Aerosol and Air Quality Research, 14: 905–915, 2014

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2013.04.0125

Study of Aerosol Optical Properties Based on Ground Measurements over Sichuan Basin, China

Ran Tao[1,2], Huizheng Che[2*], Quanliang Chen[1], Jun Tao[3], Yaqiang Wang[2], Junying Sun[2], Hong Wang[2], Xiaoye Zhang[2]

[1] *Plateau Atmospheric and Environment Key Laboratory of Sichuan Province, College of Atmospheric Sciences, Chengdu University of Information Technology, Chengdu 610225, China*
[2] *Key Laboratory for Atmospheric Chemistry (LAC), Institute of Atmospheric Composition, Chinese Academy of Meteorological Sciences (CAMS), CMA, Beijing 100081, China*
[3] *South China Institute of Environmental Sciences, MEP, Guangzhou 510655, China*

ABSTRACT

The characteristics of aerosol optical depth (AOD) and Ångström exponent as well as the relationship between the AOD and particulate matter (PM_{10}), were measured and analyzed at the Chengdu station over the Sichuan Basin in China from February 2007 to December 2009. High monthly AODs were observed in March, August and December, while a low value was observed in October. Monthly variations in Ångström exponent were opposite to the AODs in March and August. The averaged PM_{10} showed a significantly seasonal variation with a peak in winter. There is a complicated (not linear) positive correlation between total AOD and PM_{10} near the surface. Three typical cases under the conditions of dust and haze were studied, and the results showed that the AODs on the dust days were largest while minimum AODs occurred on haze days. On the contrast, the Ångström exponent distributions among three weather conditions were opposite to the AODs. The 3-day back-trajectory analysis indicated that the origin of the air masses largely affected the aerosol optical properties over the Sichuan Basin.

Keywords: AOD; Ångström exponent; Sichuan Basin; PM_{10}; Back-trajectory analysis.

INTRODUCTION

Atmospheric aerosols affect the earth's climate (Charlson *et al.*, 1992) in two ways: direct radiative forcing by scattering and absorbing solar radiation and indirect effects on the lifetime of clouds and precipitations. Aerosols can also serve as cloud condensation nuclei (CCN) or ice nuclei (IN) (Hansen *et al.*, 1997; Hansen *et al.*, 2000). Aerosol optical properties research is indispensable in the aerosol radiative effect study (Aoki and Fujiyoshi, 2003).

There are many significant researches concerning the optical properties of aerosols in global (Remer *et al.*, 2008) and regional scales (Eck *et al.*, 2005). Because of heavy aerosol loading from natural and anthropogenic activities in China, there are numerous studies concerning the optical properties of several regions, including the northeast, the northwest, the Yangtze River Region and the South of China (Wang *et al.*, 2001; Li *et al.*, 2003a; Xia *et al.*, 2005; Cheng *et al.*, 2008; Che *et al.*, 2009a; Wang *et al.*, 2010; Che *et al.*, 2011; He *et al.*, 2012a; Wu *et al.*, 2012; Che *et al.*, 2013).

Sichuan Basin is located in the southwest of China, which is influenced by the East Asian and Indian monsoon. Luo *et al.* (2000) have retrieved and analysed the spatial distribution and decadal changes of the AOD over China from 1961 to 1990 and found that there were two maximum centres of Sichuan Basin and South Xin Jiang Basin near 100°E latitude. Li *et al.* investigated the characteristics of AOD distributions and variations over Sichuan Basin from MODIS data and found that the highest AOD occurred in the spring because of the dust events (Li *et al.*, 2003b). However, there are few studies about the column aerosol optical properties from ground-based measurements over the Sichuan Basin. The primary aim of this paper is to investigate the column aerosol optical properties (i.e., AOD and Ånsgström exponent) by measurements of CE-318 sunphotometer over Chengdu, where the characteristics of aerosols have some degree of representativeness for the urban area of the Sichuan Basin (Li *et al.*, 2003b; Zhang *et al.*, 2008; Lin *et al.*, 2012). Results of this paper will benefit the validation of satellite retrievals and improvement of aerosol modelling over the Sichuan Basin in the future.

* Corresponding author.
Tel.: +86-10-5899-3116; Fax: 86-10-6217-6414
E-mail address: chehz@ cams.cma.gov.cn

METHODS AND DATA

Site Description

A Cimel CE-318 sun-photometer was installed on the roof of a tall building next to the Chengdu Meteorological Administration (104°02′20″E, 30°39′16″N, 587.0 m) in 2007 and is still running at present. This site is situated in the middle of the Sichuan Basin and to the east of the Qinghai-Tibet Plateau. There are no tall buildings around the platform, avoiding the influence of local terrain and severe local pollution on the data collections. The aerosol optical properties at this site can be representative of the urban areas of the Sichuan Basin.

Instrument

The CE-318 sun-photometer, manufactured by the CIMEL Electronique Company, France, is a multi-channel, automatic, sun-and-sky scanning radiometer that measures not only direct solar irradiance (sun direct channel) but also the sky radiance (sky scattering channel). This type of sun-photometer has eight channels: 1020 nm, 870 nm, 670 nm, and 440 nm bands, three 870 nm polarization channels and a 940 nm channel for water vapour measurements (Holben *et al.*, 1998). Measurements through the sun direct channel at these bands are used to calculate the aerosol optical depth (AOD). Observations by sky scattering channel including almucantar (ALM) and principal plane (PPL) scenario measurements, have sky diffuse irradiance data at four bands of 440 nm, 670 nm, 870 nm, 1020 nm, which can be used for aerosol optical property retrievals such as single scattering albedo, size distribution, refractive index, asymmetry factor, phase function, etc. (Dubovik *et al.*, 2000). The sun-photometer at the Chengdu site is calibrated annually to verify the accuracy and reliability of the data. The calibration procedure has been described by Che *et al.* (2009b).

In addition, PM_{10} data were acquired from Cao Tang substation of the Chengdu Environmental Monitoring Center, which is not far from the CE-318 sun-photometer site. PM_{10} is measured by Tapered Element Oscillating Microbalance (TEOM) instruments (Thermo Fisher Scientific Inc., Franklin, MA; Model 1400a), with a precision of 1.0 $\mu g/m^3$.

Data and Methodology

The sun-photometer measurements over Chengdu from Feb 1st, 2007, to Dec 31st, 2009, were used in this study. The AOD data were calculated with the ASTPwin software (Cimel Ltd. Co.) for the Level 1.0 AOD (raw results without cloud screening), the Level 1.5 AOD (cloud-screened AOD based on the work of Smirnov *et al.*, (2000)) and the Ångström exponent between 440 and 870 nm. Daily and monthly mean values of the AOD, Ångström exponent and PM_{10} were calculated. During daily average calculation, only those data ≥ 10 times per day were selected for the statistics (Table 1). Finally, there were 3276 observations obtained during the full measurement period. Four seasons are divided into spring (March to May), summer (June to August), autumn (September to November) and winter (December to February) to investigate the seasonal variations of aerosol optical properties in this study. Linear correlation is used to investigate the relationship between the AOD and the PM_{10}.

RESULTS ANALYSIS

Monthly and Seasonal Variations of AOD

Figs. 1(a) and 1(b) show the monthly and seasonal variations of the AOD with standard deviations at Chengdu station, respectively. The peak values of AOD appeared in March, August and December. The maximum AOD values at 1020 nm, 870 nm, 670 nm and 440 nm in March were 0.55 ± 0.13, 0.64 ± 0.16, 0.85 ± 0.22, 1.29 ± 0.38, respectively (Fig. 1(a)). The AOD values in August at these four wavelengths were 0.42 ± 0.15, 0.53 ± 0.20, 0.76 ± 0.29 and 1.19 ± 0.38, respectively. The AOD values in December were 0.44 ± 0.11, 0.54 ± 0.14, 0.75 ± 0.22 and 1.16 ± 0.36, respectively, which were lower than the values for March and August. On the other hand, the minimum value of AOD appeared in October. The values at the 4 wavelengths above were 0.19 ± 0.06, 0.24 ± 0.08, 0.32 ± 0.12 and 0.50 ± 0.19, respectively. Overall, the values of the monthly averaged AOD at each wavelength in Chengdu were generally quite large, which is consistent with conclusions from previous studies (Luo *et al.*, 2000; Yang *et al.*, 2008). There are two potential reasons for the high AOD values over the Basin. One is the topography of the Sichuan Basin (Zhang *et al.*, 2009).The surface wind speed is low all-year around the Basin. There are high relative humidity and frequent occurrence of calm wind, which lead to a long residence time for aerosol particles and are not conductive to aerosol diffusion. The other reason is due to the large population of Sichuan Province, which is more than 80 million from 2010 according to the sixth national census. Increasing human activities could be one of major factors for the large AOD over the Sichuan Basin.

The mean AOD in autumn is clearly lower than those in other seasons (Wang *et al.*, 2011) with values of 0.27 ± 0.06, 0.32 ± 0.07, 0.43 ± 0.09 and 0.68 ± 0.15 at 1020 nm, 870 nm, 670 nm and 440 nm, respectively (Fig. 1(b)). Large AOD values appeared in the winter and spring and ranged from 0.45 to 0.47, from 0.53 to 0.55, from 0.72 to 0.74 and from 1.07 to 1.13 for each wavelength, respectively. In spring, the Sichuan Basin region could be affected by dust storms from North China (Gong *et al.*, 2003), which could contribute high AOD over the Basin. While in winter, the cold air has weak effect on the Sichuan Basin, aerosol particles from local pollution sources could not diffuse well. Additionally, there is substantial water vapour suspended in the air due to the fog in the winter morning. These factors

Table 1. Statistics of the effective measurements at Chengdu site (2007.1.1–2009.12.31).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Observation days	5	11	13	15	19	17	15	14	14	6	18	11
Measurements	117	327	355	343	530	390	283	242	358	127	485	169

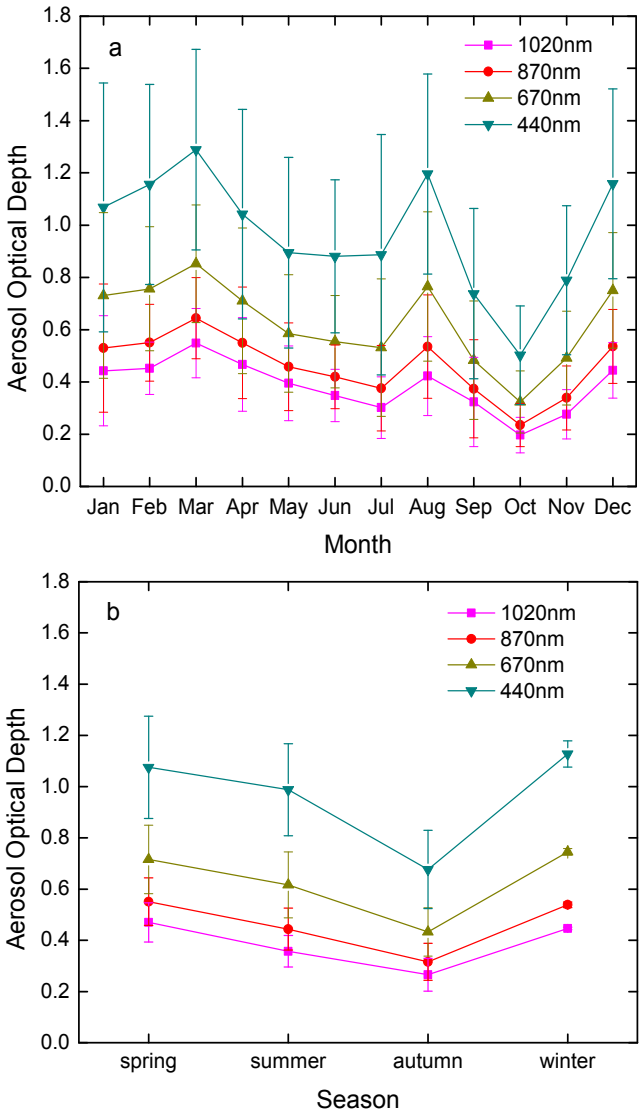

Fig. 1. Monthly (a) and seasonal (b) averaged values and standard deviations of AOD.

contributed to the high AOD in the winter. The high AODs in the summer may be caused by the effect of subtropical anticyclone, which affects most parts of China. The average surface wind speed all over the whole basin is relatively low under the control of the subtropical anticyclone in summer, which is not conducive to the local aerosol transports to other regions. In addition, the relative humidity during summer (Table 2) are large, which could benefit the hygroscopic growth of particles. High temperature also can cause the increase of the secondary organic aerosol particles (Kroll *et al.*, 2008). All of these factors above may be related to a high AOD in summer. In autumn, the change of atmospheric circulation led to autumn precipitation in west China. (Li *et al.* 2012). Precipitation is beneficial to the diffusion and removal of pollutants in the atmosphere.

Variations in the Monthly and Seasonal Ångström Exponent

Figs. 2(a) and 2(b) show the variation of monthly and seasonal averaged Ångström exponents and the standard deviations at the Sichuan Basin. All of the monthly and seasonal averaged values of the Ångström exponent were more than 0.90, suggesting that the aerosol particle size is small and that the proportion of fine particles is larger than that of coarse particles. The minimum value of the Ångström exponent occurred in April (0.94 ± 0.31), and the maximum value is 1.24 ± 0.16 in November. The fluctuation in the Ångström exponent is not obvious and demonstrated that there is little variation in the aerosol effective radius over the Sichuan Basin.

Low Ångström exponents over the Sichuan Basin all appeared in spring, at approximately 0.96 ± 0.03, while high Ångström exponents appeared primarily in summer (July and August) at 1.21 ± 0.13 and 1.21 ± 0.20, respectively. High values also occurred at the end of autumn (November) at 1.24 ± 0.16.

Combined with the variations in AOD, the main reason for high AOD but low Ångström exponent in spring is the long-distance transport of dust particles from the north and northwest of China (Wang *et al.*, 2011; Gong *et al.*, 2003).

Table 2. Monthly precipitation and relative humidity during 2007 and 2009.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007	(mm)	11.5	2.7	4.5	24.6	84.6	77.9	78.3	183.9	75.1	62.3	9.1	10
	RH (%)	80	72	71	68	62	72	78	83	82	87	84	82
2008	(mm)	6.3	16.8	33	47	69.7	124	235.8	147.2	267	58.8	22.6	0
	RH (%)	76	75	75	71	67	71	77	80	79	80	76	75
2009	(mm)	12	3.1	12.6	51.1	35.6	33.5	195.2	169.1	154.8	42.3	8	6.9
	RH (%)	75	70	70	71	65	69	79	77	78	79	76	75

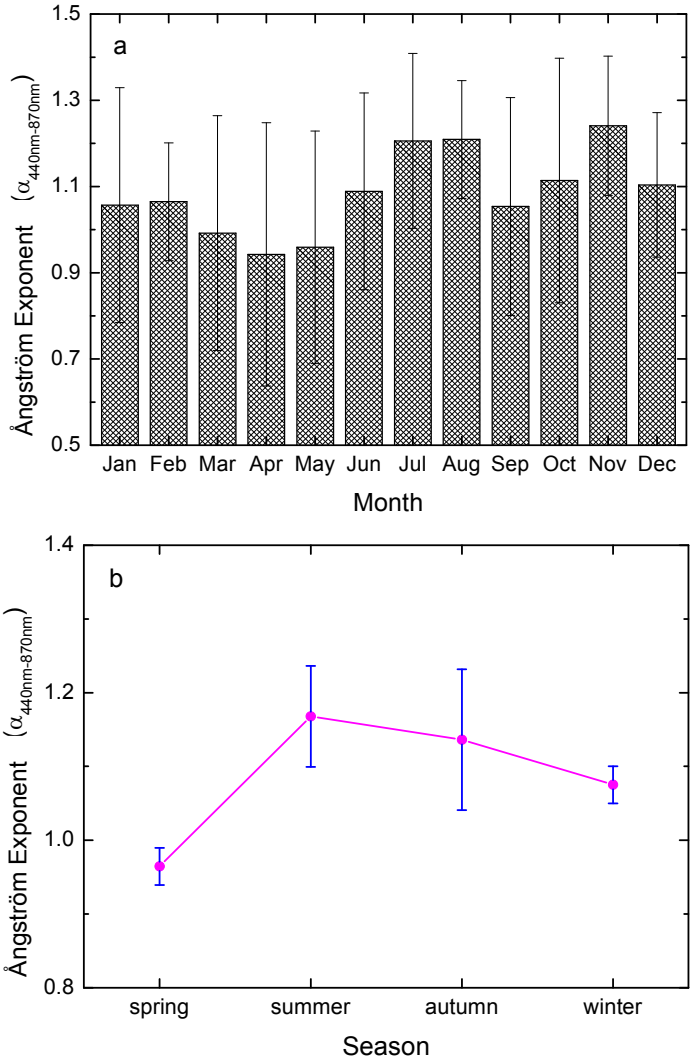

Fig. 2. Monthly (a) and seasonal (b) averaged values and standard deviations of Ångström exponent

Convective precipitation occurs frequently in summer with the majority of coarse particles eliminated by wet settlement. The fine particles remained in the atmosphere with long suspension times, which maybe caused high Ångström exponent in summer. During the period of autumn rain in West China (September to November), the relative humidity is high (Table 2), which enhances the hygroscopic growth and thus reduces the Angstrom exponent in autumn.

Relationship between the AOD and Ångström Exponent

Fig. 3 shows the scatter-plot of AOD at 440 nm and the Ångström exponent based on all 3726 measurements during the observation period. Evidently, the relationship between the AOD and Ångström exponent is not a simple linear but rather complicated. The open circles with X error bars mean the averaged AOD for ranges of the Ångström exponent (0.00–0.30, 0.30–0.60, 0.60–0.90, 0.90–1.20 and 1.20–1.50). Except for the range of 0.00–0.30, the AOD at 440 nm increased with an increasing Ångström exponent, which illustrated that fine particles were responsible for the high AOD over the Sichuan Basin.

He *et al.* (2012b) pointed out that the wind speed and

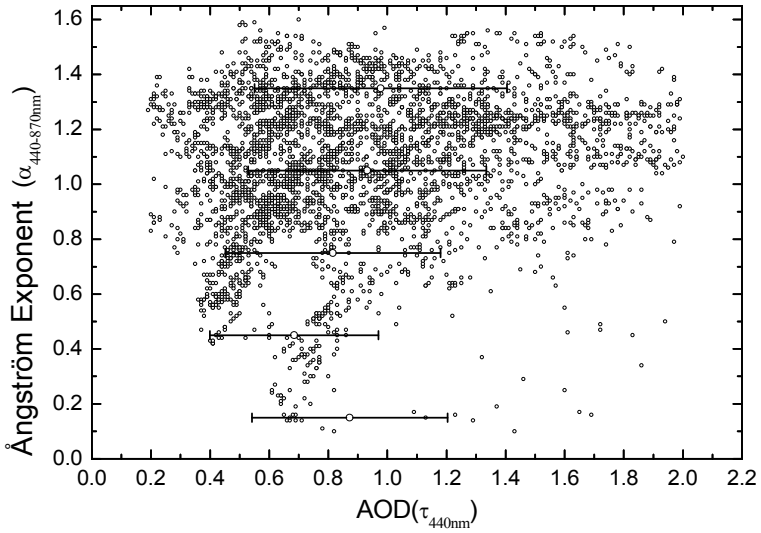

Fig. 3. Scatter-grams of the AOD vs. Ångström exponent.

direction could affect aerosol optical properties. Fig. 4 shows the AOD and Ångström exponent variation depending on surface wind speed at Chengdu. In this study, the surface wind speed is classified by 8 bins of ≤ 2.0, 2.0–2.5, 2.5–3.0, 3.0–3.5, 3.5–4.0, 4.0–4.5, 4.5–5.0 and ≥ 5.0 m/s. In general, the AOD (e.g., $\tau_{440\ nm}$) decreases with wind speed increasing especial during wind speed less than 4.0 m/s. This probably indicates the wind effect on aerosol particles diffusing. Similar to AOD, the Ångström exponent also decrease with the wind speed increasing, which suggests aerosol particle size becomes larger depending on the wind speed. This can be speculated that large particles could be emitted to the atmosphere or transported from far away by strong surface wind. However, all these speculations should be studied deeply in future.

Relationship between AOD and PM_{10}

The relationship between AOD at 440 nm and PM_{10} is studied to analyse whether chemical composition could influence the optical properties of atmospheric aerosol. The relationship between the monthly AOD at 440 nm and the monthly averaged concentration of PM_{10} is investigated using a linear fit method. As Fig. 5 show, it is evident that there is a positive correlation between the AOD at 440 nm and the PM_{10} under some circumstances. The correlation coefficient between the AOD at 440 nm and the PM_{10} is 0.43 based on 147 samples, which indicated that the AOD at the Sichuan Basin is related not only to the concentration but also to the chemical and other physical characteristics of aerosol particles (Tao *et al.*, 2011, 2013). Fig. 6 shows the monthly variation of the AOD, PM_{10} and relative humidity

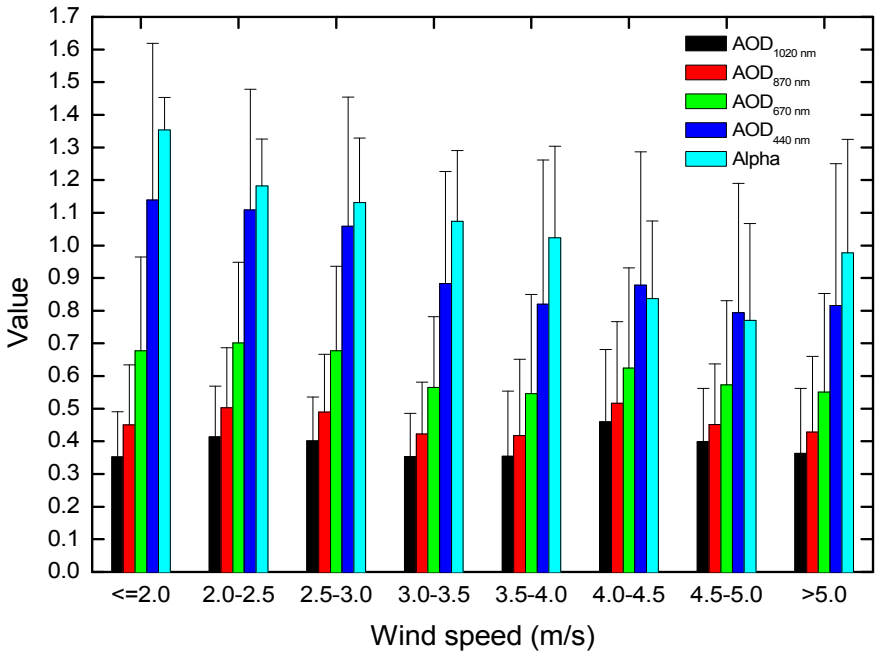

Fig. 4. AOD at 440 nm and Ångström exponent variation depending on wind speed.

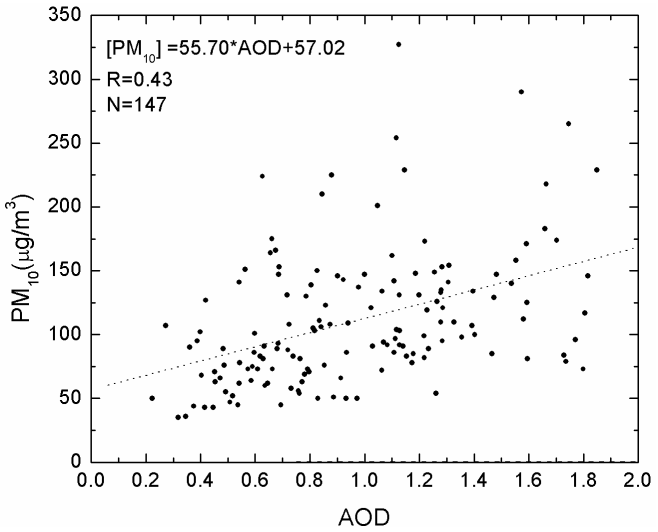

Fig. 5. Correlation between AOD at 440 nm and PM_{10}.

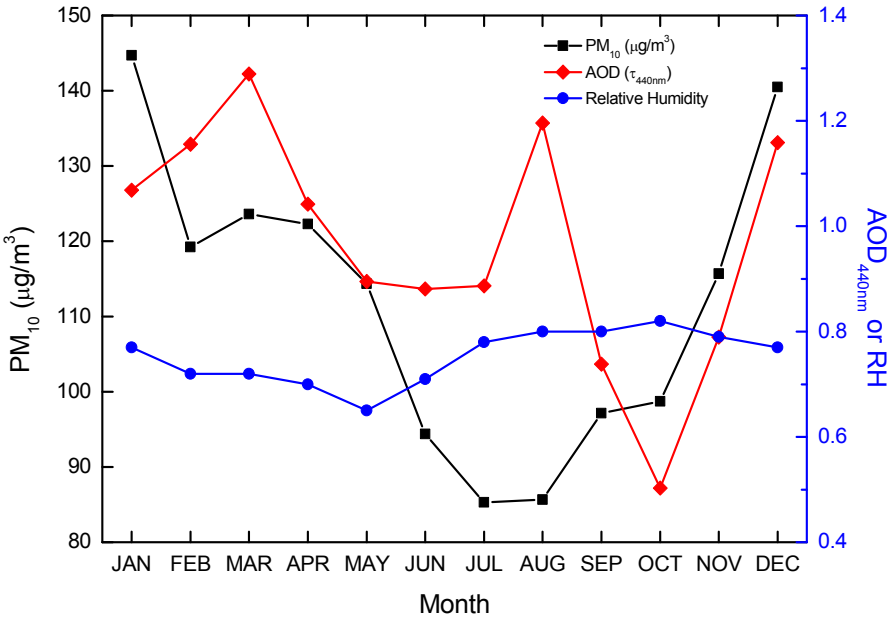

Fig. 6. Comparison of monthly variations between AOD at 440 nm and the concentration of PM_{10} with the variation of relative humidity.

(Li *et al.*, 2005). Values from February to May and from October to December showed the same trend as the concentration of PM_{10}. This type of positive correlation suggested that PM_{10} most likely contributed to the AOD. However, a negative correlation also existed for the rest of the year. This phenomenon could probably reflect the hygroscopic growth of aerosol particles, especially in summer and early autumn (June–September), when the precipitation and relative humidity is high during this period. AOD reflect the aerosol column extinction characteristic while the PM_{10} reflects the "dry" aerosol particles' concentration because there is a heating system to eliminate the moisture when the measurement is carried out. This could be one of the reasons which cause the different variation of AOD and PM_{10} in summer and early autumn.

The aerosol chemical compositions have effect on the optical properties. This effect is complicated and not characterised by a simple linear relationship. The AOD data represented the integration of the extinction coefficient of the whole atmospheric column while the PM_{10} data just reflected the aerosol concentration of the near surface layer. Thus, more studies concerning the vertical distribution of aerosol particles are needed in future work.

Comparison of Aerosol Optical Properties under Dust and Haze Conditions

Three typical cases of "dust", "haze", and "mixture of dust and haze" were selected according to variations in the aerosol optical properties and the PM_{10} as well as the ground meteorological data. In this study, the "dust" case

means the aerosol particles of the Sichuan Basin were mainly affected by dust events from deserts of Northwest China. The "haze" means the horizontal visibility is less than 10 km and the relative humidity is less than 90% at the same time. It is caused by severe pollution dominated by local emission. The case of "mixture of dust and haze" is representative for a day affected both by dust event and local pollution. The daily average concentrations of PM_{10} of the three case days are 668 μg/m^3 (April 25, 2009), 140 μg/m^3 (March 22, 2009) and 103 μg/m^3 (November, 22, 2009), respectively. One can see that the AOD under dusty conditions (Fig. 7(a)) was obviously higher than that under hazy conditions (Fig. 7(c)). Under the dusty condition, the daily averaged AODs were 1.70 ± 0.04, 1.75 ± 0.04, 1.81 ± 0.04 and 1.90 ± 0.04 at 1020 nm, 870 nm, 670 nm and 440 nm, respectively. However, the AODs were only 0.24 ± 0.06, 0.31 ± 0.09, 0.50 ± 0.13 and 0.82 ± 0.19, respectively, on the hazy day. The AODs on the day with the mixture of dust and haze (Fig. 7(b)) were intermediate between the other two conditions, at approximately 0.75 ± 0.07, 0.88 ± 0.08, 1.12 ± 0.11 and 1.54 ± 0.13, respectively. The Ångström exponent is about 0.12 ± 0.02, 0.83 ± 0.05 and 1.43 ± 0.10 on the dusty day, the day with a mixture of dust and haze and the hazy day, respectively. These distributions suggested that coarse particles dominated the size distribution on the dusty day, while the fraction of small particles is large on the hazy day. On the day with a mixture of dust and haze, the Ångström exponent is intermediate between the other two weather conditions, indicating the effect of both coarse and fine particles.

The 3-day back-trajectory analyses on elevations of 100 m, 500 m and 1000 m AGL (Above Ground Level) were used to study the aerosol sources under different weather conditions using the HYSPLIT mode of the NOAA (Draxler

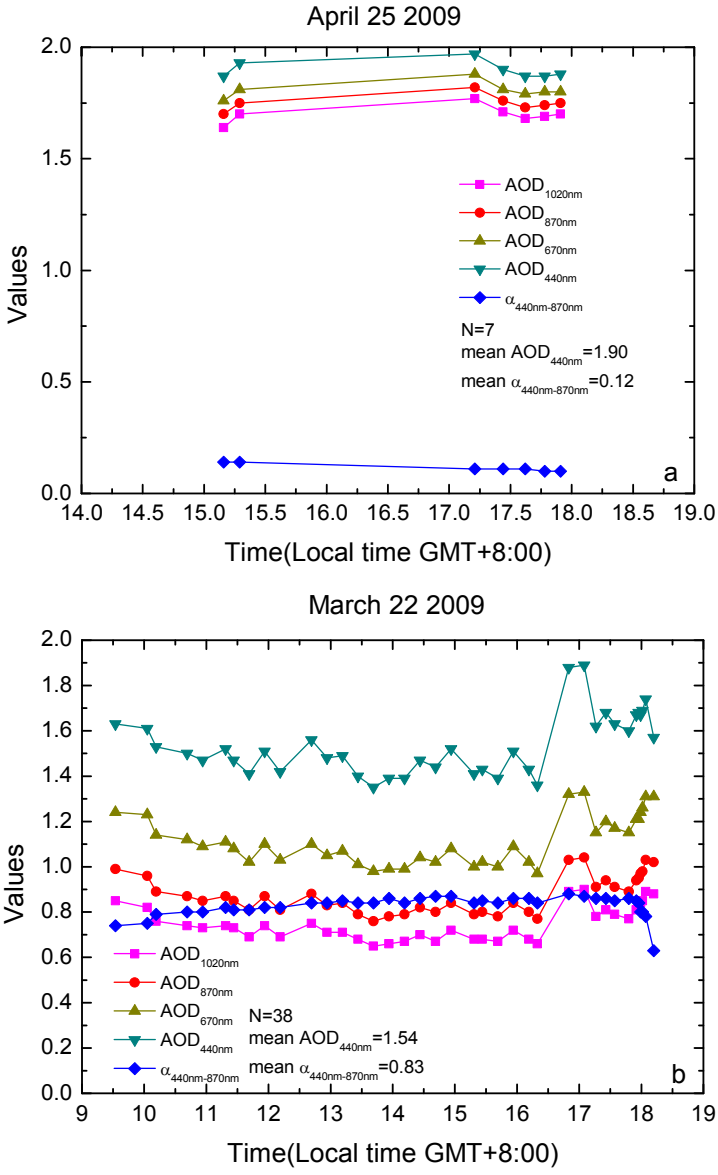

Fig. 7. Daily variation of AOD and Ångström exponent ($\alpha_{440nm\text{-}870nm}$) on the dust day (a), haze + dust day (b) and haze day(c).

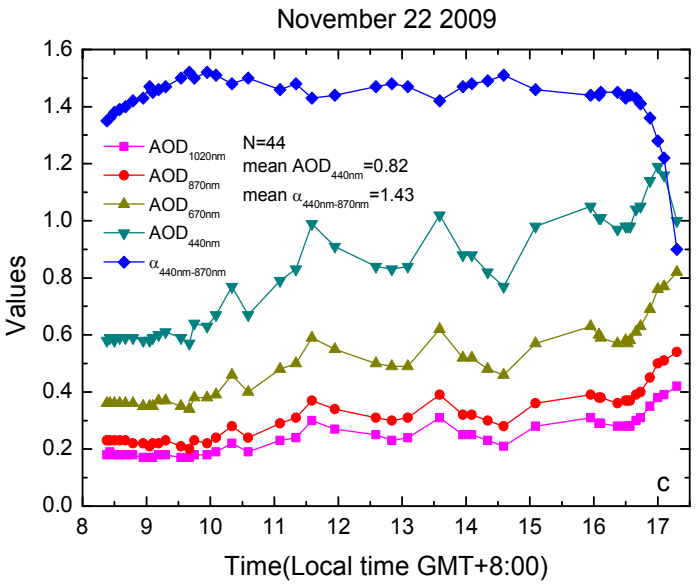

Fig. 7. *(continued).*

and Rolph, 2003). There were different transport paths for days with dust, haze and a mixture of dust and haze. Fig. 8(a) illustrates the paths of air mass motion for the dusty day. Both the air masses of 500m and 1000 m above ground level on April 25th, 2009 passed through the Gobi and deserts of North China, which are considered to be the major sources of Asian dust in spring (Gong *et al.*, 2003; Zhang *et al.*, 2003).

Fig. 8(b) shows the air masses on the day with a mixture of dust and haze. Air masses at the 1000 m level were from the Qinghai-Tibet Plateau, where has few human activity. Air masses at the level of 500 m originated from Xinjiang China and went through the Badain Jaran and Tengger Deserts in North China, which could carry substantial quantities of dust particles over Sichuan Basin. Although air mass path at the level of 100 m is similar to that at the level of 500 m, however the air mass just moved along the height of 100 m above ground level which could be affected by the anthropogenic aerosol emission easily. Thus the mean AOD at 440 nm is about 1.54 and the Ångström exponent is about 0.83 due to the mixture of dust and anthropogenic particles.

The back-trajectory analyses on the hazy day are shown in Fig. 8(c). All air masses at the levels of 100 m, 500 m and 1000 m came from East Europe and passed through western Siberia,the Junggar Basin and Qinghai-Tibet Plateau of China where are all regarded as clean regions. Despite the air masses from clean regions, the daily averaged AOD at 440 nm is still as high as approximately 0.82 with the average Ångström exponent about 1.42. This is mainly due to the effect of fine particles emitted from local anthropogenic activities of the Sichuan Basin.

SUMMARY AND DISCUSSION

AOD over the Sichuan Basin was generally high based on nearly 3 years of continuous measurements. AOD variation shows obvious seasonal characteristics. High AOD values appeared in winter and spring while the low AOD values appeared in summer and autumn. Low Ångström exponents appeared in spring while high Ångström exponents appeared primarily in summer. Dust events from North China could contribute to the high AOD and low Ångström exponents in spring over the Basin. Anthropogenic activities have large effect on the aerosol optical properties in other seasons.

The relationship between the AOD and Ångström exponent over Sichuan Basin is not simplely linear but rather complicated. The AOD increased with an increasing Ångström exponent, which illustrated that fine particles were responsible for the high AOD over this region.

There is a positive correlation between the AOD and the PM_{10}. However, the correlation coefficient did not reach the 95% significance level, which indicated that the AOD at the Basin is related not only to the concentration but also to the chemical and other physical characteristics of aerosol particles. The mechanisms connecting the chemical composition and optical properties of aerosols require further investigation.

Through the analysis of the HYSPLIT 3-day back trajectory, aerosol optical properties over the Sichuan Basin can be affected obviously by different air masses. Frequent dust event in spring and local anthropogenic activities throughout whole year around are the major aerosol sources over the Sichuan Basin.

ACKNOWLEDGEMENT

This work is financially supported by grants from the Project (41005086, 41005021 and 41130104) supported by NSFC, the Special Scientific Research Funds for Environment Protection Common wealth Section (201009001), the National Key Project of Basic Research (2014CB441201 & 2011CB403401), CAMS Basis Research Project (2012Y02), the research talent fund of Chengdu university of information technology (J201112).

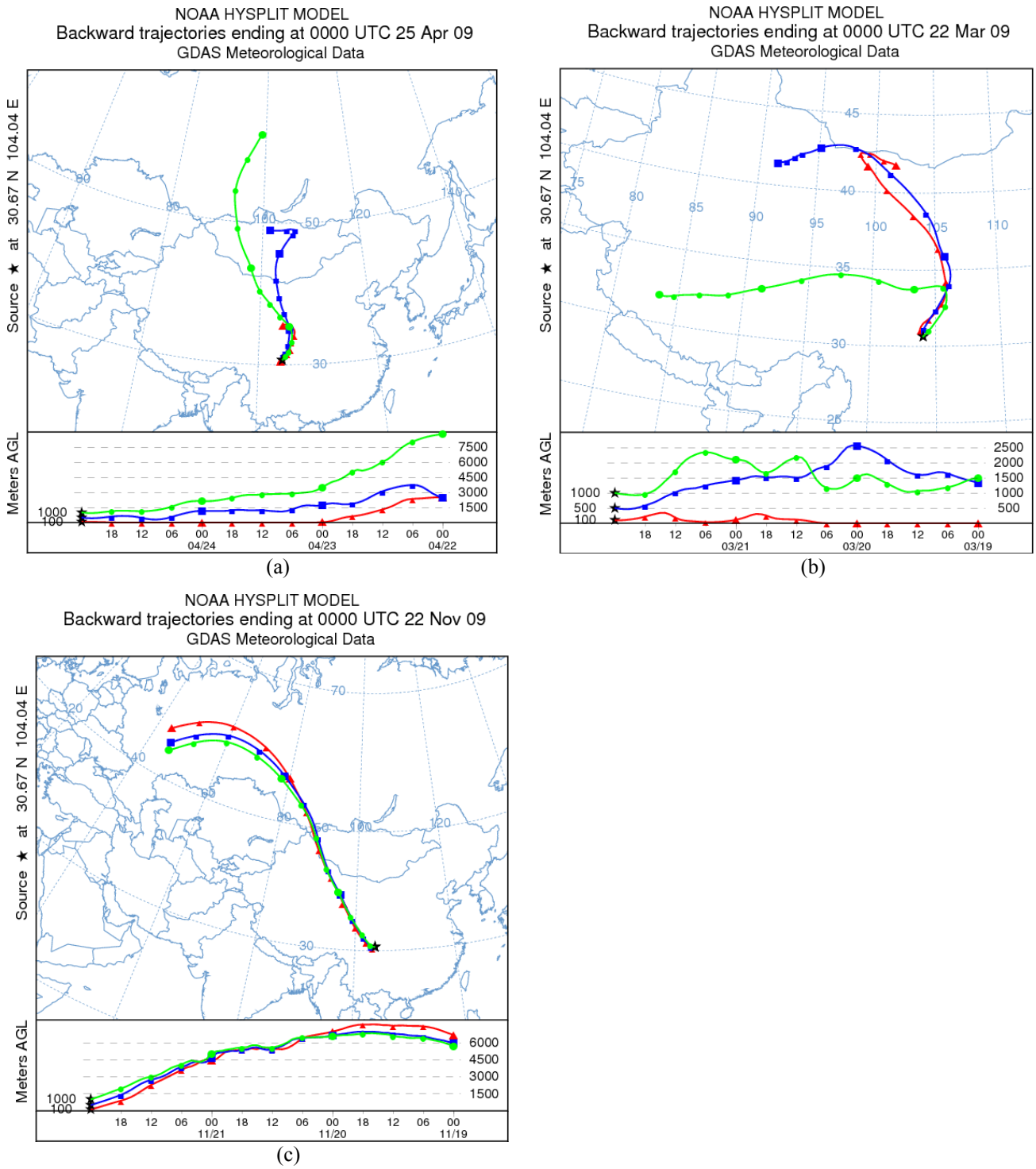

Fig. 8. HYSPLIT back-trajectories on the dust day (a), haze + dust day (b) and haze day (c).

REFERENCES

Aoki, K. and Fujiyoshi, Y. (2003). Sky Radiometer Measurements of Aerosol Optical Properties over Sapporo, Japan. *J. Meteorol. Soc. Japan* 81: 493–513.

Charlson, R.J., Schwartz, S.E., Hales, J.M., Cess, D., Coakley, J.A. andHansen, J.E. (1992). Climate Forcing by Anthropogenic Aerosols. *Science* 255: 423–430.

Che, H.Z., Yang, Z.F., Zhang, X.Y., Zhu, C.Z., Ma, Q.L., Zhou, H.G. and Wang, P. (2009a). Study on the Aerosol Optical Properties and Their Relationship with Aerosol Chemical Compositions over Three Regional Background Stations in China. *Atmos. Environ.* 43: 1093–1099.

Che, H., Zhang, X., Chen, H., Damiri, B., Goloub, P., Li, Z., Zhang, X., Wei, Y., Zhou, H., Dong, F., Li, D. and Zhou T. (2009b). Instrument Calibration and Aerosol

Optical Depth Validation of the China Aerosol Remote Sensing Network. *J. Geophys. Res.* 114: D03206, doi: 10.1029/2008JD011030.

Che, H.Z., Wang, Y.Q. and Sun, J.Y. (2011). Aerosol Optical Properties at Mt.Waliguan Observatory, China. *Atmos. Environ*. 45: 6004–6009.

Che, H.Z., Wang, Y.Q., Sun, J.Y., Zhang, X.C., Zhang, X.Y. and Guo, J.P. (2013). Variation of Aerosol Optical Properties over the Taklimakan Desert in China. *Aerosol Air Qual. Res.* 13: 777–785, doi: 10.4209/aaqr.2012.07.0200.

Cheng, T.T., Zhang, R.J., Han, Z.W. and Fang, W. (2008). Relationship between Ground-based Particle Component and Column Aerosol Optical Property in Dusty Days over Beijing. *Geophys. Res. Lett.* 35: L20808, doi: 10.1029/2008GL035284.

Draxler, R.R. and Rolph, G.D. (2003). Hybrid Single-Particle Lagrangian Integrated Trajectory Model Access via NOAA ARL READY. NOAA AIR Resources Laboratory, Silver Spring, MD, Website, Http://www.arl.noaa.gov/ready/open/hysplit4.html.

Dubovik, O. and King, M.D. (2000). A Flexible Inversion Algorithm for the Retrieval of Aerosol Optical Properties from Sun and Sky Radiance Measurements. *J. Geophys. Res*. 105: 20673–20696.

Eck, T.F., Holben, B.N., Dubovik, O., Smirnov, A., Goloub, P., Chen, H.B., Chatenet, B., Gomes, L., Zhang, X.Y., Tsay, S.C., Ji, Q., Giles, D. and Slutsker, I. (2005). Columnar Aerosol Optical Properties at AERONET Sites in Central Eastern Asia and Aerosol Transport to the Tropical Mid-Pacific. *J. Geophys. Res.* 110, doi: 10.1029/2004JD005274.

Gong, S.L., Zhang X.Y., Zhao, T.L., Mckendry, I.G., Jaffe, D.A. and Lu, N.M. (2003). Characterization of Soil/Distribution during 2001 ACE-Asia, 2. Model Simulation and Validation. *J. Geophys. Res*. 108: 42–62, doi: 10.1029/2002JD00263.

Hansen, J., Sato, M. and Ruedy, R. (1997). Radiative Forcing and Climate Response. *J. Geophys. Res*. 102: 6831–6864.

Hansen, J., Sato, M., Ruedy, R., Lacis, A. and Oinas, V. (2000). Global Warming in the Twenty-first Century: An Alternative Scenario. *Proc. Nat. Acad. Sci. U.S.A.* 97: 9875–9880.

He, Q., Li, C., Geng, F., Yang, H., Li, P., Li, T., Liu, D., Pei, Z. (2012a). Aerosol Optical Properties Retrieved from Sun Photometer Measurements over Shanghai, China. *J. Geophys. Res.* 117: D16204, doi: 10.1029/2011JD017220.

He, Q., Li, C., Geng, F., Lei, Y. and Li, Y. (2012b). Study on Long-term Aerosol Distribution over the Land of East China Using MODIS Data. *Aerosol Air Qual. Res.* 12: 304–319, doi: 10.4209/aaqr.2011.11.0200.

Holben, B.N., Eck, T.F., Slutsker, I., Tanre, D., Buis, J.P., Setzer, A., Vermote, E., Reagan, J.A., Kaufman, Y. ., Nakajima, T., Lavenu, F., Jankowiak, I. and Smirnov, A. (1998). AERONET - A Federated Instrument Network and Data Archive for Aerosol Characterization. *Remote Sens. Environ.* 66: 1–16.

Kroll, J.H. and Seinfeld, J.H. (2008). Chemistry of Secondary Organic Aerosol: Formation and Evolution of Low-volatility Organics in the Atmosphere: *Atmos. Environ.* 42: 3593–3624.

Li, C.C., Mao, J.T., Lau, A.K.H., Liu, X.Y., Liu, G.Q. and Zhu, A.H. (2003a). Research on the Air Pollution in Beijing and Its Surroundings with MODIS AOD Products. *Chin. J. Atmos. Sci.* 27: 869–880.

Li, C.C., Mao, J.T. and Lau, K.H. (2003b). Characteristics of the Aerosol Optical Depth Distributions over Sichuan Basin Derived from MODIS Data. *J. Appl. Meteorol.* 14: 1–7 (in Chinese).

Li, C.C., Mao, J.T., Lau, Alexis K.H., Yuan, Z., Wang, M. and Liu X. (2005). Application of MODIS Satellite Products on the Air Pollution Research in Beijing. *Sci. China, Ser. D Earth Sci.* 48: 209–219.

Li, Y., Li, W.J., Ai, W.X. and Chen, Y. (2012). Analysis of Autumn Rainfall Characteristics and Its Causes in West China in 2011. *Adv. Meteorol. Sci. Technol.* 2: 27–33(in Chinese).

Lin, M., Tao, J., Chan, C., Cao, J., Zhang, Z., Zhu, L. and Zhang, R. (2012). Characterization of Regression Relationship between Recent Air Quality and Visibility Changes in Megacities at Four Haze Regions of China. *Aerosol Air Qual. Res.* 12: 1049–1061, doi: 10.4209/aaqr.2011.11.0220.

Luo, Y.F., Li, W.L., Zhou, X.J., He, Q. and Qing, J.Z. (2000). Analysis of the Atmospheric Aerosol Optical Depth over China in 1980s. *Acta Meteorol. Sinica* 14: 490–502

Remer, L.A., Kleidman, R.G., Levy, R.C., Kaufman, Y.J., Tanré, D., Mattoo, S., Martins, J.V., Ichoku, C., Koren, I., Yu, H.B. and Holben, B.N., (2008). Global Aerosol Climatology from the MODIS Satellite Sensors. *J. Geophys. Res*. 113: D14S07, doi: 10.1029/2007JD009661.

Smirnov, A., Holben, B.N., Eck, T.F., Dubovik, O. and Slutsker, I. (2000). Cloud Screening and Quality Control Algorithms for the AERONET Database. *Remote Sens. Environ.*73: 337– 349.

Tao, J., Chai, F.H., Zhu, L.H., Gao, J., Cao, J.J., Wang, Q.Y. and Luo, L. (2011). Charateristics and Sources of Carbonaceous Aerosol in the Urban Chengdu during Spring of 2009. *Acta Sci. Circumst* 31: 2756–2761(in Chinese).

Tao, J., Zhang, L.M., Engling, G., Zhang, R.J., Yang, Y.H., Cao, J.J., Zhu, C.S., Wang, Q.Y. and Luo, L. (2013). Chemical Composition of $PM_{2.5}$ in an Urban Environment in Chengdu, China: Importance of Springtime Dust Storms and Biomass Burning. *Atmos. Res*. 122: 270–283.

Wang, M.X., Zhang, R.J. and Pu, Y.F. (2001). Recent Researches on Aerosol in China. *Adv. Atmos. Sci.* 18: 576–586.

Wang, P., Che, H.Z., Zhang, X.C., Song, Q.L., Wang, Y.Q., Zhang, Z.H., Dai, X. and Yu, D.J. (2010). Aerosol Optical Properties of Regional Background Atmosphere in Northeast China. *Atmos. Environ.* 44: 4404–4412.

Wang, Y. Xin, J., Li, Z., Wang, S.; Wang, P., Hao, W.M., Nordgren, B.L., Chen, H., Wang, L .and Sun, Y. (2011). Seasonal Variations in Aerosol Optical Properties over China. *J. Geophys. Res.* 116: D18209, doi: 10.1029/2010JD015376.

Wu, Y, Zhang, Renjian, Pu, Yifen, Zhang, Leiming, Ho, K.F.

and Fu, C.B. (2012). Aerosol Optical Properties Observed at a Semi-arid Rural Site in Northeastern China. *Aerosol Air Qual. Res.* 12: 503–514, doi: 10.4209/aaqr.2011.11.0202.

Xia, X.A., Chen, H.B., Wang, P.C., Zong, X.M. and Gouloub, P. (2005). Aerosol Properties and Their Spatial and Temporal Variations over North China in Spring 2001. *Tellus Ser. B* 57: 28–39.

Yang, K., Sun, Z.B. and Ni, D.H. (2008). Characteristics of Atmospheric Aerosol Optical Depth over China during 1999-2003. *J. Nanjing Inst. Meteorol.* 31: 92–96 (in Chinese).

Zhang, R.J., Xu, Y.F. and Han, Z.W. (2003). Inorganic Chemical Composition and Source Signature of $PM_{2.5}$ in Beijing during ACE-Asia Period. *Chin. Sci. Bull.* 48: 1002–1005.

Zhang, W.C., Tian, Y.L., He, C.R., Shi, J.G., Xie, G.Q., Chen, X.M. and Duan, W. (2009). The Comparison of MODIS Data and Sun- Photometer Observations of Aerosol Optical Depth over Southwest China. *J. Yunnan Univ. (Nat. Sci. Ed)* 31: 421–425 (in Chinese).

Zhang, X.Y., Wang, Y.Q., Zhang, X.C., Guo, W., Niu, T., Gong, S.L., Yin, Y.Y., Zhao, P. Jin, J.L. and Yu, M. (2008) Aerosol Monitoring at Multiple Locations in China: Contributions of EC and Dust to Aerosol Light Absorption. *Tellus Ser. B* 60: 647–656.

Received for review, April 15, 2013
Accepted, July 27, 2013