3}$), and a sharp decrease in aerosol concentration occurred above 2 km. The region was dominated by the westsoutherly before the vortex while the low vortex weakened and turned northwards, with the high pressure system located at sea shifted east-westwards at 500 hPa level at 20:00 LT. Shijiazhuang was located at the east of the inverted trough at 850 hPa level with easterly affecting the region and relatively higher surface pressure fields (see Fig. 4).

The vertical profiles taken on 18th October 2010, case of BAL, exhibited a decrease tendency with height below 1 km, and then increased gradually at altitudes between 1 km and 2 km, inducing an aerosol layer at the altitude of the boundary layer height. Inversion layer was located at roughly 1.5 km over the region with the intensity of 6.25 °C km$^{-1}$ according to the airborne detected temperature profile. Average aerosol concentration of the aerosol layer was 1596 cm$^{-3}$, 2.7 times higher than that in ED cases at the same altitudes (591 cm$^{-3}$). The study area was under the influence of a westerly trough at high altitudes, inducing drizzles in the daytime by exerting cold airflow over the region, but the precipitation was too weak to destroy the stable layer. Surface cold high pressure system situated at the north-eastern part of China, and influenced the circulation and surface weather of the region by cold air flow shifting from northeasterly to southerly, finally affecting Shijiazhuang (see Fig. 4). Warm airflow with high humidity from the southwest arose over the cold surface at 850 hPa, facilitating significant inversion at altitudes between 1 km and 2 km, thus the stable condition suppressed the convection and turbulence activities. Aerosols were subject to stagnation at the boundary layer because of weak uplifting from the low levels.

Results from the last section show highly dependence of aerosol profiles on large scale of synoptic characteristics. One should see that since aerosols are suspended in the atmosphere, atmospheric motion, like convergence and divergence, would contribute to aerosol vertical variations. To investigate the effect of meteorological variables on aerosol vertical profiles, microphysical parameters analysis of the selected cases from the three classifications were performed. In Fig. 5, vertical velocities (w) profiles with altitudes

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**Fig. 4.** Surface charts for (a) 12:00 UTC on 16 October, 2009, (b) 06:00 UTC on 23 September, 2007, (c) 03:00 UTC on 18 October, 2010. Red solid circle denoted the location of Shijiazhuang. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
between 0–1.25 km and 1.25–2.5 km, respectively during 2006–2010. The average aerosol number concentration of 0.1–3 μm over the NCP in SAL and BAL for all research flights is $4 \times 10^4$ cm$^{-3}$ and $3.7 \times 10^4$ cm$^{-3}$, respectively, and the volume concentration is 140 μm$^3$ cm$^{-3}$ and 104.6 μm$^3$ cm$^{-3}$ respectively.

One can see that aerosol number size distribution in BAL peaks only at 0.16 μm. Fig. 6(a) depicts a large degree of variability in the slope of the number concentration in SAL over the size range 0.15–0.3 μm. While tri-modal volume size distribution is observed in SAL and BAL with common peak diameters of 0.28 μm and 2.75 μm, and the other peak at diameters of 0.8 μm and 0.16 μm, respectively.

### 3.4.2. Aerosol size distribution of ED cases

Fig. 7 presents the four lognormal model that has been fitted to the aerosol number size distribution of ED cases at different altitudes and different seasons. Total number concentrations of particles of the four modes and the parameters that characterized the number size distributions at different altitudes of three seasons are listed in Table 3. Note that the three altitude ranges are 0–1.25 km, 1.25–2.5 km, and 2.5–7 km, respectively, since the first two are average altitudes of SAL and BAL.

In general, it can be seen that average aerosol number size distribution has a successive distribution for smaller particles (<0.3 μm) and a sharp decrease at 0.3 μm, since burning emissions can elevate number concentrations of aerosols at 0.11–0.28 μm (Zellner, 2000). This has four modes, as illustrated by the colored straight lines in Fig. 7. Geometric mean diameter of Mode I–Mode IV varies from 0.08–0.11, 0.185–0.26, 0.3–0.71, 2.1–2.8 μm, along with a corresponding total number concentration of each mode, 4634, 849, 25, 2 cm$^{-3}$, respectively. In the mixed layer (0–1.25 km), a four modal lognormal distribution with the mean mode diameters of 0.1, 0.22, 0.4, 2.17 μm is sufficient to present the measured aerosol number size distribution. Aerosols at altitude of 1.25–2.5 km shows a particle number size distribution at Mode I with its major mode at about 0.09 μm, with additional modes observed at 0.24, 0.47, and 2.43 μm diameter. The lower free troposphere has a larger geometric diameter of Mode III in average (0.69 μm) than the other two layers. The total aerosol number concentration of each mode decreased with altitude.

Seasonal variation was strongest in the concentration of particles, which was clearly degraded due to wet removal in summer. The spring peaks of average aerosol number concentration at Mode IV give a representative picture of dust transport influence during the season. Particle number concentration in Mode II and Mode III elevated in autumn can be attributed to the biomass burning during the dry season over the NCP (Wu et al., 2008). $\sigma_g$ doesn’t have a clear seasonality.

### 3.4. Statistic characteristics of aerosol size distributions

Number size distribution can well characterize smaller particles, linked with higher number concentration. While for aerosol particles larger than 1 μm, volume size distribution analysis is conducted when number concentration significantly decreases due to dry or wet deposition. Figs. 6 and 7 show aerosol number size distribution and volume size distribution over size ranges 0.1–0.3 μm from the PCASP instrument in aerosol layers and in different altitudes of ED cases.

#### 3.4.1. Particle size distribution in aerosol layers

Fig. 6 illustrates the average particle size distributions calculated from 34 cases of SAL and 21 cases of BAL, at an average altitude are plotted for three cases. One can see that updraft above 1 km ($w > 0$) and downdraft below 1 km ($w < 0$), associated with convergence motion above 1 km and the divergence motion below 1 km (figure omitted), facilitated the aerosol layer formation from surface to 1 km level in case on 18th October 2010.

Convective instability is the main driving force of aerosol vertical transport, leading to the aerosol layer, when $\theta_e$ during the aerosol layer height range (0–1.5 km on 23rd September 2007; 1–2 km on 18th October 2010) according to the radiosonde dataset from meteorological station, where $\theta_e$ represents pseudo-equivalent temperature. Unstable or neutral atmospheric stability is associated with cases when aerosol concentration decreases with height, where $\theta_e < 0$ in atmosphere.
The multi-lognormal model fit captures the total aerosol number size distribution at 0.1–3 μm reasonably well, as shown in Fig. 7. Therefore, the fit results can provide measurement basis for global aerosol models.

A prevailing two-modal distribution of aerosol volume size distribution was measured of ED cases with the accumulation mode centered at around 0.25 μm and the coarse mode centered at around 2.75 μm.

3.5. The scale height of aerosols in ED cases

The scale height of the average profile of ED cases from 2006 to 2010, derived from equation (2) using the least squares method, is about 1.1 km (0.5-2.3 km). It should be noted the average scale height of aerosols during spring, summer and autumn is 1.0 km (0.7-1.5 km), 1.6 km (1.1-2.3 km) and 1.0 km (0.5-1.4 km), respectively, demonstrating a large seasonal dependence. One can see that the scale height of aerosols in spring is only 0.15 km higher than that in autumn. Given that the mixed layer is higher due to a strong vertical development over the NCP, the aerosol scale height in summer is the highest among the research seasons, or more specifically, 0.6 km higher than that in spring and autumn. The scale height of aerosols in summer (1.6 km) is low compared with that in Oklahoma, America (2.0 km) (Turner et al., 2001). The autumn peak of the scale height of aerosols over Shijiazhuang (1.4 km) appears low compared to that over continental regions in South China (2.2 km) (Wei et al., 2006).

When combined with surface aerosol distribution, it is found that Type I, Type II and Type III account for 67%, 30% and 3% of ED cases, i.e., aerosol vertical profiles satisfied an exponential decline tendency, with an average scale height of 1.14 km, 1.12 km and 0.90 km, respectively. Thus higher scale height of aerosols in Type I indicates intensive vertical mixing, while the lower scale height of aerosols in Type III suggests suppressed aerosol vertical diffusion.

![Fig. 7. Seasonal variation of aerosol size distribution at different altitudes and the four modal lognormal fitting results.](image)

| Table 3 | Lognormal distribution parameters for total aerosol number size distributions for each altitude in different seasons. |
|---|---|---|---|---|---|---|
| Altitude | Season | Mode I | Mode II | Mode III | Mode IV |
| | | $N_0$ (cm$^{-3}$) | $D_g$ (μm) | log$s$ | $N_0$ (cm$^{-3}$) | $D_g$ (μm) | log$s$ | $N_0$ (cm$^{-3}$) | $D_g$ (μm) | log$s$ |
| 0–1.25 km | Spring | 11,478 | 0.10 | 0.49 | 1914 | 0.23 | 0.22 | 57 | 0.48 | 0.53 |
| | Summer | 6001 | 0.10 | 0.35 | 1700 | 0.185 | 0.25 | 15 | 0.30 | 0.6 |
| | Autumn | 9048 | 0.10 | 0.45 | 2784 | 0.24 | 0.24 | 104 | 0.42 | 0.47 |
| 1.25–2.5 km | Spring | 3000 | 0.11 | 0.4 | 300 | 0.26 | 0.12 | 35 | 0.35 | 0.9 |
| | Summer | 5971 | 0.10 | 0.45 | 307 | 0.20 | 0.17 | 1.5 | 0.51 | 0.47 |
| | Autumn | 3614 | 0.10 | 0.45 | 487 | 0.245 | 0.19 | 9.7 | 0.57 | 0.35 |
| 2.5–7 km | Spring | 387 | 0.10 | 0.45 | 47 | 0.24 | 0.17 | 3.5 | 0.71 | 0.45 |
| | Summer | 980 | 0.10 | 0.42 | 36 | 0.24 | 0.13 | 0.95 | 0.70 | 0.37 |
| | Autumn | 1225 | 0.10 | 0.48 | 70 | 0.23 | 0.18 | 1.85 | 0.64 | 0.38 |
4. Conclusions

We have presented here a statistical analysis of 104 flights of airborne aerosol measurements over Shijiazhuang, China. It is found that surface aerosol concentration has a negative correlation with wind speed. In addition to wet removal of aerosols owing to precipitation in the summer, vertical transport of aerosols from surface to high levels is strongly influenced by convective stability (CAPE, LIFT etc.), which contributes to the seasonality of aerosol vertical profiles.

The analysis identifies three types of surface aerosols under a wide variety of weather conditions: Type I, Type II, and Type III, for cases of surface aerosol concentration less than $5.0 \times 10^3$ cm$^{-3}$, $5.0 \times 10^3$ cm$^{-3}$ and more than $1.0 \times 10^4$ cm$^{-3}$, respectively. Cyclonic low as well as the front-frontal warm regions, are the main favorable synoptic conditions of aerosol uplifted into the troposphere, together with the aforementioned synoptic situations could result in cases of Type I. The following weather conditions favor Type III aerosol: windless conditions in the relatively low pressure zones ahead of the surface high, and sinking airflow in closed high pressure which can prohibit aerosol uplifting, thus facilitate the accumulation of surface aerosols. Finally, Type II is dominated when the region is located in the middle area of two surface highs usually associated with comparatively weak winds. In addition, appropriate combination of high and surface synoptic patterns can also contribute to the medium surface aerosol loading situation, which includes surface conditions favoring diffusion with upper level restraintment of aerosol vertical transport, and vice versa.

The aerosol vertical profiles under a wide range of synoptic conditions can be categorized as “ED” (exhibiting an exponential declining tendency with altitude), “SAL” (aerosol layers existing near surface), and “BAL” (aerosol layers at the boundary layer height). Since the atmosphere is the carrier of aerosols, vorticity distribution with height plays the most significant roles on aerosol accumulation and dissipation. Temperature inversions and vertical velocity are seen to substantially affect aerosol vertical transport. Hence, three types of aerosol vertical profiles can be attributed to specific synoptic conditions and atmospheric movements.

A four modal lognormal size distribution with 10-base logarithm is applied to fit the measured aerosol size distribution at different altitudes of three seasons and it captures the total aerosol number size distribution at 0.1–3 μm reasonably well. Therefore the fit results can provide a measurement basis for global aerosol models.

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