Atmospheric Research 99 (2011) 241–247

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

A comparative analysis of aerosol properties in dust and haze-fog days in a Chinese urban region

Xingna Yu [a,*], Bin Zhu [a], Yan Yin [a], Jun Yang [a], Yanwei Li [a], Xiaoli Bu [b]

[a] Key Laboratory of Meteorological Disaster of Ministry of Education, Department of Atmospheric Physics, Nanjing University of Information Science and Technology, Nanjing 210044, China

[b] School of Science, University of Nanjing Forestry, Nanjing 210037, China

ARTICLE INFO

Article history:
Received 6 December 2009
Received in revised form 9 October 2010
Accepted 11 October 2010

Keywords:
Dust
Haze-fog
Aerosol
Beijing

ABSTRACT

A comparative study on the aerosol optical properties of two severe pollution phenomena occurred in Beijing, i.e. dust and haze-fog, was analyzed using solar and sky radiance measurements from 2001 to 2007. The aerosol optical depth (AOD) showed a distinct variation under different weather conditions, with an average 1.70 in dust days and 1.26 in haze-fog days. The values of Ångström exponent (α) in dust days were significantly lower than those of haze-fog days, with an average of 0.48 in dust days and 1.11 in haze-fog days. The fine modes of volume size distributions showed the maxima peak at radius 0.09–0.25 μm in dust days and radius 0.11–0.25 μm in haze-fog days. The coarse modes showed the maxima peak at radius 2.2–2.9 μm in dust days, and radius 2.2–3.8 μm in haze-fog days. The size distributions showed a distinct difference in dominant mode for the different weather conditions. For haze-fog days, the fine mode was dominant in the aerosol size distribution. However, the coarse mode was dominant in the aerosol size distribution of dust days with the average volume concentration ratio of coarse to fine modes being 8.3. The averages of single scattering albedo (SSA) were found to be about 0.92 for dust days and 0.89 for haze-fog days at 440, 675, 870 and 1020 nm. In comparison with dust days and haze-fog days, the growth in SSA was due to the addition of amount of dust particles. In view of climate, the asymmetry factor at wavelengths 440–1020 nm were about 0.70 for dust days and 0.65 for haze-fog days in Beijing. The scattering phase functions of dust days at forward and backward directions were commonly larger than those of haze-fog days, with values of 381.18 at 0° and 0.23 at 180° for dust days, and lower values of 86.48 at 0° and 0.20 at 180° for haze-fog days.

1. Introduction

Beijing, the capital of China, has been facing the serious particulate pollution in air quality due to the large energy consumption and rapid increase of the number of vehicles (~15% per year) (He et al., 2001), plus the invaded dust from outside Beijing throughout the entire year further burdens the air pollution in Beijing, especially in spring. Thus, Beijing has been listed as one of the top ten pollution cities in the world.

Dust storms are frequent in northern China during spring, and typically invade Beijing in March and April (Liu et al., 1981; Gao et al., 2002). They are generated over dry/semi-dry areas (including deserts) by strongwinds near cold fronts (Gao et al., 2000; Husar et al., 2001) and are transported to large part of northern China, Korea, Japan and even the west of America across the North Pacific Ocean (Zhuang et al., 2001; Ma et al., 2001; Chun et al., 2001; Murayama et al., 2001; Tratt et al., 2001; Husar et al., 2001). As the dust storms reach Beijing, the coarse particles often peak hours before their fine particles do (Zhang et al., 2000). Some researchers have been studying dust aerosol with transport, chemical, physical and optical properties (Tanré et al., 2001; Zhang et al., 1993, 1998; Maring et al.,

* Corresponding author. Tel.: +86 25 58731592; fax: +86 25 58699771.
E-mail address: xnyu@nuist.edu.cn (X. Yu).

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doi:10.1016/j.atmosres.2010.10.015

2003; Kim et al., 2005; Mori et al., 2003). These efforts have led to a good understanding of the effects of dust on air quality, the global biogeochemical cycle and the global environmental change.

At the same time, the phenomena of haze-fog have been observed frequently in Beijing in recent years (Sun et al., 2006), especially during the cold winter and spring seasons because of the enhanced heating/traffic/industrial emissions and the stable synoptic conditions. Haze-fog pollution has also attracted much interest for its impact on visibility, cloud formation, public health, agriculture, and even the global climate (Chameides et al., 1999; Meng et al., 2000; Okada et al., 2001; Schichtel et al., 2001; Chen et al., 2003; Yadav et al., 2003; Kang et al., 2004; Herckes et al., 2007). The chemical characteristics and formation mechanisms of aerosol in haze-fog episodes in Beijing have been investigated (Wang et al., 2006; Sun et al., 2006). However, studies on optical properties of haze-fog in Beijing are rather limited.

In this study, a comparative study was performed to investigate the difference in aerosol optical properties of two severe pollution phenomena occurred frequently in Beijing, i.e. dust and haze-fog. The results could provide us a valuable data to improve the knowledge of aerosol properties in different pollution episodes in Beijing.

2. Site description and measurement

Beijing is located at the northwestern border of the Great North China Plain and surrounded by mountainous area in the west, the north, and the northeast. In the east and south of Beijing, the elevation is close to sea level. The climate of Beijing is known as “continental monsoon” and has four distinct seasons each year. The cold and windy weather mainly occurs during winter (December, January and February) and spring (March–May) because of frequent outbreaks of cold air from west Siberia. Spring occasionally is impacted by the dust episodes transported by northwesterly and westerly winds from the Kumutage and Taklimakan deserts in western China or by northerly winds from Mongolian deserts (Sun et al., 2001). In summer (June–August), it is characterized by relatively hot and humid weather and accounts for about 74% of annual precipitation. Autumn (September–November) is considered to be the best season with a relatively clear and clean sky. Winter is the heating season from mid-November to mid-March.

We selected the data acquired at Beijing sites to study the difference of aerosol properties in dust and haze-fog days. According to the definition of Meteorological Observing Criterion from the National Weather Bureau of China (1979), dust storm, blowing dust and floating dust belong to a category called dust storm events. The dust storm is generally defined as a storm that carries a great deal of dust and sand lofted by strong wind. It is a disastrous weather event which makes air quite turbid and lowers horizontal visibility to <1000 m. Blowing dust is generally defined as a weather phenomenon which is formed by big winds carrying a lot of dust and sand, and can reduce horizontal visibility to 10,000–1000 m. Floating dust is generally defined as weather phenomenon in which fine dust is suspended in the lower troposphere with horizontal visibility of <10,000 m. Haze is defined as the weather phenomenon which leads to atmospheric visibility less than 10 km due to the moisture, dust, smoke, and vapor in the atmosphere, while fog leads to atmospheric visibility less than 1 km and is composed of fine droplets of water suspended in the air near the Earth's surface. Visibility degradation is caused by the haze when the relative humidity (RH) is less than 80%, by the fog when RH is larger than 90%, and by the mixture of haze and fog when RH was 80–90%. The formation of haze-fog is closely related to the meteorological conditions and the amount of pollution in the atmosphere. Here the dust days and haze-fog days were selected on the basis of three kinds of dust storm events, and relative humidity and visibility, respectively, and were confirmed by the surface weather records, satellite images even media reports and published paper.

The CIMEL CE-318 sun/sky radiometer was installed on the roof of the Institute of Atmospheric Physics (IAP) building, Beijing (39.977°N, 116.38°E). The observation period in Beijing is from March 2001 to October 2007, and the detailed information is given in Table 1. The measurements with instrument are a part of the Aerosol Robotic Network (AERONET). The description details of automatic tracking sun and sky scanning radiometers were given by Holben et al. (1998). An automated cloud-screening algorithm was applied to the direct sun measurements of aerosol optical depth (Smirnov et al., 2000). A flexible inversion algorithm was used to retrieve columnar aerosol volume size distributions, refractive indices and single scattering albedos from the direct sun and diffuse sky radiance measurements (Dubovik and King, 2000). The CIMEL sun and sky radiometer measured direct sun radiance in the eight spectral channels between 340 and 1020 nm (340, 380, 440, 500, 675, 870, 940 and 1020 nm). The 940 nm channel was used to estimate the water vapor content, and the remaining seven channels were used to retrieve aerosol optical depth. The uncertainty in aerosol optical depth was found to be less than ± 0.01 for $\lambda > 440$ nm and less than ± 0.02 for shorter wavelength, was $\pm 10\%$ for water vapor, and was $< \pm 5\%$ in the sky radiance measurements (Dubovik et al., 2000). The data of aerosol optical properties were publicly available and were downloaded from the AERONET website (http://aeronet.gsfc.nasa.gov/new_web/data.html). Data presented in this study were the AERONET level 2.0 quality-assured data that had been prefield and postfield calibrated automatically cloud screened and manually inspected (Smirnov et al., 2000).

3. Results

3.1. Aerosol Optical Depth (AOD) and Ångström exponent (α)

Fig. 1a–b shows the scattergrams of AOD at 440 nm and Ångström exponent for dust and haze-fog days occurred in Beijing during 2001–2007. The AOD in dust days varied from 0.9 to 3.0 with the total average 1.70, which was about 2 times larger than the average value in spring of Beijing (0.89, 440 nm) during 2002–2007, and was less than the daily-average AOD (3.1, 670 nm) appeared on 12 April of 2001 at Dunhuang (Yu et al., 2006, 2009). Xin et al. (2005) had observed the daily-average of AOD at 550 nm was about 2.0 during the dust storms in southeast of the Tengger Desert which is one of important dust storm centers in northwest China. The AOD in haze-fog days showed a wider range between 0.14 and 2.87 with an average 1.26, which was a

Table 1
The selected dust and haze-fog dates occurred in Beijing.

Episodes		2001	2003	2004	2005	2006	2007
Dust	March	23, 24		14, 15, 27, 28		10, 20, 30, 31	
	April	8, 10			29, 30	9, 14, 16, 22, 23	
	May	1, 2, 3, 4				16, 17	
Haze-fog	January		1			14, 15, 18, 19, 21, 22, 23, 24, 25, 26, 27	1, 2, 3, 4
	March						9, 13, 14
	April			10			
	October			8			25
	November			30			
	December			1, 15		10, 11	

factor of 1.85 higher than the 6-year average value in winter of Beijing (Yu et al., 2009). In general, the averages of AOD in dust days were commonly higher than haze-fog days. This may be attributed to a strong contribution to the solar light extinction of large amounts of coarse particles in dust days.

The value of Ångström exponent computed from AOD measurements at 870 and 440 nm is found to increase when the particle size decreases, with the maximum value equal to 4 corresponding to molecules and the minimum value near zero or even negative for super-coarse particles. The value α was found to vary from −0.05 to 1.06 with an average of 0.48 in dust days, and ranged from 0.43 to 1.38 with a high average of 1.11 in haze-fog days. In dust days, the values of α appeared in Beijing were evidently lower than those of dust source regions. For example, the average α in dust days was 0.05 in Dunhuang and 0.20 in Yulin (Yu et al., 2006). This could be explained by the predominance of coarse mineral particles over source regions, the existence of fine mineral particles together with pollutant aerosol particles over downwind regions. As seen in Fig. 1b, the values of Ångström exponent occurred in haze-fog days were commonly higher than dust days. This result indicated the fine particles were predominant in haze-fog days.

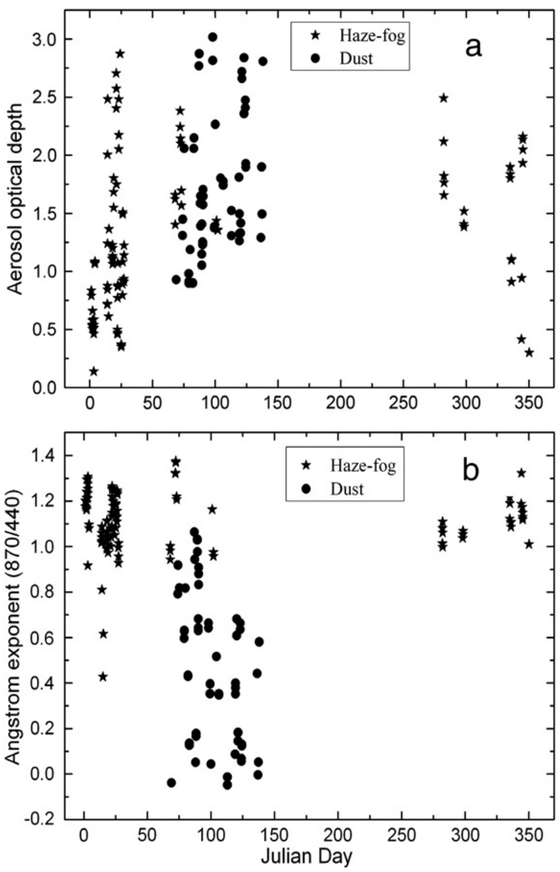

Fig. 1. (a) The scattergrams of AOD at 440 nm, and (b) Ångström exponent for dust and haze-fog days in Beijing during 2001–2007.

3.2. Size distribution

The average volume size distributions of aerosols in dust and haze-fog days during 2001–2007 in Beijing are shown in Fig. 2, in which the distributions have been averaged over individual size distributions and sorted according to the AOD measured at 440 nm. The aerosol volume size distributions were found to be bimodal logarithm normal structure: fine mode (r<0.6 μm) and coarse mode (r>0.6 μm). The fine modes commonly showed the maxima peak at radius 0.09–0.25 μm in dust days, and radius 0.11–0.25 μm in haze-fog days. The coarse modes showed the maxima peak at radius 2.2–2.9 μm in dust days, and 2.2–3.8 μm in haze-fog days. As shown in Fig. 2, the amplitude of fine mode was found to be larger in haze-fog days compared to dust days, suggesting the complexity of aerosol components significantly influenced by pollution emissions in haze-fog days. It is evident that the size distribution showed a distinct difference in dominant mode for the different weather conditions. For haze-fog days, the fine modes were dominant in the aerosol size distribution except for AOD was 1.4. However, the coarse modes were dominant in the aerosol size distribution of dust days in any AOD due to the presence of dust particles with relative big size, with the volume concentration ratio of coarse to fine modes being from 3.0 to 12.4 for all AOD with an average of 8.3.

The median radius of fine modes in dust and haze-fog days commonly showed an increasing trend with AOD. The median radius of fine modes centered at 0.09–0.11 μm for AOD less than 2.0 and 0.25 μm for AOD larger than 2.0. For haze-fog days, the fine mode centered at radius 0.11–0.15 μm when AOD less than 1.4, and 0.19-0.25 μm when AOD larger than 1.4. The median radii of fine mode in haze-fog days were higher than dust days when AOD less than 1.4. This increase of the median radius of fine mode may be related to the growth of hygroscopic particles when water vapor content was found to be high during haze-fog days. The coarse modes

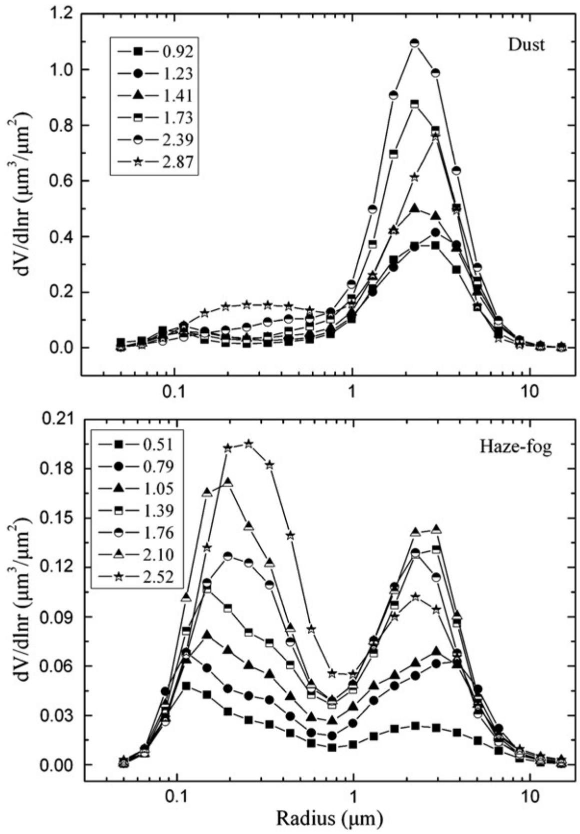

Fig. 2. The average volume size distributions derived from the sky radiance as a function of particle radius in dust and haze-fog days in Beijing during 2001–2007. The distributions have been averaged over individual size distribution and sorted according to the aerosol optical depth measured at 440 nm.

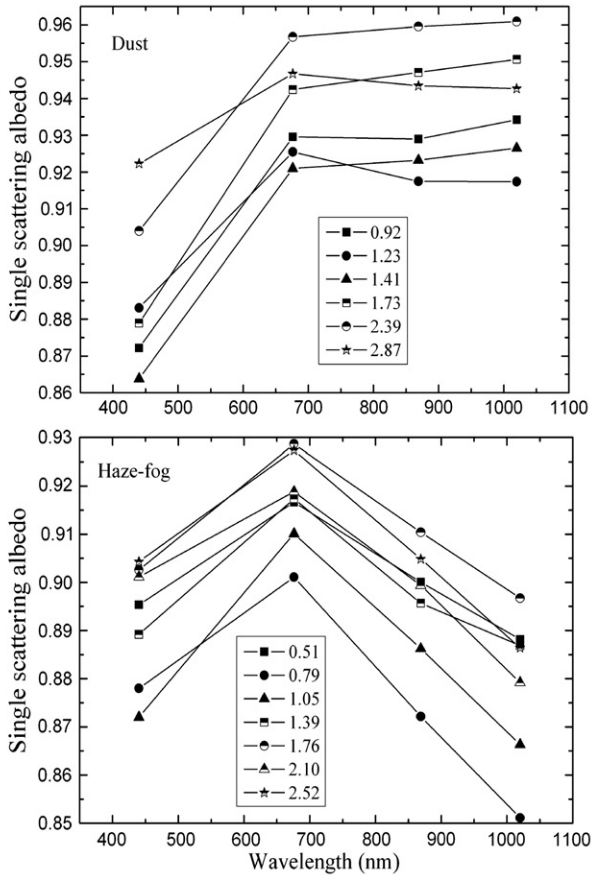

Fig. 3. The averages of SSA at 440, 675, 870 and 1020 nm in dust and haze-fog days in Beijing during 2001-2007. The single scattering albedos have been averaged and sorted according to the aerosol optical depth measured at 440 nm.

of size distribution varied with AOD in one nonlinear approach in dust and haze-fog days. For example, the coarse modes centered at radius 2.9 μm when AOD less than 1.4, 2.2 μm for AOD between 1.4 and 2.5, and 2.9 μm for AOD larger than 2.5 in dust days.

3.3. Single scattering albedo (SSA)

Fig. 3 shows the average SSA at 440, 675, 870 and 1020 nm in dust and haze-fog days in Beijing during 2001–2007, in which the albedos have been averaged and sorted according to the AOD measured at 440 nm. For dust days, the single scattering albedo almost showed a wild increasing trend with wavelengths, with the averages were 0.88–0.94 at the four wavelengths. The SSA were commonly higher at later three wavelengths than early wavelength, with average 0.89 at 440 nm and 0.94 at 675–1020 nm. The value was lower than the results observed at desert dust regions, such as the values were up to 0.93 at Cape Verde during 1993–2000 and 0.92 at Saudi Arabia at 440 nm (Dubovik et al., 2002). Kim et al. (2005) reported that the mean SSA at Gosan, Korea during dust episodes in April of 2001 was up to 0.91 (550 nm). For haze-fog days, the SSA was found to increase at 440–675 nm and then decrease at 675–1020 nm, with the averages of 0.89, 0.92, 0.90 and 0.88 at the four wavelengths respectively. Noh et al. (2009) have recently presented that the average SSA of Gwangju was up to 0.90 at 532 nm during haze episode. From Fig. 3, the SSA showed a low sensitivity to AOD with a range of 0.86–0.96 during dust days and 0.85–0.93 during haze-fog days at the four wavelengths. The SSA varied with AOD in one nonlinear approach due to the changes of aerosol loading, size distribution and vertical profile. The averages of SSA in dust days were higher than haze-fog days between 675 nm and 1020 nm. In comparison with dust days and haze-fog days, the growth in SSA was due to the addition of amount of dust particles. In general, the averages of SSA were found to be about 0.92 for dust days and 0.89 for haze-fog days at the four wavelengths during 2001–2007 in Beijing.

3.4. Asymmetry factor

The asymmetry parameter represents an estimation of the asymmetry distribution of the dispersed radiation. For symmetric scattering, Rayleigh scattering, the asymmetry parameter is considered to be 0 and for a purely forward scattering aerosol is taken as 1. For a cloudless atmosphere, the asymmetry factor ranges from 0.1 in very clean conditions to 0.75 in polluted ones (Zege et al., 1991).

The averages of asymmetry factor at 440, 675, 870 and 1020 nm for dust and haze-fog days in Beijing are shown in Fig. 4, in which the factors have been averaged and sorted according to the AOD measured at 440 nm. The asymmetry factor almost decreased at 440–870 nm and then increased at 870–1020 nm for dust days, and showed a decreasing trend with wavelengths for haze-fog days. The asymmetry factor showed a lower sensitivity to wavelengths during 675–1020 nm than 440–675 nm. For example, the averages of asymmetry factor were up to 0.73 at 440 nm, 0.69 at 675–1020 nm for dust days, and 0.71 at 440 nm and 0.63 at 675–1020 nm for haze-fog days. The increase of asymmetry factor in dust days was possibly attributed to the higher contribution of large particles, and indicated the dust particles were predominant in forward scattering. As seen in Fig. 4, the asymmetry factor in haze-fog days commonly showed an increasing trend with AOD. However, the asymmetry factor varied with AOD in one nonlinear approach in dust days. For example, the asymmetry factor at four wavelengths showed an increasing trend in AOD range of 1.3–2.4 and a decreasing trend at high AOD (>2.4). In general, the asymmetry factor at wavelengths 440–1020 nm was about 0.70 for dust days and 0.65 for haze-fog days in Beijing.

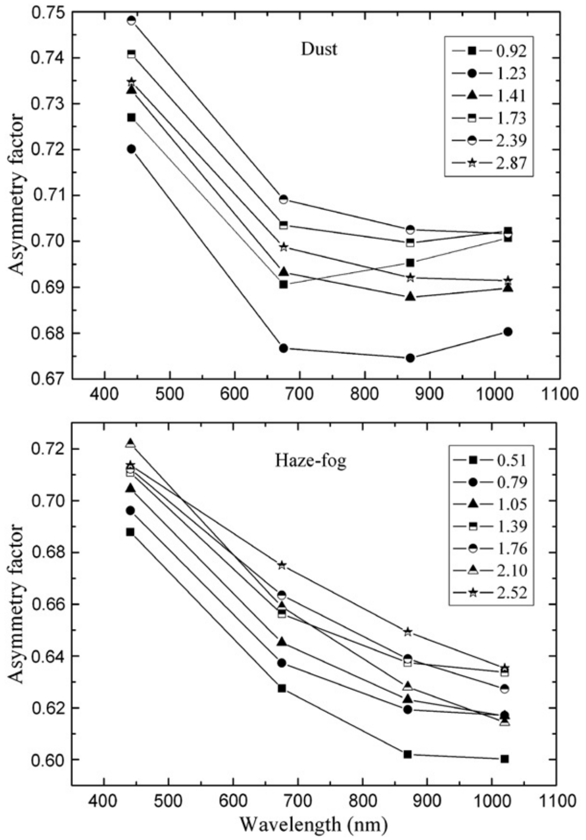

Fig. 4. The averages of asymmetry factor at 440, 675, 870 and 1020 nm for dust and haze-fog days in Beijing during 2001–2007. The factors have been averaged and sorted according to the aerosol optical depth measured at 440 nm.

3.5. Phase function

Fig. 5 shows the averages of phase function from scattering angle 0° to 180° at 440 nm in dust days and haze-fog days in Beijing. The values of phase function have a minimum at a scattering angle around 130° and a maximum at around 0° in dust and haze-fog days, indicating the particles were predominant in forward scattering. The scattering phase functions of dust days at forward and backward directions were commonly larger than those of haze-fog days due to nonsphericity, with values of 381.18 at 0° and 0.23 at 180° for dust days, and lower values of 86.48 at 0° and 0.20 at 180° for haze-fog days. For dust and haze-fog days, the phase function showed an increasing trend with scattering angles from 130° to 180°, and a decreasing trend with angles from 0° to 130° especially in dust days. From Fig. 5, the phase function in dust days was smaller than that of haze-fog days at the scattering angles from 10° to 90°, and larger at scattering angles from 0° to 10° and from 90° to 180°. These results indicated that large amounts of coarse particles occurred in dust days, and nonsphericity effects in dust days were larger than that in haze-fog days.

4. Conclusion

The optical properties of aerosol in dust and haze-fog days were presented from the Aerosol Robotic Network (AERONET) measurements in urban Beijing, China between 2001 and 2007. The aerosol optical depth (AOD) showed a distinct variation under different weather conditions in Beijing. The AOD varied from 0.9 to 3.0 with the total average 1.70 in dust days, and from 0.14 to 2.87 with an average 1.26 in haze-fog days. The averages of AOD in dust days were commonly higher than haze-fog days. This result may be attributed to a strong contribution to the solar light extinction of large amounts of coarse particles in dust days. The values of Ångström exponent (α) in dust days were found to lower than those of haze-fog days, with an average of 0.48 in dust days and 1.11 in haze-fog days. For dust days, the values of α appeared in Beijing were evidently lower than those of dust

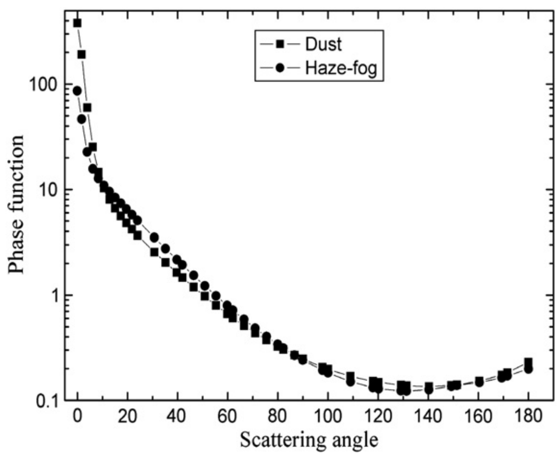

Fig. 5. Averages of phase function from scattering angle 0° to 180° at 440 nm in dust and haze-fog days in Beijing during 2001–2007.

source regions, such as the average α was 0.05 in Dunhuang and 0.20 in Yulin.

The aerosol volume size distributions were found to be bimodal logarithm normal structure: fine mode ($r<0.6$ μm) and coarse mode ($r>0.6$ μm). The fine modes showed the maxima peak at radius 0.09–0.25 μm in dust days, and radius 0.11–0.25 μm in haze-fog days. The coarse modes showed the maxima peak at radius 2.2–2.9 μm in dust days, and 2.2–3.8 μm in haze-fog days. The size distribution showed a distinct difference in dominant mode for the different weather conditions. For haze-fog days, the fine mode was commonly dominant in the aerosol size distribution. However, the coarse modes were dominant in dust days due to the presence of dust particles with relative big size, with the average volume concentration ratio of coarse to fine modes being 8.3.

The single scattering albedo (SSA) showed a low sensitivity to AOD with a range of 0.86–0.96 during dust days and 0.85–0.93 during haze-fog days at the four wavelengths. In general, the averages of SSA were about 0.92 for dust days and 0.89 for haze-fog days at the four wavelengths. The asymmetry factor decreased at 440–870 nm and then increased at 870–1020 nm for dust days, and showed a decreasing trend with wavelengths for haze-fog days. In view of climate, the asymmetry factor at wavelengths 440–1020 nm were about 0.70 for dust days and 0.65 for haze-fog days in Beijing. The values of phase function have a minimum at a scattering angle around 130° and a maximum at around 0° in dust and haze-fog days. The scattering phase functions of dust days at forward and backward directions were commonly larger than those of haze-fog days due to nonsphericity and polarization, with values of 381.18 at 0° and 0.23 at 180° for dust days, and lower values of 86.48 at 0° and 0.20 at 180° for haze-fog days.

Acknowledgements

This work was partially supported by a grant from the National Program on Key Basic Research Project of China (973 Program) (No. 2009CB426313), National Natural Science Foundation of China (No. 41005089, 40975086 and 41030962), the Special Fund of Industrial (Meteorology) Research for Public Welfare of China (No. GYHY200906012), and the Natural Science Foundation of the Jiangsu Higher Education Institutions of China (No. 10KJB170009). We thank Chen H. and Goloub P. for their effort in establishing and maintaining Beijing site of AERONET related to this investigation.

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