Aerosol Optical Properties over an Urban Site in Central China
Determined Using Ground-based Sun Photometer Measurements

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Abstract

Sun photometer measurements at urban Jiaozuo in Central China from July 2016 to February 2018 were used to investigate the aerosol optical and microphysical properties, including the climatological variation of aerosol properties, aerosol classification and aerosol properties under haze and dust events. The annual mean aerosol optical depth at 440 nm (AOD\textsubscript{440 nm}) and the Ångström exponent (AE\textsubscript{440-870 nm}) were 0.84 ± 0.55 and 1.12 ± 0.17, respectively. The highest AOD being in summer may be associated with the hygroscopic growth of aerosols under enhanced relative humidity. Accordingly, high volume of fine-mode particles was observed in summer. In addition, the carbonaceous aerosols from biomass burning increased the volume of fine particles in June and September. Whereas the coarse-mode particles (mainly dust) dominated...
during spring, especially in May with a maximum volume of 0.16 $\mu m^3 \mu m^{-2}$. The seasonal mean single scattering albedo at 440 nm (SSA$_{440\ nm}$) was lower in spring (0.87 ± 0.05) and higher in summer (0.95 ± 0.04). On the contrary, absorption aerosol optical depth at 440 nm (AAOD$_{440\ nm}$) was higher during spring (0.079 ± 0.019) and lower during summer (0.045 ± 0.021). The increased absorptivity of aerosols in spring and strong scattering ability in summer may be associated with aerosol particles from different sources. The predominant aerosol type was absorbing aerosols (fine and mixed) according to the classification technique using fine mode fraction (FMF), SSA and AE. This urban site was not only influenced by anthropogenic aerosols from local emissions and the surrounding regions but also affected by dust from northwestern China. The mean AOD and AE were 1.66 and 1.38 on haze days, while slightly low AOD of 0.95 and extremely low AE of 0.18 on dust days. This study provides a comprehensive understanding of aerosol properties in this area, and the results will help to optimize the satellite aerosol inversion algorithm and promote regional climate change research.

**Keywords:** Aerosol optical properties; Aerosol classification; Sun photometer measurements; Jiaozuo.
INTRODUCTION

Aerosol particles are an important component of the earth–atmosphere system, directly influencing its radiative energy balance by absorbing and scattering solar radiation (Kaufman et al., 1997), and indirectly altering the microphysical properties of cloud by acting as cloud condensation nuclei (Twomey et al., 1984). In addition, atmospheric aerosol, as a major pollutant in the atmosphere, can cause various atmospheric environmental problems, such as the degradation of air quality (Seneviratne et al., 2017) and visibility (Che et al., 2007), ultimately threatening human health (Pope and Dockery, 2006; Kumar et al., 2015). Therefore, long term measurements of aerosol optical properties need to be conducted for further exploring the effects of aerosols on climate change and environmental pollution.

Due to the high variability in the spatial and temporal distribution of the optical and microphysical properties of aerosol particles (Liu et al., 2009; Ma et al., 2011), their impact on Earth's climate is highly uncertain (Schwartz and Andreae, 1996; Hansen et al., 2000). Therefore, a large number of aerosol in-situ measurements of the optical and microphysical properties is imperative. Satellite remote sensing and ground-based observation are two effective methods for measuring aerosol, each with their own strengths and weaknesses. Satellite remote sensing can detect continuous distributions of aerosol features [e.g., aerosol optical depth (AOD)] (Zhang et al., 2018; He et al., 2018; Qin et al., 2018) and quickly obtain global-scale aerosol information on them regardless of the limits imposed by conditions on the ground; however, some other aerosol optical properties, e.g., absorption aerosol optical depth (AAOD) and absorption Ångström exponent (AAE), are harder to retrieve via this route. Ground-based observation, meanwhile, is
an effective approach for characterizing the optical and microphysical properties of aerosols and can achieve high levels of accuracy (Dubovik and King, 2000). Although ground-based observation can only reflect aerosol information within a certain range around a site, a number of global or regional aerosol observation networks have been established worldwide. For example, AERONET (Holben et al., 1998), PHOTONS (Goloub et al., 2008), SKYNET (Nakajima et al., 2003), AEROCAN (Bokoye et al., 2001), and CARSNET (Che et al., 2009; Che et al., 2015a).

In recent decades, China has experienced a period of rapid economic development that has attracted worldwide attention. Accompanied by the rapid increase in the level of industrialization and urbanization, many cities have encountered severe air pollution with considerable contributions from atmospheric particulate matter (PM) (Chan and Yao, 2008). These aerosol particles are mainly derived from natural sources and anthropogenic emissions. Aerosol particles are not usually homogeneous in most Chinese cities; rather, they are made up of a mixture of absorbing and non-absorbing particles. Absorbing aerosol particles include carbonaceous aerosols produced by coal combustion and biomass burning, as well as iron oxides in mineral dust (Yang et al., 2009). Non-absorbing aerosols comprise not only sulfate and nitrate emitted by the burning of fossil fuel and present in vehicle exhaust, but also ammonium-salt and sea-salt. A great number of studies on aerosol optical properties have been conducted in China, together contributing immensely to our understanding of urban air pollution (Che et al., 2015b; Li et al., 2016; Zhao et al., 2018). For example, Li et al. (2017) studied the optical and microphysical properties of aerosols in summer in North China; aerosol optical properties and direct radiative forcing in Northeast China were analysed by Che et al. (2015c); and Wang et al. (2011) reported
seasonal changes in aerosol optical characteristics in different regions of China. However, most
studies of this type have concentrated mainly on the Yangtze River Delta (YRD) region (Cheng
et al., 2015; Qi et al., 2016; Che et al., 2018), the North China Plain (Che et al., 2014; Zhu et al.,
2014; Zheng et al., 2017), Northeast China (Wang et al., 2010; Zhao et al., 2013; Che et al.,
2015c), and some other heavily polluted areas (Wang et al., 2015a; Li et al., 2017; Liu et al.,
2017). Only a few studies have focused on the aerosol optical properties in central China, due to
the limited availability of aerosol observations in this region. Among those few studies, Wang et
al. (2015a, 2015b) and Zhang et al. (2017a) used ground-based observation data to study the
aerosol optical properties in the areas of Wuhan and Songshan mountain; yet, to the best of our
knowledge, due to short of ground site or observation, no attempt has been made to investigate
the aerosol optical and microphysical properties in an urban region in Henan Province which has
suffered from serious air pollution. Crucially, Henan Province is located in the Beijing–Tianjin–
Hebei atmospheric transmission channel, meaning its aforementioned serious air pollution may
have measurable effects on the air quality over the Beijing–Tianjin–Hebei region, which,
socioeconomically, is a highly important part of China. Therefore, it is imperative to study the
aerosol optical properties in this area for improving our understanding of local air pollution and
regional aerosol-climate interactions.

The purpose of the present reported work was to investigate the aerosol optical properties in
Jiaozuo using one and a half years (July 2016 to February 2018) of ground-based sun photometer
data. Specifically, monthly and seasonal variations of AOD, AAE, AAOD, Ångström exponent
(AE), single scattering albedo (SSA), and volume size distribution were analysed. Additionally,
two typical pollution processes (namely, haze and dust) were selected to analyse the aerosol optical properties and identify the sources of aerosol. The results of this study reflect the characteristics of aerosol optical properties in Henan, and to a certain extent even in other urban areas of central China, and may assist in improving the aerosol model over China, optimizing satellite aerosol inversion algorithms and advancing regional climate change research.

SITE, DATA AND METHODS

Site and Instruments

Fig. 1 shows the geographic location of the Jiaozuo-HPU site, which is the only urban site in Henan Province for measuring aerosol optical properties. The site is on the campus of Henan Polytechnic University (HPU) in the city of Jiaozuo, Henan Province, China, where a CE-318 sun photometer (Cimel Electronique, Paris, France) was installed on the roof of the School of Surveying and Land Information Engineering building (35.3°N, 113.3°E, 113 m) in July 2016. Jiaozuo is an industrial city located in northwestern Henan Province, with the Taihang Mountains to the north and the Yellow River to the south, about 60 km from Zhengzhou (the capital of Henan Province). The climate type in Jiaozuo is northern temperate monsoon, typified by abundant rainfall and high temperatures in summer.

The type of sun photometer at Jiaozuo-HPU is CE318N-EDPS9 which is termed as polarized version. It can measure direct solar radiation for each 15 minutes in nine bands (1640, 1020, 870, 670, 500, 440, 380, 340, and 936 nm) with a 1.2° full field-of-view (Holben et al., 1998). Measurements in the first eight bands can be used to retrieve the spectral AOD, while total precipitable water vapor can be obtained by the strong water vapor absorption band at 936 nm.
(Holben et al., 1998; Che et al., 2009). The level 1.5 AOD data [cloud-screened AOD, according to Smirnov et al. (2000)] from July 2016 to February 2018 were calculated in the ASTPwin software (Cimel Ltd. Co.). To achieve more reliable results, only AODs observed more than 10 times a day and on 10 days or more in a month were used to calculate the daily and monthly AOD, respectively (Che et al., 2009; Zhao et al., 2013) (Table 1). The AE (α) was derived from the AOD between 440 and 870 nm by Eq. (1) as follows:

$$\alpha = -\frac{\ln(\tau_1/\tau_2)}{\ln(\lambda_1/\lambda_2)}$$

(1)

where $\tau_1, \tau_2$ are AOD at bands of $\lambda_1$ and $\lambda_2$, respectively.

In addition, the aerosol microphysical properties and other optical properties, such as SSA, AAOD, AAE, and volume size distribution, were retrieved from the almucantar sky radiance observations at 440, 670, 870 and 1020 nm, in conjunction with the measured AOD (Dubovik and King, 2000; Dubovik et al., 2002; Che et al., 2009; Zhao et al., 2013). Among them, AAOD and AAE were calculated by Eqs. (2) and (3) (Russell et al., 2010; Giles et al., 2012).

$$\text{AAOD}(\lambda) = AOD(\lambda) \times (1 - \text{SSA}(\lambda))$$

(2)

$$\text{AAE} = -d \ln[\text{AAOD}(\lambda)]/d \ln(\lambda)$$

(3)

The uncertainty of AOD is approximately 0.01-0.02 (Eck et al., 1999). The SSA with error of about 0.03 can be retrieved only for AOD$_{440\,\text{nm}} \geq 0.40$ for solar zenith angles $> 50^\circ$, to avoid the larger error from the limited information content under lower AODs (Dubovik et al., 2002; Che et al., 2015c).

**Data and Analytical Methods**

In this work, in addition to the CE-318 sun photometer data, meteorological data (relative humidity and wind speed) from the China Meteorological Administration and hourly
observations of PM concentrations from the China National Environmental Monitoring Centre (http://www.cnemc.cn/) were used to investigate the variation in aerosol optical properties during the two pollution processes of haze and dust. We also used ERA-Interim data (http://apps.ecmwf.int/datasets) downloaded from the European Centre for Medium-Range Weather Forecasts (ECMWF) to analyse the wind field variation at different pressure levels during these pollution processes. Moderate Resolution Imaging Spectroradiometer (MODIS) true color images, with a spatial resolution of $1 \times 1$ km, were used, to identify dust storms, fog and haze, and cirrus cloud. During the dust episode, the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) data was also used to provide vertical profiles of aerosol and cloud layers and aerosol subtypes (Omar et al., 2009). In this work, we mainly analyzed the nighttime CALIPSO V3.40 data and the daytime data was only as a reference due to being influenced by the noise of solar radiation.

The 72-h backward trajectories arriving at Jiaozuo-HPU at multiple altitudes were calculated using software called TrajStat (Ngan et al., 2015). We also used Potential Source Contribution Function (PSCF) analysis to further determine the probable source locations of the pollution (Xin, 2016). The Concentration Weighted Trajectory (CWT) method was also applied in this regard, because of its advantages in separating strong and weak sources, which is something PSCF is unable to do. To reduce the level of uncertainty in the values obtained, a weighting function was applied for PSCF and CWT (WPSCF and WCWT, respectively).

RESULTS AND DISCUSSION
**Particle Radius and Volume Size Distributions**

The effective radii of aerosol particles in the Jiaozuo area are listed in Table 1. The monthly effective radii of the total particles varied between 0.30 and 0.45 μm, and the annual mean effective radii of fine-mode and coarse-mode particles were 0.17 and 2.12 μm, respectively. Remarkably, the fine-mode aerosol effective radii in summer (June–August) (0.19–0.22 μm) were larger than those in spring (March–May) (0.14–0.15 μm). This result may be attributable to aerosol hygroscopicity in summer (Che et al., 2018). The monthly mean aerosol volume and size distribution are shown in Fig. 2. Clearly, the size distribution in Jiaozuo has a typical bimodal distribution (Fig. 2(a)). There were slight differences in the peak radii for fine-mode and coarse-mode particles in different months, in which the fine-mode particle radii were mainly concentrated within 0.15–0.35 μm and the coarse-mode particle radii within 1.9–3.5 μm.

From Fig. 2(b), the volume of coarse-mode aerosol particles was obviously higher than that of fine-mode particles in spring. In April and May, coarse-mode particles accounted for the highest proportion, exceeding 65%. The percentage was 66.73% in May, with a volume of 0.16 μm³ μm⁻², which was twice as much as the fine mode particles. It is also evident, from the size distribution (Fig. 2(a)), that the coarse mode particles were dominant in April and May, with peak radii of 2.4 and 1.8 μm, respectively. This may be due to the area being located in the middle and lower reaches of the Yellow River, where the soil is loose and strong winds in spring cause localized blowing-sand weather to enhance the concentration of coarse particles in the atmosphere. In addition, long-distance dust transportation from northwestern China in spring may lead to elevated coarse-particle concentrations (Che et al., 2011). Indeed, Sun et al. (2018)
highlighted that Henan Province (Jiaozuo) is located on the pathway of dust particles being transported from northwestern China to the YRD region.

In summer, the volume of coarse particles decreased significantly compared with spring; the percentage in July and August was only about 30%. This may be attributable to the removal of coarse particles by heavy precipitation. The dominance of the fine mode particles in summer is also apparent in the size distribution and the peak radii moving toward the shortwave infrared wavelengths with the increase in precipitation from June to August (Fig. 3(c)); specifically, the radius increased from 0.2 to 0.35μm. The reason is that the size of hygroscopic aerosol, containing sulfate, nitrate and ammonium, is strongly influenced by high relative humidity (Shen et al., 2015; Huang et al., 2016). Furthermore, similar results have been observed in different areas of China, such as the North China Plain (Zhu et al., 2014), Northeast China (Che et al., 2015c), and the YRD region (Che et al., 2018). However, there are slight differences in some of the details. For example, a high volume of fine-mode particles was reported in June and September in the YRD region, owing to the mei-yu floods and autumn-rain, but a relatively low volume in July and August thanks to subtropical anticyclonic circulation (Che et al., 2018). The strong precipitation that occurred in July and August in Jiaozuo and the high volume for the fine mode particles in June and September may have been due to increased concentrations of black carbon aerosol caused by the burning of wheat and corn crops. The volume of fine-mode particles reached 0.16, 0.18, 0.17 and 0.14 μm^3/μm^2 in June to September, respectively. It should also be noted that Eck et al. (2012) reported that a large size range of fine-mode aerosol particles may be formed by cloud processing.
Aerosol Optical Depth, Ångström Exponent and Water Vapor Content

The annual mean AOD at 440 nm in Jiaozuo was 0.84 (0.73 at 500 nm), with a standard deviation of ±0.55, which suggests high aerosol loading. The AOD in Jiaozuo was higher than that reported for Longfengshan in northeastern China (0.35) (Wang et al., 2010), Xinglong in northern China (0.28) (Zhu et al., 2014), and Songshan mountain in central China (0.60 at 500 nm) (Wang et al., 2015b), the latter of which is regarded as the regional background site in Henan Province, 90 km south of Jiaozuo-HPU. Additionally, it was also higher than in several metropolises, such as Beijing (0.76) (Che et al., 2015a), Shanghai (0.70) (He et al., 2012a), Hangzhou (0.76) (Che et al., 2018), and Shenyang (0.75) (Zhao et al., 2015). The annual average AE$_{440-870}$ nm was 1.12 ± 0.17, suggesting that the main particles in the Jiaozuo area were fine-mode particles.

The temporal variations of monthly average AOD$_{440}$ nm, AE$_{440-870}$ nm, and water vapor content (WVC) are shown in Fig. 3. As shown in Fig. 3(a), the monthly variation of AOD was significant. The maximum value of AOD was in July, at 1.11 ± 0.59. The AOD in June, August and September was also relatively high, at 0.98 ± 0.42, 0.96 ± 0.52, and 1.07 ± 0.72, respectively. The minimum value of AOD was 0.57 ± 0.41, in April. The monthly average WVC showed an almost parabolic variation similar to Yangtze River Basin reported by He et al (2017), with high values in June to September and the maximum value (4.71 cm) in July and August (Fig. 3(c)) due to more precipitation. The high AOD values may have been related to the high WVC in these months. As Eck et al. (2005) pointed out, a high WVC in the atmosphere in summer is conducive to the hygroscopic growth of fine particles. Therefore, the hygroscopic effect of fine particles
may have caused high levels of extinction in June to September. Besides, the high AOD in June
and September may also have been affected by the burning of crop straw. From Fig. 3(b), the
monthly mean AE values were all greater than 0.8, indicating the Jiaozuo area was dominated by
fine-mode aerosol during this period. The maximum monthly AE occurred in June (1.37 ± 0.15)
and the minimum in April (0.81±0.37), which is consistent with the analysis of aerosol
microphysical characteristics mentioned above.

Additionally, there were clear seasonal variations of AOD and AE. The mean values of
AOD\textsubscript{440nm} in four seasons were 0.69 ± 0.41, 1.02 ± 0.53, 0.88 ± 0.54 and 0.72 ± 0.61,
respectively. The maximum AOD occurring in summer was likely related to the combined effect
of several factors. Firstly, high relative humidity in summer can cause an increase in AOD (Deng
et al., 2012). Secondly, the combustion of straw will produce additional aerosol particles. And
thirdly, secondary organic aerosol particles can be generated by photochemical reactions under
high temperatures in summer (Kroll and Seinfeld, 2008). Compared with autumn (September–
November), the AOD in winter (December–February) was lower, possibly associated with
governmental efforts to treat air pollution at that time of year. The seasonal average values of AE
were 0.92 ± 0.35, 1.27 ± 0.22, 1.09 ± 0.25 and 0.98 ± 0.32, respectively. The AE in spring
was lower than in the other seasons, indicating there were more coarse-mode particles in the
atmosphere during that season. In summer, abundant precipitation can eliminate coarse-mode
particles via wet deposition, meaning the fine mode particles begin to dominate. There was a
lower AE in winter compared with the background site at Songshan mountain (1.23). This may
be explained by higher levels of fugitive dust in the city (Che et al., 2014).
Single Scattering Albedo

The SSA is an important optical parameter that characterizes the scattering ability of aerosol, which is the proportion of scattering AOD to total AOD. It is mainly determined by the size and composition of aerosol particles (Dubovik et al., 2002). As shown in Fig. 4, there were distinct month-to-month variations of SSA at different wavelengths (440, 670, 870 and 1020 nm). From February to May, the SSA presents a decreasing trend, reaching a minimum in May, with values of 0.86, 0.87, 0.85 and 0.84 in the four bands, respectively. This tendency reveals the increasing absorptivity of aerosol particles. The SSA increased sharply from May to August and then declined. The seasonal mean values for SSA at 440 nm were 0.87±0.05, 0.95±0.04, 0.92±0.05 and 0.90±0.04 for spring, summer, autumn and winter, respectively. The minimal SSA in spring, especially in May, implies light-absorbing dust particles in the atmosphere. The maximum SSA in summer can be attributed to hygroscopic growth under high relative humidity, wherein the size of aerosol particles can modify the spectral properties of the SSA, resulting in an increase in its scattering ability (Xia et al., 2007). Meanwhile, the larger difference between the four wavelengths may imply that hygroscopic aerosol particles are more sensitive to wavelength variation. Compared with summer, a slight decrease in autumn was observed, which can be explained by light-absorbing carbonaceous aerosols from biomass burning (Arola et al., 2011). Thereafter, in winter, the greater concentrations of black carbon aerosol particles in the atmosphere generated by domestic heating emissions may be responsible for the relatively lower SSA values in that season. An interesting phenomenon is that the SSAs at 670 nm, 870 nm and 1020 nm differed little between autumn and winter, which might be indicative of the SSA being insensitive to wavelength variation within 670–1020 nm because of the presence of carbonaceous
Absorption Aerosol Optical Depth and Absorption Ångström Exponent

The AAOD represents the extent of the absorptive extinction of aerosol particles. Fig. 5(a) plots the monthly variation in AAOD at 440 nm. It shows that the maximum value (0.084±0.018) of the monthly mean was reached in May and the minimum (0.038±0.021) in August. The seasonal averages were 0.079 ± 0.019, 0.045 ± 0.021, 0.060 ± 0.029 and 0.066 ± 0.036 for spring, summer, autumn and winter, respectively. A high AAOD value generally reflects the absorption properties of carbonaceous aerosols and dust aerosols (Torres et al., 2005). The maximum value of AAOD being in spring reflected the strongest absorption ability occurring in that season because of the long-range transportation of absorptive dust particles from surrounding and remote areas of northwest China. It is worth noting that the AAOD reaching its maximum in spring was accompanied by the minimum SSA, followed by a significant drop when entering the summer season. As a result, the AAOD in summer was at a minimum, suggestive of high concentrations of light-scattering particles. Such a pattern in summer may be associated with the wet deposition of dust particles in the rainy season. Besides, another reasonable explanation for low AAOD is increasing concentrations of secondary aerosols, such as nitrates and sulfates, from different sources (e.g., industrial emissions, photochemical reactions, vehicle exhaust). After summer, the occurrence of black carbon aerosol particles generated by straw combustion in early autumn, as well as the rise in domestic heating later that season, were likely responsible for the increased AAOD in September and November, respectively. As for winter, the AAOD was higher than the values (< 0.05) previously observed in Hangzhou (Che et al., 2018) and Hefei (Liu et al., 2017),
but lower than that (0.1) in Shenyang (Zhao et al., 2015). The use of coal for heating purposes produces substantial amounts of absorbing black carbon aerosols in the Jiaozuo area. The same is true of Shenyang; plus, more absorbing particles generated by heavy industry in Shenyang and its surrounding areas contribute there to its high AAOD values. Relatively lower values appear in winter in southern China (e.g., in Hangzhou and Hefei), owing to comparatively low emissions of absorptive particles from domestic heating.

The types of absorbing aerosol particles (e.g., black carbon, organic matter, and dust) can be distinguished based on the AAE (Giles et al., 2012). Fig. 5(b) shows the monthly variations of AAE. From April to August, the monthly mean AAE was generally lower than 1. The occurrence of black carbon coated with absorbing or non-absorbing materials has been cited as a possible cause of the AAE being far lower than 1 (Bergstrom et al., 2007; Gyawali et al., 2009). However, it might also be related to measurement uncertainties and/or errors in retrieving the SSA (Dubovik and King, 2000). Thus, more observations are needed in the future to confirm these apparently low AAE values. The average AAE was relatively high (> 1) in the colder months of September to March. Indeed, from the perspective of seasonal variation, the AAE was significantly higher in autumn (1.41 ± 0.26) and winter (1.49 ± 0.36) than in spring (0.87 ± 0.25) and summer (0.89 ± 0.30). The AAE values in autumn and winter exceeded 1.10, indicating an obvious increase in organic aerosol concentrations from biomass burning and mineral dust (Lack and Cappa, 2010; Russell et al., 2010). Looking at the year as a whole, the annual mean AAE value was 1.09 ± 0.41, which is close to 1, possibly indicative of the absorbing aerosols in the Jiaozuo region being primarily composed of black carbon produced by fossil fuel.
combustion (Bergstrom et al., 2007).

**Aerosol Type Classification**

Aerosols originating from different sources have a diverse range of atmospheric effects (Dubovik et al., 2002; Alam et al., 2016); hence, it is essential in any study like the present one to identify the types of aerosols observed. The mostly commonly used classification technique is correlating the AOD with the AE and then classifying the aerosols into “dust”, “anthropogenic” or “marine”. However, this approach is incapable of sorting aerosols into “absorbing” or “non-absorbing” (Lee et al., 2010; Xia et al., 2016). The absorptivity of aerosol has a substantial effect on the process of direct radiative forcing (IPCC, 2013), which plays a crucial role in quantifying the influence of aerosols on Earth’s climate. It is, however, possibly to distinguish between absorbing and non-absorbing aerosols based on their SSA values (Lee et al., 2010). In addition, the Fine Mode Fraction (FMF), which is defined by $\text{AOD}_{\text{fine}(440 \text{ nm})}/\text{AOD}_{440 \text{ nm}}$, and the AE, can be used to characterize the dominant size mode of aerosols. In this work, aerosol optical parameters (FMF, SSA and AE) from the Jiaozuo-HPU site were used to classify aerosols into eight types following the method described in Zheng et al. (2017) and Che et al. (2018). Table 2 summarizes the SSA and AE threshold values for the eight types.

The aerosol types and their proportions in the Jiaozuo area are illustrated in Figs. 6 and 7, respectively. From Figs. 6(a) and 7(a), we can see that the aerosols were dominated by absorbing fine particles (Type I, II, III) and mixed absorbing particles (Type V), accounting for 36.89% and 35.35%, respectively. This indicates that high emissions of absorbing fine-mode aerosols, such as carbonaceous aerosols from agricultural and industrial activities, existed in Jiaozuo. The
non-absorbing fine particles (Type IV) accounted for 10.85%, with a value of 0.91 for the FMF, suggesting the presence of some sulfate and nitrate aerosols from the burning of fossil fuel. The proportion of mixed non-absorbing particles (Type VI) was 10.42%, which was slightly lower than the Type IV proportion, and the FMF almost exceeded 0.9. The non-absorbing coarse particles (Type VIII) showed a negligible percentage of total aerosol (0.51%), which might have been associated with the region being far away from the sea. Additionally, a significant seasonal difference in aerosol types is apparent from Figs. 6(b–e) and Figs. 7(b–e). The absorbing coarse particles (mainly dust) (Type VII) accounted for 15.12%, 0%, 4.46% and 6% in the four seasons, respectively, and the FMF varied from 0.44 to 0.52. The highest percentage of dust being in spring was mainly related to the long-range transport activities of that season (Yan et al., 2015); whereas, dust particles were almost eliminated in summer because of heavy rainfall. Owing to the existence of more nitrate and sulfate being produced by high-intensity human activity and/or photochemical reactions under high temperatures (Hennigan et al., 2008), the percentage of Type IV was higher in summer than in other seasons, at 20.87% (FMF: ~0.96). The absorbing fine-mode aerosols (Type I, II, III), as the highest proportion in Jiaozuo, accounted for 34.15%, 29.13%, 39.88% and 40.25% in spring, summer, autumn and winter, respectively, and the FMF values of these particles varied from 0.86 to 0.93.

**Relationship between AOD and Meteorological Conditions**

The accumulation and diffusion of aerosols are both influenced considerably by meteorological factors (Che et al., 2014; Wang et al., 2018). In this next part of our study, we examined the relationship between two such meteorological factors (namely, relative humidity and wind speed).
Fig. 8(a) and 8(b) show the variation trends of AOD as a function of relative humidity and wind speed, respectively. Clearly, relative humidity and wind speed have opposite effects on aerosol particles. Fig. 8(a) shows that AOD increased with relative humidity, and was only $0.30 \pm 0.17$ in the range of 0–20%. However, the AOD rose to $1.18 \pm 0.55$, reaching a maximum, when the relative humidity was greater than 70%. These results indicate that relative humidity has a significant effect on the hygroscopic growth of fine hydrophilic particles (Gui et al., 2016; Zhang et al., 2017b). Besides, Hennigan et al. (2008) reported that secondary aerosol particles, such as $\text{NO}_3^-$ and $\text{SO}_4^{2-}$, as well as other secondary organic compounds, form easily in conditions of high relative humidity, which is analogous to the situation in cloud processing. As shown in Fig. 8(b), in contrast, there is negative correlation between AOD and wind speed, and AOD showed a gradual declining trend with higher wind speed. When the wind speed was lower than 1 m/s, the AOD was as high as $0.93 \pm 0.57$; whereas, the AOD dropped to a low level of $0.49 \pm 0.16$ with the wind speed increasing to 5–6 m/s, reflecting the effect of wind on the diffusion of aerosol particles (He et al., 2012b; Gui et al., 2016; Li et al., 2016). The specific impact of the wind direction on pollutants is discussed below in the context of two pollution processes (haze and dust).

### Pollution Source Analysis during Dust and Haze Events

To further investigate the variation in aerosol optical properties and pollution sources, two typical pollution outbreak processes (haze and dust) that occurred in Jiaozuo during the study period were selected based on their associated news reports, meteorological data and satellite data. The MODIS true color images during the dust and haze episodes are displayed in Fig. 9.
Compared with Figs. 9(a) and 9(g), there is a clear haze coverage over Jiaozuo in Figs. 9(b-f). Figs. 9(i) and 9(j) show the presence of dust. In addition, this dust event can be confirmed by the NASA Earth Observatory (https://earthobservatory.nasa.gov/NaturalHazards/).

Figs. 10(a) and 10(d) depict the 72-h backward trajectories at multiple heights during the haze and dust cases over Jiaozuo. From Fig. 10(a) it can be seen that the trajectories over haze can be grouped into four clusters. Cluster-4, at an altitude below 500 m, contributes the maximum percentage of 38.89%, which is from the north part of Anhui Province. Cluster-2 accounts for 31.48% and originates from southern Shaanxi, passing over northern Shaanxi and southern Shanxi and then to Jiaozuo. The air masses associated with cluster-3 originate from north of Xinjiang, at the highest altitude of 4000 m, accounting for the minimum proportion of 5.56%. Similar to cluster-2, cluster-3 also arrives via southern Shanxi. Cluster-1 originates from the border area between the provinces of Henan, Shandong and Hebei, at an altitude below 500 m, accounting for 24.07%. As shown in Fig. 10(d), the potential source region is mainly located in the area to the northwest of Jiaozuo during dust episodes. The air mass trajectories originate from an altitude above 4000 m and then gradually decline to 2000 m, before eventually travelling across the Tai hang Mountains to the receptor site in Jiaozuo. Cluster-1 originates from the Gobi deserts lying on the eastern edge of Xinjiang, accounting for 36.11%, and passes over the Badain Juran Desert and Tengger Desert (Inner Mongolia), northern Ningxia Hui Autonomous Region, northern Shaanxi, southern Shanxi, and then on into Jiaozuo. The air masses associated with cluster-2 have long-range and high-altitude trajectories originating from Russia and travelling over the arid and semi-arid regions of Mongolia (Wang et al., 2006), accounting for 63.89%.
When the air masses enter China, they passed over the Ulan Buh Desert, the Mu Us Desert, and southern Shanxi, before reaching Jiaozuo. Hence, cluster-2 has a sizeable effect on PM$_{10}$ concentrations in Jiaozuo.

Figs. 10(b) and 10(c) show the results from the WPSCF and WCWT analyses for a haze event that took place from Dec 25 to Dec 31. It is clear that the distributions of WPSCF and WCWT are similar in pattern. In general, the high WPSCF values (> 0.8) are mainly located in Henan Province and surrounding areas, including southern Hebei, western Shandong, northern Anhui, northern Shaanxi, and southern Shanxi, which can be regarded as the most likely source areas. Interestingly, Fig. 10(b) shows the WPSCF values in northern Henan Province to have exceeded 0.9, suggesting local emissions contributed greatly to PM$_{2.5}$ concentrations. Meanwhile, it is apparent from Fig. 10(c) that northern Henan, eastern Henan, southern Shaanxi, northern Anhui, southwestern Inner Mongolia, northern Shaanxi, and Southern Shanxi, with rather high WCWT values of around 120 μg/m$^3$, seemed to be the areas contributing to the deterioration in air quality in Jiaozuo. Indeed, the long and narrow area from southwestern Inner Mongolia to southern Shanxi is an important coal base in China. The mining, utilization and transportation of coal inevitably leads to serious air pollution problems. Southern Hebei and western Shandong, contiguous to Henan Province, also contributed greatly to the PM$_{2.5}$ values of 80–120 μg/m$^3$. Furthermore, pollutant transport from southern Jiangsu Province (including Shanghai), which is a well-developed region in China with high levels of anthropogenic activity, also increased the accumulation of PM$_{2.5}$ in Jiaozuo, by 90–120 μg/m$^3$.

The distributions of WPSCF and WCWT values under dust conditions showed significant
diversity compared with haze days. Unlike the potential sources of haze mentioned above coming from different directions, the region to the northwest of Jiaozuo contributed almost all of the PM$_{10}$ concentration under dust. The WPSCF value (Fig. 10(e)) in the western part of Inner Mongolia was about 0.5, which Zhang et al. (1998) termed the ‘Northern High Dust Desert’, including the Badain Juran Desert, the Ulan Buh Desert, and the Hobq Desert. The contribution of the ‘Northern High Dust Desert’ to the PM$_{10}$ loadings in Jiaozuo varied from 100 – 200 μg/m$^3$, and was even more than 300 μg/m$^3$ in some areas (Fig. 10(f)). Additionally, the arid and semi-arid areas of western Mongolia contributed to the high PM$_{10}$ in Jiaozuo by 160 – 250 μg/m$^3$. Moreover, what is striking in Figs. 10(e) and 10(f) is that extremely high values of WPSCF (> 0.9) and WCWT (> 300 μg/m$^3$) exist in northern Shaanxi and southern Shanxi provinces, suggesting these areas contributed the most PM$_{10}$. On the one hand, the air masses associated with cluster-1 and cluster-2 flowed together in Shaanxi and Shanxi; on the other hand, this area was a dust source owing to its location in the eastern part of the Loess Plateau.

The atmospheric vertical information including the 532 nm total attenuated backscatter (top), the volume depolarization ratio (middle), and aerosol subtype (bottom) provided by CALIPSO data for the dust event is shown in Fig. 11. Volume depolarization ratio (VDR) can distinguish dust and anthropogenic aerosols (Liu et al., 2008; Tao et al., 2014), and aerosol subtypes include clean marine, dust, polluted and clean continental, polluted dust, and smoke (Omar et al., 2009; Liu et al., 2017). On 3 May and 4 May, the satellite swept across Shaanxi province and Inner Mongolia. The VDR values (> 0.2) indicated that the particles are predominantly non-spherical (dust) on 4 May. The CALIPSO vertical detections showed that dust particles were concentrated
at the height of 2-4 km in the middle atmospheric layer. The satellite was across northwestern Henan Province on 5 May, and the height of dust particles has declined according to the aerosol subtype. These airborne dust may follow the air mass in Fig. 10(d) to the Jiaozuo area. On 6 May, the VDR values (> 0.2) were concentrated in upper part of the aerosol layer and dropped to less than 1 km. The aerosol subtype results are also confirmed that the dust particles deposited in Jiaozuo and downstream areas.

Aerosol Optical Properties under Dust and Haze Events

Before analysing the aerosol optical properties during haze and dust events, we investigated the temporal variation of meteorological elements (the wind field) and PM concentrations, both of which contribute to the overall air pollution situation. As Fu et al. (2014) demonstrated, the wind direction can affect the transportation of pollution and determine the spatial distribution of atmospheric pollutants.

Figs. 12(a) and 13(a) show the wind field at the surface along with the daily mean PM$_{2.5}$ and PM$_{10}$ concentrations during the entirety of the haze process that occurred from 25 Dec to 31 Dec. The PM$_{2.5}$ and PM$_{10}$ concentrations on 25 Dec, the day before the haze “explosion”, were at relatively low levels of 49 μg/m$^3$ and 114μg/m$^3$, respectively—levels that were lower than China’s national ambient air quality standards (GB3095-2012, http://kjs.mep.gov.cn/hjbhbz/bzwb/dqhjhb/dqhjzlbz/201203/t20120302_224165.htm) (75 μg/m$^3$ for PM$_{2.5}$ and 150 μg/m$^3$ for PM$_{10}$) and therefore suggestive of good air quality in Jiaozuo. This may have been the result of strong southwesterly wind on that day (> 3 m/s), which was consistent with the direction of the Taihang Mountains being unfavorable for the accumulation.
of pollutants. The pollutants from eastern Henan and western Shandong were brought to Jiaozuo by easterly wind and southeasterly wind with high speeds (> 2 m/s) during the development stage of the haze on 26 and 27 Dec. Pollutants gradually accumulated, resulting in an increase in PM$_{2.5}$ and PM$_{10}$ concentrations. This suggests that the haze in the Jiaozuo area was affected not only by local emissions but also by transmission from other areas. Afterwards, the wind speed decreased to below 1 m/s and the PM$_{2.5}$ concentration increased rapidly to 205 μg/m$^3$ on 28 Dec. On 29 Dec, the PM$_{2.5}$ and PM$_{10}$ concentrations continued to rise, reaching peak values of 245 μg/m$^3$ and 340 μg/m$^3$, respectively. Thereafter, the wind direction turned northwesterly with increasing wind speed (> 4 m/s), creating favorable conditions for the dissipation of pollution. Consequently, the concentration of PM$_{2.5}$ slumped to 94 μg/m$^3$ on 30 Dec. The decline continued on 31 Dec and the concentrations of PM$_{2.5}$ and PM$_{10}$ fell to within desirable air quality standards, signalling a complete end to the haze episode.

The daily wind fields at 750 hPa (height of 3000 m above ground level) from ERA-Interim (Fig. 12(b)) during a dust event that occurred in May demonstrate how the pollutants from northeastern China were transported to the Jiaozuo area. Northwesterly winds with high speeds (> 14 m/s) prevailed over northeastern China during this dust event, creating conditions for the transportation of dust. However, strong southeasterly wind was dominant in the Jiaozuo region on 3 May, meaning coarse particles did not arrive and there was low PM$_{10}$ (67 μg/m$^3$) that day (Fig. 13(b)). The next day, however, the wind direction at 750 hPa changed from southeasterly to northerly and the wind speed increased to 16 m/s, contributing to the accumulation of PM$_{10}$ mass concentration by 219 μg/m$^3$. The wind speed gradually declined, which was conducive to the
formation of stable conditions on 5 March, resulting in the highest PM$_{10}$ of 440 μg/m$^3$. On 6 March, the wind speed increased to 10 m/s, indicating favorable diffusion conditions and leading to a sharp decrease in the concentration of PM$_{10}$ (116 μg/m$^3$) in Jiaozuo.

The aerosol optical properties retrieved from the CE318 sun photometer during haze and dust episodes are exhibited in Fig. 13 (the missing data were mainly due to the accumulation of clouds). Relatively low AOD was observed on 25 Dec, being 0.38, 0.25, 0.21 and 0.19 at 440, 670, 870 and 1020 nm, respectively (Fig. 13(a)). On that day, the AE was 0.84, indicating a relatively higher proportion of coarse particles compared with the next few days that the AE varied from 1.34-1.41, and it is also as reflected by the value of 43% for PM$_{2.5}$/PM$_{10}$. The AOD showed a sustained increase from 26 Dec to 29 Dec and a maximum value of AOD$_{440\text{ nm}}$ (2.54) was observed on 29 Dec. The mean AOD$_{440\text{ nm}}$ was 1.66 during this period of haze. Meanwhile, the daily AE was 1.38 and the value of PM$_{2.5}$/PM$_{10}$ was larger than 60%, suggesting a large quantity of fine aerosol particles caused this haze. Accordingly, fine-mode particles dominated during the haze “explosion” (27 Dec). The result is analogous to that reported by Zheng et al. (2017). On 30 Dec, the strong northwesterly (> 4 m/s) mentioned above in Jiaozuo favored the horizontal diffusion of aerosol particles, and the AOD$_{440\text{ nm}}$ decreased to 0.57. On the same day, the AE dropped dramatically to 0.18, suggesting an increase in the concentration of coarse particles. It is clear from Fig. 13(c) that coarse particles were dominant on 30 Dec, with a volume of 0.27 μg/m$^3$ for the coarse mode particles. This may have been related to elevated levels of fugitive dust under the high wind speeds (Che et al., 2014), which might explain why the minimum value of SSA$_{440\text{ nm}}$ occurred on 30 Dec. During the haze “explosion” (27 Dec), the
larger difference within 670-1020 nm may imply that fine aerosol particles are more sensitive to longer wavelength compared with coarse particles. Of note is that the value of AAOD during this haze was higher than on the clean day (25 Dec and 31 Dec), suggesting a large number of absorptive aerosol particles existed in the atmosphere.

The dust originating from the area to the northwest of Jiaozuo caused this dust storm in early May analyzed above. On 3 May, the day before the dust storm, the AE was 1.27 and the AOD at 440 nm was 0.85. The AOD in the four bands gradually increased over the next two days, coinciding with the AOD at 440 nm to be 0.90 on 4 May and 0.99 on 5 May, which means that the mean AOD reached 0.95 during the dust event. Correspondingly, the AE declined sharply, reaching extremely low levels of around 0.18 because of increasing concentrations of coarse particles. Furthermore, compared with 3 May, the coarse mode particles were remarkably dominant on 4 May, the peak radius of which was around 1.3 μm. The volume of coarse particles was also twice as large as it was the day before, accompanied by a rise in AAOD and a drop in SSA, to 0.11 and 0.88 respectively, at the wavelength of 440 nm. In short, the absorptive ability of aerosol particles increased on 4 May. The high volumes of coarse particles observed on 6 May might be related to dry deposition of dust particles or more fugitive dust in the atmosphere.

CONCLUSION

To the best of our knowledge, this is the first study to have carried out a detailed analysis of the aerosol optical and microphysical properties at Jiaozuo-HPU, an urban site in Henan Province with important implications for the Beijing–Tianjin–Hebei region. Our study was performed from
July 2016 to February 2018, during which time we also analyzed cases of two typical pollution processes (dust and haze) to further investigate the aerosol optical properties and pollution sources. The following conclusions can be drawn from our work:

The aerosol volume size distributions showed significant monthly and seasonal variations. Coarse-mode aerosol particles dominated in spring, with a maximum concentration of 0.16 $\mu$m$^3$μm$^{-2}$ in May, possibly related to large quantities of mineral dust particles brought by dust storms in that season, as well as localized blowing-sand weather. Low volumes of coarse particles were observed in summer owing to wet removal by abundant rainfall. In contrast, the highest volumes of fine-mode aerosols occurred in summer, and their peak radii moved toward longer wavelengths, from 0.2 $\mu$m in June to 0.35 $\mu$m in August, which was associated with the hygroscopic growth of fine hydrophilic aerosols under conditions of high relative humidity. In addition, carbonaceous aerosols from biomass burning in June and September increased the volume of fine particles.

The monthly mean values of AOD$_{440}$nm varied from 0.57 ± 0.41 in April to 1.11 ± 0.59 in July, with an annual mean of 0.84 ± 0.55, suggesting a high aerosol loading in the Jiaozuo area. The seasonal mean AOD$_{440}$nm values were 0.69 ± 0.41, 1.02 ± 0.53, 0.88 ± 0.54 and 0.72 ± 0.61 for spring, summer, autumn and winter, respectively. The highest AOD being in summer was attributed to the hygroscopic growth of aerosols under enhanced relative humidity, increased agricultural activity (e.g., biomass combustion) and the formation of secondary aerosol particles (e.g., sulfate and nitrate). The annual mean AE was 1.12 ± 0.17, indicating that fine particles were dominant in Jiaozuo. A lower AE occurred in spring (0.92 ± 0.35) compared with
the other seasons, reflecting the existence of more coarse-mode particles in that season. The monthly SSA (AAOD$_{440\text{ nm}}$) presented a decreasing (increasing) trend from February to May, which revealed the increasing absorptivity of aerosols, and increased (decreased) sharply from May to August. A distinct seasonal variation in SSA was also observed, with the highest value in summer (0.95 ± 0.04) and the lowest value in spring (0.87 ± 0.05). On the contrary, AAOD$_{440\text{ nm}}$ was higher in spring (0.079 ± 0.019) and lower in summer (0.045 ± 0.021). The seasonal difference may be due to dust particles in spring, high industrial emissions and hygroscopic growth of fine particles in summer, biomass burning in autumn, and coal combustion for domestic heating in winter. The annual AAE value was 1.09 ± 0.41, which being close to 1 indicated a significant source of absorbing black carbon aerosols from fossil fuel combustion.

The aerosols in Jiaozuo were sorted into eight types according to their SSA, FMF and AE values. The absorbing aerosols (fine and mixed) were found to be predominant in the Jiaozuo area, accounting for 36.89% and 35.35% respectively, which we attributed to carbonaceous aerosols from agricultural and industrial activities. An obvious seasonal difference in aerosol types was found. The absorbing coarse particles dominated in spring and accounted for 15.12%, indicating elevated levels of mineral dust particles. The percentage of non-absorbing fine particles was higher in summer than in the other seasons, attributable to the greater abundance of sulfate and nitrate generated by high-intensity human activity and/or photochemical reactions.

The enhanced AODs were observed during the two pollution processes of haze and dust. The mean AOD was 1.66 (0.95) on haze (dust) days. A high AE of 1.38 was observed on haze days, suggesting fine-mode aerosol particles were dominant. However, low AE values occurred on dust
days because of high concentrations of dust particles being dominant. According to WPSCF and WCWT analysis, pollutants both from surrounding regions and local emissions contributed to this haze episode, while the dust aerosols in this site mainly originated from northwestern China.

ACKNOWLEDGMENTS

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Aircraft Study of Aerosol Vertical Distributions over Beijing and Their Optical Properties.


Table Captions

Table 1. Monthly mean effective radii of aerosols and statistics of level 1.5 sun direct data for AOD and Ångström exponent at Jiaozuo-HPU.

Table 2. Threshold values of aerosol properties for different absorbing types of aerosol.
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<table>
<thead>
<tr>
<th>Month</th>
<th>$R_{\text{eff}}$ (µm)$^a$</th>
<th>$R_{\text{eff fine}}$ (µm)$^b$</th>
<th>$R_{\text{eff coarse}}$ (µm)$^c$</th>
<th>Days</th>
<th>Instantaneous Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>0.39 ± 0.13</td>
<td>0.15 ± 0.03</td>
<td>1.99 ± 0.36</td>
<td>15</td>
<td>553</td>
</tr>
<tr>
<td>Feb</td>
<td>0.41 ± 0.18</td>
<td>0.14 ± 0.06</td>
<td>2.06 ± 0.38</td>
<td>22</td>
<td>987</td>
</tr>
<tr>
<td>Mar</td>
<td>0.35 ± 0.08</td>
<td>0.15 ± 0.03</td>
<td>2.26 ± 0.36</td>
<td>14</td>
<td>462</td>
</tr>
<tr>
<td>Apr</td>
<td>0.44 ± 0.15</td>
<td>0.14 ± 0.05</td>
<td>2.07 ± 0.61</td>
<td>18</td>
<td>673</td>
</tr>
<tr>
<td>May</td>
<td>0.45 ± 0.13</td>
<td>0.14 ± 0.02</td>
<td>1.94 ± 0.56</td>
<td>24</td>
<td>924</td>
</tr>
<tr>
<td>Jun</td>
<td>0.30 ± 0.04</td>
<td>0.19 ± 0.03</td>
<td>2.43 ± 0.29</td>
<td>19</td>
<td>633</td>
</tr>
<tr>
<td>Jul</td>
<td>0.32 ± 0.06</td>
<td>0.22 ± 0.06</td>
<td>2.20 ± 0.42</td>
<td>36</td>
<td>1002</td>
</tr>
<tr>
<td>Aug</td>
<td>0.32 ± 0.07</td>
<td>0.22 ± 0.06</td>
<td>2.15 ± 0.27</td>
<td>28</td>
<td>820</td>
</tr>
<tr>
<td>Sep</td>
<td>0.35 ± 0.11</td>
<td>0.17 ± 0.04</td>
<td>2.40 ± 0.26</td>
<td>18</td>
<td>758</td>
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<tr>
<td>Oct</td>
<td>0.32 ± 0.04</td>
<td>0.21 ± 0.07</td>
<td>1.93 ± 0.39</td>
<td>12</td>
<td>361</td>
</tr>
<tr>
<td>Nov</td>
<td>0.34 ± 0.09</td>
<td>0.16 ± 0.04</td>
<td>1.93 ± 0.34</td>
<td>39</td>
<td>1394</td>
</tr>
<tr>
<td>Dec</td>
<td>0.33 ± 0.11</td>
<td>0.15 ± 0.04</td>
<td>2.13 ± 0.36</td>
<td>44</td>
<td>1571</td>
</tr>
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</table>

$^a$ Effective radii of the total particles. $^b$ Effective radii of fine particles. $^c$ Effective radii of coarse particles.
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<table>
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<tr>
<th>Group</th>
<th>Aerosol type</th>
<th>AE</th>
<th>SSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>Fine highly-absorbing</td>
<td>&gt; 1.2</td>
<td>≤ 0.85</td>
</tr>
<tr>
<td>Type II</td>
<td>Fine moderately-absorbing</td>
<td>&gt; 1.2</td>
<td>≥ 0.85 and &lt; 0.9</td>
</tr>
<tr>
<td>Type III</td>
<td>Fine slightly absorbing</td>
<td>&gt; 1.2</td>
<td>≥ 0.9 and &lt; 0.95</td>
</tr>
<tr>
<td>Type IV</td>
<td>Fine non-absorbing</td>
<td>&gt; 1.2</td>
<td>&gt; 0.95</td>
</tr>
<tr>
<td>Type V</td>
<td>Mixed absorbing</td>
<td>≥ 0.6 and &lt; 1.2</td>
<td>≤ 0.95</td>
</tr>
<tr>
<td>Type VI</td>
<td>Mixed non-absorbing</td>
<td>≥ 0.6 and &lt; 1.2</td>
<td>&gt; 0.95</td>
</tr>
<tr>
<td>Type VII</td>
<td>Coarse absorbing</td>
<td>≤ 1.2</td>
<td>≤ 0.95</td>
</tr>
<tr>
<td>Type VIII</td>
<td>Coarse non-absorbing</td>
<td>≤ 1.2</td>
<td>&gt; 0.95</td>
</tr>
</tbody>
</table>
Figure Captions

**Fig. 1.** True color image and locations of Henan Province in China. The red dot denotes the location of Jiaozuo-HPU.

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**Fig. 3.** Monthly variations of (a) AOD$_{440\text{ nm}}$, (b) AE$_{440-870\text{ nm}}$ and (c) water vapor content (WVC) at Jiaozuo-HPU. The boxes represent the 25th to 75th percentiles of the distributions while the middle line and red dots indicate the means and medians, respectively.

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**Fig. 6.** The aerosol type classification using SSA, AE and FMF data for (a) annual, (b) spring, (c), summer, (d) autumn and (e) winter. See text in Table 2 for description of groups I-VIII.

**Fig. 7.** The frequency distribution of aerosol types for (a) annual, (b) spring, (c), summer, (d) autumn and (e) winter. See text in Table 2 for description of groups I-VIII.

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