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# **Profiling the PM<sub>2.5</sub> mass concentration** vertical distribution in the boundary layer

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## Abstract

Fine particle ( $PM_{25}$ ) affects human life and activities directly; the detection of  $PM_{25}$ mass concentration profile is very essential due to its practical and scientific meanings (such as, quantifying of air quality and its variability, and improving air quality forecast  $_{\rm 5}$  and assessment). But so far, it is difficult to detect PM<sub>2.5</sub> mass concentration profile. The proposed methodology to study the relationship between aerosol extinction coefficient and  $PM_{25}$  mass concentration is described, which indicates that the  $PM_{25}$ mass concentration profile could be retrieved by combining a charge-coupled device (CCD) side-scatter lidar and a PM<sub>2.5</sub> sampling detector. When the relative humidity is less than 70%, PM<sub>25</sub> mass concentration is proportional to aerosol extinction coeffi-10 cient, and then the specific coefficient can be calculated. Using this specific coefficient, aerosol extinction profile is converted to PM<sub>2.5</sub> mass concentration profile. Three cases of clean night (on 21 September 2014), pollutant night (on 17 March 2014), and heavy pollutant night (on 13 February 2015) are studied. The characteristic of PM<sub>25</sub> mass concentration profile in near-ground during these three nights' cases in the western suburb of Hefei city was discussed. The PM<sub>2.5</sub> air pollutant concentration is compara-

tively large in close surface varying with time and altitude. The experiment results show that the CCD side-scatter lidar combined with a  $PM_{2.5}$  detector is an effective and new method to explore pollutant mass concentration profile in near-ground.

#### 20 1 Introduction

Atmospheric aerosol is defined as suspended particle in the air, and its size distribution is from 0.001 to 100  $\mu$ m in diameter in liquid or solid state. PM<sub>2.5</sub> is a particular group of particle, whose size is less than 2.5  $\mu$ m, and it is an important part of aerosol. PM<sub>2.5</sub> is also called fine particle because of its small size. PM<sub>2.5</sub> is considered to be the most serious pollutant in the urban areas all over the world due to its adverse health effects.

<sup>25</sup> serious pollutant in the urban areas all over the world due to its adverse health effects, including cardiovascular diseases, respiratory irritation, and pulmonary dysfunction (An



et al., 2000; Mai et al., 2002; Xu et al., 2007). The  $PM_{2.5}$  poses the great health risks, compared to the coarse particle matter because the increased surface areas have high potential to adsorb or condense toxic air pollutants (An et al., 2000). Meanwhile  $PM_{2.5}$  can degrade the atmospheric visibility and affect traffic safety by extinction effect.

<sup>5</sup> In recent years, a series of experiments or monitors about fine particle matter are researched in many mega cities in China by institutes (Mao et al., 2002), and the results indicated that the PM<sub>2.5</sub> mass concentration were increased.

Precise knowledge on the vertical distribution of  $PM_{2.5}$  is required for at least two reasons: (1) it is better for quantifying of air quality and its variability since, for example, the vertical location of  $PM_{2.5}$  near the earth surface or not has very different impact on public health; (2) it is likely to significantly enhance the  $PM_{2.5}$  estimation and provide data information for model evaluation, improvement, and development for daily air quality forecast.

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Currently, the direct detecting device for  $PM_{2.5}$  is the particle matter sampling monitor, which is mostly installed on the surface ground. Using the meteorological tower, only a few researchers put  $PM_{2.5}$  monitors at different altitudes in Beijing and Tianjin to get the profile of  $PM_{2.5}$  mass concentration within 325 m (Wu et al., 2009; Yang et al., 2005). So it is difficult to obtain  $PM_{2.5}$  mass concentration profile in a few kilometers. However, some important atmospheric processes (i.e. particle formation, trans-

- <sup>20</sup> portation and mixing processes) take place predominantly at a higher altitude in the planetary boundary layer. Lidar in principle can provide the ability to observe these processes where they occur. Backscattering lidar is a powerful tool to detect aerosol profile, and is widely used in atmospheric monitor (Weitkamp, 2005; Winker et al., 2007; Bo et al., 2014; Wang et al., 2014b). But the common backscattering lidar system has
- <sup>25</sup> a shortcoming in the lower hundreds of meters because of the geometric form factor (GFF) caused by the configuration of the transmitter divergence and receiver's field-ofview (FOV) at the near range (Mao et al., 2012; Wang et al., 2015b). With the recently developed technique of the CCD side-scattering lidar (Bernes et al., 2003; Tao et al., 2014a; Ma et al., 2014), the problem caused by the GFF could be solved. Moreover,



the nearer range, the better spatial resolution could be obtained. So the side-scattering lidar is very suitable to detect aerosol spatial distribution in the boundary layer from the surface.

In this paper, the aerosol extinction coefficient profile is retrieved by our selfdeveloped CCD side-scattering lidar, and PM<sub>2.5</sub> mass concentration is measured simultaneously in ground level by a particle matter monitor. Syncretizing these two datasets measured at same time and same place, the profile of PM<sub>2.5</sub> mass concentration can be derived in the boundary layer. In Sect. 2, the instrumentation is introduced; and the methodology for extinction and PM<sub>2.5</sub> profiles is shown in Sect. 3; then the results is discussed in Sect. 4; followed by the summary and conclusion in the last Sect. 5.

#### 2 Instruments

The measurement system is consisted of a CCD side-scattering lidar and a PM<sub>2.5</sub> mass monitor as shown in Fig. 1. The subsystem of side-scattering lidar consists of laser, CCD camera, geometric calibration, data acquisition and control computer. The light source is a Nd:YAG laser (Quantel Brilliant) emitting laser pulses in 20 Hz at 532 nm wavelength. The side-scattering light is received by a CCD camera with 3352 × 2532 pixels. The exposed time is set 5 min according to the signal-to-noise ratio with a maximum relative error of 1.5 % caused by noises (Ma et al., 2014), and there is an interference filter with 30 nm bandwidth in front of CCD lens. Using geometric calibration,
 the relationship between the pixels and corresponding to the scattering lights in laser

- <sup>20</sup> the relationship between the pixels and corresponding to the scattering lights in laser beam is determined. The computer acquires the CCD camera data and controls timing sequence between laser and CCD camera.  $PM_{2.5}$  mass monitor works simultaneously, and the output product is the average  $PM_{2.5}$  mass concentration through one hour. In Fig. 1, *z* is the detecting distance, *D* is the distance from CCD camera to laser beam,
- θ is the scattering angle, dθ is the FOV of one pixel. The detailed specifications of the CCD side-scattering lidar (C-lidar) are described in the previous work (Tao et al., 2014a) and shown in Table 1.



The  $PM_{2.5}$  mass monitor, named Thermo Scientific TEOM 1405 Ambient Particulate Monitor, can carry out continuous measurement of ambient particulate concentrations with the resolution of 0.1 µg m<sup>-3</sup> and the precision of ±2.0 µg m<sup>-3</sup> (one hour averaged).

#### 3 Methodology

#### 5 3.1 Retrieved method of aerosol extinction profile

The side-scattering lidar equation is expressed as (Tao et al., 2014b):

$$P(z,\theta) = \frac{P_0 K A}{D} \left( \frac{\beta_1(z,\pi)}{f_1(\pi)} f_1(\theta) + \frac{\beta_2(z,\pi)}{f_2(\pi)} f_2(\theta) \right) \cdot \exp\left(-\tau - \frac{\tau}{\cos(\pi - \theta)}\right) d\theta$$
(1)

Where  $P(z,\theta)$  is the received power at height z and scattering angle  $\theta$  by a pixel,  $P_0$ is laser pulse energy, K is a system constant including the optical and electronic efficiency and A is the area of CCD camera lens,  $\beta(z, \pi)$  is backscattering coefficient,  $f(\theta)$ is phase function. Subscripts "1" and "2" represent aerosol and molecule scattering, respectively.  $\tau$  is optical depth,  $\alpha(z)$  is extinction coefficient, and  $\tau = \int_{0}^{z} (\alpha_{1}(z') + \alpha_{2}(z')) dz'$ . In general, for Eq. (1), there is six unknown variables, i.e. phase function, backscattering and extinction coefficients of aerosol and molecule. Three unknown variables for molecule are calculated from standard molecular model using Rayleigh scatter theory. 15 A prior assumption has to be given, i.e. lidar ratio (extinction-to-backscattering ratio) of aerosol, in order to reduce an unknown. The value of 50 sr is used as lidar ratio at 532 nm wavelength in our algorithm. The aerosol phase function is determined from a sky-radiometer (for example, a Prede POM-02 sky-radiometer made in Japan). Then only one variable (the backscattering or extinction coefficient of aerosol) is left, which 20 can be retrieved from Eq. (1) as following.

In our experiment, vertical-pointing backscattering lidar (V-lidar) and C-lidar worked simultaneously. For V-lidar data processing, it is a traditional way to select the clear point about the tropopause as reference point where assumed has minimum aerosol.



The V-lidar signals and C-lidar signals have an overlap region around 1 km in height in our case. For C-lidar, the reference point is selected in this overlap region. Aerosol backscatter coefficient value  $\beta_c$  at reference point thus can be given from V-lidar retrieval. When the aerosol backscatter coefficient value at the scattering angle  $\theta_c$  as reference point is known, according to Eq. (1), the backscattering or extinction coefficient of aerosol can be derived by our proposed numerical inversion method (Tao et al., 2014b). The validation experiments and error analysis are shown in the reference (Tao et al., 2015). When comparative experiments were performed, the C-lidar and V-lidar worked at the same position simultaneously, as well as another horizontalpointing backscattering lidar (H-lidar). The result shown in the Fig. 2 of the reference (Tao et al., 2015) indicates a good agreement and the total relative error of extinction coefficient is less than 18 % accordingly by applying the error propagation method and taking the typical example.

## 3.2 Retrieved method of PM<sub>2.5</sub> profile

<sup>15</sup> Some researchers (Pesch et al., 2007; Sano et al., 2008; He et al., 2010; Cordero et al., 2012) studied the relationship between the PM<sub>2.5</sub> mass concentration and aerosol optical depth from the view of statistics. The aerosol optical depth is the integral result of aerosol extinction to range, which may match the column PM<sub>2.5</sub> mass concentration. However, the aerosol extinction and PM<sub>2.5</sub> mass concentration both are changing along
 <sup>20</sup> altitude. So the PM<sub>2.5</sub> mass concentration has close relation with the aerosol extinction in theory.

The aerosol size distribution n(r) is defined as

$$n(r) = \frac{\mathrm{d}N}{\mathrm{d}r}$$

where dN is the particle number concentration in radius interval range  $(r \rightarrow r + dr)$ .



(2)

Total particle matter mass concentration  $C_{\text{Total}}$  can be written as

$$C_{\text{Total}} = \int_{0}^{\infty} \rho\left(\frac{4}{3}\pi r^{3}\right) n(r) \mathrm{d}r$$

where  $\rho$  is the aerosol mass density. PM<sub>2.5</sub> mass concentration  $C_{PM_{2.5}}$  can be written as

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$$C_{\text{PM}_{2.5}} = \int_{0}^{2.5\mu m} \rho\left(\frac{4}{3}\pi r^3\right) n(r) \mathrm{d}r$$

Aerosol extinction coefficient  $\alpha$  can be described as

$$\alpha = \int_{0}^{\infty} \pi r^2 Q_{\text{ext}} n(r) \mathrm{d}r$$

where  $Q_{\text{ext}}$  is the factor of extinction efficiency.

The mean and integral properties of the particle ensemble that are calculated from the inverted particle size distribution are effective radius, i.e. the surface-area-weighted mean radius as

$$r_{\rm eff} = \frac{\int_0^\infty r^3 n(r) \mathrm{d}r}{\int_0^\infty r^2 n(r) \mathrm{d}r}$$

So, the relationship between aerosol extinction and total particle mass concentration is gotten (Li et al., 2013)

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$$\alpha = \frac{3Q_{\text{ext}}}{4r_{\text{eff}}\rho}C_{\text{Total}}$$

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Using the ratio of total particle matter mass concentration to  $PM_{2.5}$  mass concentration ( $\eta = C_{Total}/C_{PM_{2.5}}$ ), finally we got the following relationship

$$\alpha = \frac{3Q_{\text{ext}}\eta}{4r_{\text{eff}}\rho}C_{\text{PM}_{2.5}} = K \cdot C_{\text{PM}_{2.5}}$$

Eq. (8) is the formula to convert aerosol extinction profile to  $PM_{2.5}$  mass concentration <sup>5</sup> profile, where  $K = \frac{3Q_{ext}\eta}{4r_{ex0}}$  is the specific coefficient.

In Eq. (8), the specific coefficient K is related to aerosol size distribution, refractive index, and atmospheric relative humidity. In planetary boundary layer (PBL), due to turbulence effect, the aerosol size distribution and refractive index are assumed as uniform reasonably. When the relative humidity is below 70%, the aerosol hydrophilic growth could be negligible. So, the specific coefficient K could be considered as constant under the condition of less than 70% relative humidity in PBL, i.e. K is independent of altitude.

In a measurement, the CCD side-scattering lidar and  $PM_{2.5}$  monitor operate at the same place simultaneously. Selecting the aerosol extinction coefficient value corre-

<sup>15</sup> sponding to altitude of  $PM_{2.5}$  monitor and  $PM_{2.5}$  mass concentration value, the specific coefficient *K* is got by applying Eq. (8). Then using Eq. (8) again, the  $PM_{2.5}$  mass concentration profile could be derived from aerosol extinction coefficient profile and the specific coefficient *K*.

#### 4 Results

Our CCD side-scattering lidar system was set up since April 2013 in the SKYNET Hefei site. After that, the system was operated to detect atmospheric aerosol during cloud-free night. In the following, three cases are showed to represent clean day, pollutant day, and heavy pollutant day. Before that, in order to verify the prior assumption, we investigated how aerosol extinction coefficient is associated with the atmospheric relative humidity (RH) through numerical calculation. The selected aerosol types for the



(8)

calculation are shown in Fig. 2. The parameters and components for Fig. 2 were from Optical Properties of Aerosols and Clouds (OPAC) 3.1 by Hess et al. (1998). As mentioned in previouse literature (Wang et al., 2014a, 2015a), the Hefei site is situated on the east of China, which is predominated by continental aerosol. The nearest urban in-

fluence is 15 km and therefore, the site is close enough to be influenced by local urban depending on wind direction. And in spring season, dust aerosol transported from the northern/northwest regions of China may also affect this site (Zhou et al., 2002). So, five different aerosol types are considered in Fig. 2 and there is rarely reliant on RH when RH is less than 70 %.

#### 10 4.1 Case I: clean night

On 21 September 2014, it was clear at night, with northeast wind of not more than  $3 \text{ m s}^{-1}$  near ground. The temperature varies from 21.6° C to 23.0° C with a slight decreasing trend and the RH increases from 61 to 69% during the time span of 19:30–22:00 Beijing Time (BT) as shown in Fig. 3a. The distance *D* between laser beam and CCD camera is 34.34 m.

Figure 3b plots the hourly mean value of *K* varying from 0.011 to 0.012 km<sup>-1</sup> (µgm<sup>-3</sup>)<sup>-1</sup>, which indicates an approximate constant value during this experimental case. Using the specific coefficient *K* and the aerosol extinction coefficient profile, PM<sub>2.5</sub> profile is given accordingly. Figure 3c presents spatio-temporal distribution of PM<sub>2.5</sub> mass concentration for this case in Hefei site. The PM<sub>2.5</sub> is almost enclosed below 1.5 km above ground level (a.g.l.) with a maximums value 33 µgm<sup>-3</sup>, indicating a clean night in Hefei. The floating layer of 0.6–1.5 km a.g.l. indicates a higher PM<sub>2.5</sub>, whose value is more than that below 0.3 km a.g.l. near the earth surface layer from Fig. 3c. The floating layer exists throughout the night due to a stable aerosol load-

 $_{25}$  ing. There is a clean layer between the floating layer and the earth surface layer. It is noted from Fig. 3d that the  $PM_{2.5}$  value decreases from  $28\,\mu gm^{-3}$  at the earth surface to  $12\,\mu gm^{-3}$  at 0.3 km a.g.l., and keeps a certain value at 0.3–0.6 km a.g.l., then



increases to three sub-peaks of 29, 33, and 33  $\mu$ g m<sup>-3</sup> in the floating layer, respectively. The vertical distribution of PM<sub>2.5</sub> at 21:30 BT measured in Hefei site on September 21 2014 depicts a rich structures.

## 4.2 Case II: pollutant night

- <sup>5</sup> On 17 March 2014, it was also clear at night, with the south wind of not more than  $3 \text{ m s}^{-1}$  near the earth surface. The temperature varies from 18.2 to 21.7 °C with a decreasing trend and the RH increases from 58 to 70 % during the time span of 19:30–24:00 BT as shown in Fig. 4a. The distance *D* between laser beam and CCD camera is 23.90 m.
- <sup>10</sup> Figure 4b plots the hourly mean value of *K* varying around 0.011 km<sup>-1</sup>/( $\mu$ g m<sup>-3</sup>) with the minimum 0.009 and the maximum 0.012, which also indicates an approximate constant value during this experimental case. Then PM<sub>2.5</sub> profile is given accordingly by using the specific coefficient *K* and the aerosol extinction coefficient profile. The spatiotemporal distribution of PM<sub>2.5</sub> mass concentration for this case in Hefei site is shown
- <sup>15</sup> in Fig. 4c. The  $PM_{2.5}$  is almost enclosed below 1.8 km a.g.l. with a maximums value 70 µg m<sup>-3</sup>, indicating a light pollutant night in Hefei. Between 0.6 and 1.8 km a.g.l., the  $PM_{2.5}$  value is almost constant indicating a well mixed layer. The maximum value of  $PM_{2.5}$  lies near the earth surface layer and forms a rather stable aerosol structure, which will cause a haze day with poor visibility.
- <sup>20</sup> It is remarked from Fig. 4d that the  $PM_{2.5}$  value remains  $20 \,\mu g m^{-3}$  at 0.9– 1.8 km a.g.l., and increases to  $30 \,\mu g m^{-3}$  at 0.3 km a.g.l., then increases rapidly to a peak of 55  $\mu g m^{-3}$  at the earth surface. The vertical distribution of  $PM_{2.5}$  at 21:30 BT measured in Hefei site on 17 March 2014 depicts a stable structure.

# 4.3 Case III: heavy pollutant night

<sup>25</sup> On 13–14 February 2015, it was also cloud-free at night, with the northwest wind of not more than  $3 \text{ m s}^{-1}$  near the ground. The temperature varies from 10.7 to 9.1 °C with



a decreasing trend and the RH increases speedily from 31 to 68% during the time span of 18:30-02:00 BT, then keeps around 65 % in the late period of 02:00-05:30 BT as shown in Fig. 5a. The distance D between laser beam and CCD camera is 19.40 m. Figure 5b plots the hourly mean value of K varying from 0.006 to  $_{5}$  0.007 km<sup>-1</sup> (µg m<sup>-3</sup>)<sup>-1</sup>, which also indicates an approximate constant value during this experimental case. But this value is guite different from that obtained from CASE I and CASE II maybe due to the differences of aerosol size distribution and refractive index. The  $PM_{25}$  profile is calculated accordingly by using the K value and the aerosol extinction coefficient profile. At the meanwhile, the spatio-temporal distribution of PM<sub>25</sub> mass concentration for this case in Hefei site is shown in Fig. 5c. The PM<sub>2.5</sub> is lifted up to 2.1 km a.g.l. with a maximums value  $210 \mu \text{gm}^{-3}$ , indicating a heavy pollutant night in Hefei. During the observation period, there are three distinct layers (i.e., the floating layer, the clean layer, and the earth surface layer) with a gradual fall in height from the evening to the next morning. The typical height for the floating layer decreases from 1.2-1.8 km a.g.l. to 0.5-1.0 km a.g.l. and the peak value of PM<sub>2.5</sub> for this layer is about 15 150  $\mu$ g m<sup>-3</sup>. The PM<sub>2.5</sub> value for the fair layer in middle part varies from 30 to 50  $\mu$ g m<sup>-3</sup>.

The top height of the earth surface layer decreases from 0.9 km a.g.l. at 18:00 BT to 0.3 km a.g.l. at 06:00 BT, which leads to a more stable structure. The maximum value of PM<sub>2.5</sub> lies near the earth surface layer, especially below 0.3 km a.g.l., where a high value region of  $PM_{2.5}$  (i.e., 200 µgm<sup>-3</sup>) exists all along from 20:00 to 04:00 BT, which 20 will cause a heavy haze day with worse visibility.

It is remarked from Fig. 5d that the  $PM_{2.5}$  value takes on a sub-peak of  $110 \,\mu g \,m^{-3}$  at 1.2 km a.g.l., and increases rapidly from  $20 \,\mu g \,m^{-3}$  at 0.8 km a.g.l. to another sub-peak of  $190 \mu \text{gm}^{-3}$  at 0.4 km a.g.l., then increases rapidly again to a peak of  $210 \mu \text{gm}^{-3}$  at the earth surface. The vertical distribution of PM<sub>2.5</sub> at 21:00 BT measured in Hefei site

25 on February 13-14, 2015 appears a more stable and rich structure.



#### 5 Summary and conclusion

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A new measurement technology of  $PM_{2.5}$  mass concentration profile in near-ground is present in this paper based on a CCD side-scatter lidar and a  $PM_{2.5}$  detector. Our new method is proved to be effective through three cases measured during nighttime in SKYNET Hefei site. And some useful conclusions are summarized as following:

- 1. Five types of aerosol from OPAC, prevail in Hefei site, are used to testify their extinction property depending on RH, only to find that there is rarely reliant on RH when RH is less than 70 %.
- 2. The specific coefficient *K*, which is related to aerosol size distribution, refractive index, and atmospheric relative humidity, may contain a fix value under the suitable condition when RH is less than 70 %, though it may not be the same for each case. So, the PM<sub>2.5</sub> mass concentration profile can be easily derived from vertical distribution of extinction coefficient for aerosol.
- 3. The PM<sub>2.5</sub> is always loading in the planet boundary layer with a muti-layers structure, indicating its complexity of the vertical distribution. And there is a higher lifting height under the heavy polluted weather condition, demonstrating air pollution may break through near the surface into a higher altitude and join in further transportation.
- 4. The high value of  $PM_{2.5}$  remains near the ground and forms a stable structure, especially in haze day, which will cause a bad weather condition, such as low visibility.
- 5. Our new method for  $PM_{2.5}$  mass concentration profile is a useful approach for improving our understanding of air quality, and atmospheric environment, which can also provide critical information for daily air quality forecast. Further investigation will be carried on in the near future when RH is larger than 70% including the potential variation of specific coefficient *K*.



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5 ments.

#### References

- An, J., Zhang, R., and Han, Z.: Seasonal changes of total suspended particles in the air of 15 big cities in northern parts of China, Climatic and Environ. Res., 5, 25–29, 2000.
- Bernes, J. E., Bronner, S., and Becket, R.: Boundary layer scattering measurements with a charge-coupled device camera lidar, Appl. Optics, 42, 2647–2652, 2003.
- Bo, G., Liu, D., and Wu, D.: Two-wavelength lidar for observation of aerosol optical and hygroscopic properties in fog and haze days, Chinese Journal of Lasers, 41, 0113001, doi:10.3788/cjl201441.0113001, 2014.

Cordero, L., Wu, Y., Gross, B. M., and Moshary, F.: Use of passive and active ground and

satellite remote sensing to monitor fine particulate pollutants on regional scales, Proc. SPIE 8366, Advanced Environmental, Chemical, and Biological Sensing Technologies IX, 83660M, doi:10.1117/12.918765, 2012.

He, X., Deng, Z., Li, C., Lau, A. K., Wang, M., Liu, X., and Mao, J.: Application of MIDIS AOD in surface PM<sub>10</sub> evaluation, Acta Scientiarum Naturalium Universitatis Pekinensis, 46, 178–184, 2010.

20 1

25

10

- Hess, M., Koepke, P., and Schult, I.: Optical properties of aerosols and clouds: the software package OPAC, B. Am. Meteorol. Soc., 79, 831–844, 1998.
- Li, Q., Li, C., Wang, Y., Lin, C., Yang, D., and Li, Y.: Retrieval on mass concentration of urban surface suspended particulate matter with lidar and satellite remote sensing, Acta Scientiarum Naturalium Universitatis Pekinensis, 49, 673–682, 2013.
- Ma, X., Tao, Z., Ma, M.: The retrival of side-scatter lidar signal based on CCD technique, Acta Optica Sinica, 34, 0201001, doi:10.3788/aos201434.0201001, 2014.
- Mao, F., Gong, W., and Li, J.: Geometrical form factor calculation using Monte Carlo integration for lidar, Opt. Laser Technol., 44, 907–912, 2012.



- Mao, J., Zhang, J., and Wang, M.: Summary comment on research of atmospheric aerosol in Discussion China, Acta Meteorol. Sin., 60, 625-634, 2002. Pesch, M. and Oderbolz, D.: Calibrating a ground based backscatter lidar for continuous mea-
- surements of PM<sub>2.5</sub>, lidar technology, techniques, and measurements for atmospheric remote sensing III, Proc. Of SPIE 6750, 67500K, doi:10.1117/12.737732, 2007.

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10

15

20

30

- Sano, I., Mukai, M., Okada, Y., Mukai, S., Sugimoto, N., Matsui, I., and Shimizu, A.: Improvement of PM<sub>2.5</sub> analysis by using AOT and lidar data remote sensing of the atmospheric and clouds II, Proc. Of SPIE 7152, 71520M, doi:10.1117/12.804903, 2008.
- Tao, Z., Liu, D., and Ma, X.: Development and case study of side-scatter lidar system based on charge-coupled device, Infrared and Laser Engineering, 43, 3282-3286, 2014a.
- Tao, Z., Liu, D., Wang, Z., Ma, X., Zhang, Q., Xie, C., Bo, G., Hu, S., and Wang, Y.: Measurements of aerosol phase function and vertical backscattering coefficient using a chargecoupled device side-scatter lidar, Opt. Express, 22, 1127-1134, 2014b.

Tao, Z., Liu, D., Ma, X., Shi, B., Shan, H., and Zhao, M.: Vertical distribution of near-ground aerosol backscattering coefficient measured by a ccd side-scattering lidar, Appl. Phys. B-Lasers O., 120, 631-635, 2015.

- Wang, Z., Liu, D., Wang, Z., Wang, Y., Khatri, P., Zhou, J., Takamura, T., and Shi, G.: Seasonal characteristics of aerosol optical properties at the SKYNET Hefei site (31.90° N, 117.17° E) from 2007 to 2013, J. Geophys. Res.-Atmos., 119, 6128-6139, doi:10.1002/2014JD021500, 2014a.
- Wang, Z., Liu, D., and Cheng, Z.: Pattern recognition model for haze identification with atmospheric backscatter lidars, Chinese Journal of Lasers, 41, 1113001, doi:10.3788/cil201441.1113001, 2014b.

Wang, Z., Liu, D., Wang, Y., Wang, Z., and Shi, G.: Diurnal aerosol variations do affect daily

- averaged radiative forcing under heavy aerosol loading observed in Hefei, China, Atmos. 25 Meas. Tech., 8, 2901-2907, doi:10.5194/amt-8-2901-2015, 2015a.
  - Wang, Z., Tao, Z., Liu, D., Wu, D., Xie, C., and Wang, Y.: New experimental method for lidar overlap factor using a CCD side-scatter technique, Opt. Lett., 40, 1749–1752, 2015b.
  - Weitkamp, C.: Lidar: Range-Resolved Optical Remote Sensing of the Atmosphere, Springer, New York, 2005.
  - Winker, D. H., Hunt, W. H., and McGill, M. J.: Initial performance of assessment of CALIOP, Geophys. Res. Lett., 34, 228-262, 2007.



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- Wu., Z., Liu, A., and Zhang, C.: Vertical distribution feature of PM<sub>2.5</sub> and effect of boundary layer in Tianjin, Urban Environment & Urban Ecology, 22, 24–29, 2009.
- Xu, J., Ding, G., and Yan, P.: Componential characteristics and sources identification of PM<sub>2.5</sub> in Beijing, Journal of Applied Meteorological Science, 18, 645–654, 2007.
- <sup>5</sup> Yang, L., He, K., and Zhang, Q.: Vertical distributive characters of PM<sub>2.5</sub> at the ground layer in Autumn and Winter in Beijing, Research of Environmental Sciences, 18, 23–28, 2005.
  - Zhou, J., Yu, G., Jin, C., Qi, F., Liu, D., Hu, H., Gong, Z., Shi, G., Nakajima, T., and Takamura, T.: Lidar observations of Asian dust over Hefei, China, in spring 2000, J. Geophys. Res., 107, 4252, doi:10.1029/2001JD000802, 2002.



 Table 1. The specifications of the C-lidar system.

Laser	(Quantel Brilliant) Nd:YAG
Wavelength (nm)	532
Pulse energy (mJ)	200
Repetition rate (Hz)	20
Detector	(SBIG) ST-8300M
Pixel array	3352 × 2532
Pixel size (µm)	5.4 × 5.4
A/D convecter (bits)	16
Wide-angle lens	Walmexpro f/2.8
Lens focal length (mm)	14
CCD sensor	Kodak KAF-8300
Quantum efficiency (532 nm)	~ 55 %
Interference Filter	(Semrock corporation)
Bandwidth (nm)	25.6
Peak transmittance	~ 95 %

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Interactive Discussion











**Figure 3. (a)** RH and *T* parameters with time, **(b)** *K* value for each hour, **(c)** time series of  $PM_{2.5}$  profile, and **(d)** vertical distribution of  $PM_{2.5}$  at 21:30 BT measured in Hefei site on 21 September 2014.





![](_page_19_Figure_1.jpeg)

![](_page_19_Figure_2.jpeg)

![](_page_20_Figure_0.jpeg)

![](_page_20_Figure_1.jpeg)

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