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Variation of Aerosol Optical Properties over the Taklimakan Desert in China

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ABSTRACT

The aerosol optical properties at the center of the Taklimakan Desert in Northwest China are investigated based on the measurements of aerosol optical depth (AOD) and Angstrom exponent from 2004 to 2008. A seasonal variation is found with high AOD and low Angstrom exponent values in spring and summer, due to the effect of dust storm events, and low AOD in autumn and winter. The maximum and minimum AOD occur in April (0.83 ± 0.41) and November (0.19 ± 0.10), respectively, with the maximum and minimum Angstrom exponent in January (0.70 ± 0.25) and May (0.09 ± 0.06), respectively. The diurnal variation of AOD (Angstrom exponent) shows the characteristic of high (low) values about 0.50–0.60 in the morning and evening, and is constant around 0.40 during daytime. The relationship between AOD and the Angstrom exponent can be fitted by a power equation with a R^2 of 0.55. The frequency distributions of AOD and the Angstrom exponent occurrence probability have a single peak distribution, and can be well fitted by a two-mode distribution.

Keywords: Aerosol optical depth (AOD); Angstrom exponent; Taklimakan desert; China.

INTRODUCTION

Aerosol particles can influence the radiative energy and the conversion of water vapor into cloud droplets through direct and indirect effects (Hansen *et al.*, 2000). Many studies addressed that aerosol optical property is one of the largest sources of uncertainty in the current estimating climate forcing (Ramanathan *et al.*, 2001).

Dust aerosols from arid and semi-arid regions can be transported thousands of kilometers far from their original resource regions (Wang *et al.*, 2001; Gong *et al.*, 2003; Zhang *et al.*, 2003a). It was estimated that the dust emission is of the order of 1500 Tg/yr globally (Tegen and Fung, 1995). The emission from East Asia is about 800 Tg/yr with half of them deposited back to the source and adjacent regions (Zhang *et al.*, 1997). The dust aerosol particles have great effect on global and regional climate change (Li *et al.*, 1996; Mikami *et al.* 2006).

Despite many dust aerosol studies, the optical properties are still far from being sufficient (Sokolik and Toon, 1999). In recent years, there were many studies on the optical properties of dust aerosols in Sahara desert (Zakey *et al.*, 2004), West Asia (Nakajima *et al.*, 1996; Smirnov *et al.*, 2002), India (Dey *et al.*, 2004), Australia (Kalashnikova *et al.*, 2007), and East Asia (Kim *et al.*, 2004, Eck *et al.*, 2005). As far as East Asia was concerned, arid and semi-arid regions in Western and Northern China is one of the major source regions of dust aerosols (Zhang *et al.*, 2003b, Zhang *et al.*, 2012). Some scientists have begun to investigate the optical properties (e.g., Alfaro *et al.*, 2003; Xia *et al.*, 2005; Cheng *et al.*, 2006, Gai *et al.*, 2006; Che *et al.*, 2009; Wu *et al.*, 2012) and radiative forcing (Huang *et al.*, 2009; Xia and Zong, 2009) of dust aerosols in this area. These studies are very important to understand the essential properties and variations of the dust aerosols in East Asia.

The aim of this work is to study the dust climatological aerosol optical properties in the center of Taklimakan Desert of Western China during 2004 to 2008, which will benefit the estimation of the effect of East Asian dust aerosols on global and regional climate change in future.

MEASUREMENT AND DATA

The research site of Tazhong (39°00', 83°40', 1099.3 m) were located in the center of the Taklimakan Desert, which is known as one of the largest sandy deserts in the world. Taklimakan Desert covers an area of 270000 km^2 with 1000 km long and 400 km wide which is regarded as one of the largest resources of Asian aeolian dust aerosol particles (Mikami *et al.*, 2006; Huang *et al.*, 2009). Tazhong site is

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the only meteorological observatory in the world located in 229 km deep of desert hinterland (Lu *et al.*, 2010). There are few anthropogenic activities surrounding the observation site. Annual precipitation at Tazhong is just 25.9 mm. Dust events happen more than 500 times annually (Li *et al.*, 2006). The aerosol measurements at Tazhong site could represent the characteristic of Taklimakan Desert.

A Cimel 318 sunphotometer was installed at Tazhong from 2004 and has been running at this site continuously. The sunphotometer makes direct spectral solar radiation measurements within a 1.2° full field-of-view around 15 minutes at 4 normal bands (440, 675, 870, and 1020 nm), 3 polarization bands at 870nm and 1 water vapor band at 940 nm. Measurements at 440, 675, 870, and 1020 nm are used to calculate the aerosol optical depth (AOD) (Holben *et al.*, 1998; Eck *et al.* 2005). The signals are measured by the instrument three times at one scenario. The error of these three measurements is about 1%–2% at different channels, which cause the error of retrieved AOD is about 0.01–0.02. Thus the total uncertainty is about 0.01 to 0.02 (Eck *et al.* 1999).

The sunphotometer is calibrated by using CARSNET (CMA Aerosol Remote Sensing NETwork) reference instrument annually to make sure the accuracy and reliability of the measurement data. The reference instrument has been calibrated in Izana, Spain (the WMO-GAW station) by using Langley calibration method, which follows the AERONET protocol. The inter-comparison calibration protocol has been given by Che *et al.* (2009b). During the inter-calibration process, measurements from 2:00 AM to 6:00 AM (UTC) on the clear days with AOD at 500 nm less than 0.20 were used. The interval of the measurements between the reference instrument and the instrument to be calibrated was defined as less than 10 seconds. The AOD difference between the reference instrument and the recalibrated instrument should be less than 0.01.

The AOD data are calculated by using the ASTPwin software (Cimel Ltd. Co.) for Level 1.0 AOD (raw result without cloud-screening), Level 1.5 AOD (cloud-screened AOD based on Smirnov *et al.*, 2000) and Angstrom Exponent between 440 to 870 nm. To make sure the data quality more accurately, all the data were checked manually site by site and unreasonable data were deleted. e.g., some large exceptional large AOD points were usually caused by the cloud accumulation after checking the MODIS Level-1B granule (MOD02_1km) images (http://modis-atmos.gsfc.nasa.gov/IMAGES/index_mod021km.html). Furthermore, daily averaged AOD were computed and those data with measurements less than 10 times in a day were eliminated. Daily and monthly mean values of AOD and Angstrom exponent were investigated by statistical analysis to characterize the aerosol columnar properties.

RESULT AND ANALYSIS

Frequency Distribution of AOD and Angstrom Exponent

Frequency histogram of AOD at Tazhong is shown in Fig. 1 for all the instantaneous data. There is one peak distribution composed for the AOD occurrence frequency. The accumulated frequency in the range of 0.20 to 0.50 is about 57%. The frequency distribution of AOD can be well fitted ($r^2 = 0.95$) by a bi-mode normal distribution centered about 0.23 and 0.50 with the standard deviation of 0.006 and 0.06, respectively (Fig. 1). The equation could be expressed as following:

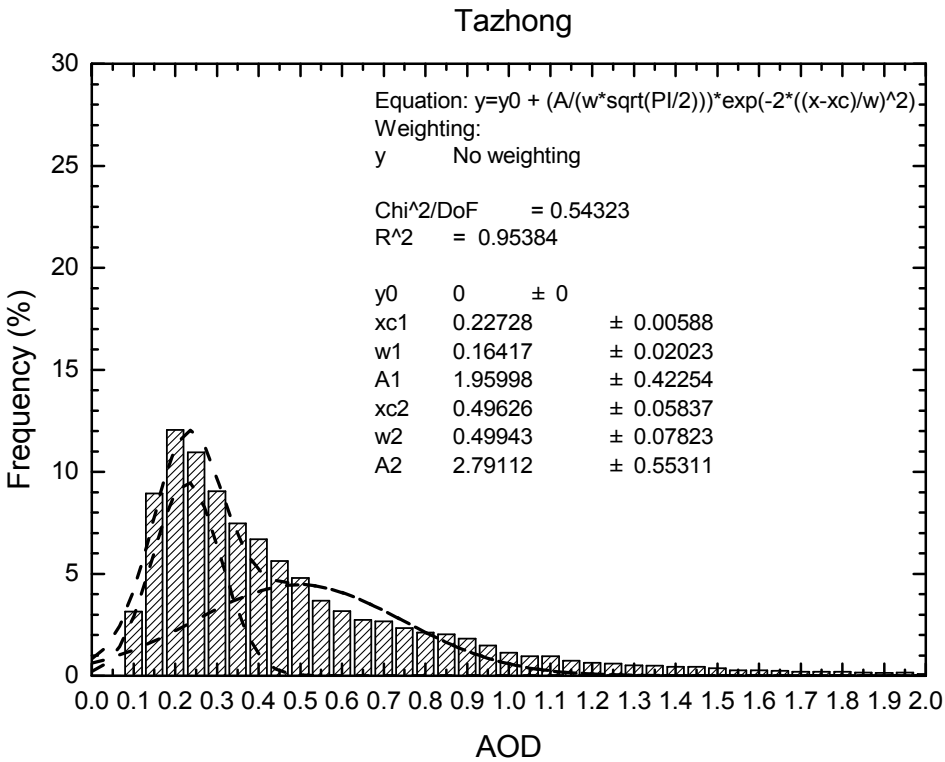

Fig. 1. Frequency of occurrences of AOD at 440 nm at Tazhong. The Dash lines mean the Gauss fitting curves.

$$Y = \left(\frac{1.96}{0.16}\times\sqrt{\frac{\pi}{2}}\right)\times\exp\left(-2\times\left(\frac{x-0.23}{0.16}\right)^2\right)+ \left(\frac{2.79}{0.50}\times\sqrt{\frac{\pi}{2}}\right)\times\exp\left(-2\times\left(\frac{x-0.50}{0.50}\right)^2\right) \quad (1)$$

O'neill *et al.* (2000) suggested that multiple peaks could usually reveal the presence of different aerosol populations and types. The mode centered ~0.23 probably corresponds to the non-dust atmospheric conditions at Tazhong and the mode centered ~0.50 to the high mineral dust burden in atmosphere, such as Asian dust from deserts in spring and early summer.

Frequency histogram of Angstrom exponent at Tazhong is shown in Fig. 2 for all the instantaneous data. The probability distribution of angstrom exponent is similar to that of AOD. There is one peak distribution for the Angstrom exponent. The Angstrom exponent frequency distribution can be well fitted (r^2 = 0.98) by a bi-modal normal distribution centered about 0.17 and 0.50 with standard deviations of 0.004 and 0.06, respectively (Fig. 2). The equation could be expressed as following:

$$Y = \left(\frac{5.52}{0.17}\times\sqrt{\frac{\pi}{2}}\right)\times\exp\left(-2\times\left(\frac{x-0.17}{0.17}\right)^2\right)+ \left(\frac{4.38}{0.50}\times\sqrt{\frac{\pi}{2}}\right)\times\exp\left(-2\times\left(\frac{x-0.49}{0.50}\right)^2\right) \quad (2)$$

The first mode includes more than half of the data and corresponds to coarse particles which are usually associated with sand storm events. Since Tazhong is at the middle of Taklimakan Desert, plenty of coarse aerosol particles could be emitted in atmosphere during the sand storm events with strong wind at surface land. The second mode corresponds to aerosols whose size distribution is also dominated by coarse particles, reflecting the effect of floating dust or dust blowing events occurring at Taklimakan Desert. One can also found that there are a few cases of Angstrom exponent larger than 1.0 in the frequency distribution. This may reflect the effect of anthropogenic activities. It has been proved that the fine particles (such as black carbon) could contribute to the composition of aerosol in Taklimakan desert. These anthropogenic particles emitted specially by coal combustion could be transported from north and south part of Xijiang province to the middle of Taklimakan desert (Li *et al.*, 2010).

Seasonal Variation of AOD and Angstrom Exponent

Fig. 3 illustrates the seasonal variation of AOD at Tazhong. In general, the mean AOD values in spring and summer are larger than those in autumn and winter. The AODs in spring and summer are about 0.75 and 0.65, respectively. In contrast, the mean AODs in autumn and winter are lower than 0.30. The 75th percentile AOD values are about 0.93, 0.84, 0.30, and 0.32 in spring, summer, autumn, and winter, respectively. High AODs in spring and summer reflect the contribution of dust events. Dust events are very frequent during spring and early summer, which causes large aerosol loading in atmosphere over Taklimakan Desert (Xue *et al.*, 2009). During autumn and winter period, there were few dust events. Although some anthropogenic activities could have effect on aerosol particles of Tazhong (Li *et al.*, 2010), the anthropogenic aerosol particles are mainly transported from outside resources. Comparing with mineral dust during spring and summer, the anthropogenic aerosol burden in autumn and winter is much less.

Eck *et al.* (2005) addressed that Angstrom exponent less than 0.80 mean coarse mode dominated aerosol cases. The 75th percentile Angstrom exponent value at Tazhong is less than 0.80 all the year (Fig. 4), which suggests coarse mode aerosol strongly dominated the AOD in Taklimakan Desert regions of China. The seasonal variation of Angstrom exponent at Tazhong shows the characteristic of small values (~0.15) in spring and summer but larger values in autumn (~0.36) and winter (~0.55), which suggests the aerosol particles are larger in spring and summer than in autumn and winter. The are some cases with Angstrom exponent larger than 0.80 in autumn and winter, which probably reflects the anthropogenic effect on aerosol particles in Taklimakan Deserts (Li *et al.*, 2010).

Monthly Variation of AOD and Angstrom Exponent

The monthly variation of AOD and Angstrom exponent is shown in Table 1. The intra-annual variation of AOD and Angstrom exponent is very obvious. The AOD increases during January to April and decreases till December while the Angstrom exponent varies contrary to AOD. The AOD variation is similar to that of Total Suspended Particles (TSP). Liu *et al.* (2011) investigated the TSP variation at Tazhong. The TSP concentration has large value range between April to August. In this article, high AOD and low Angstrom exponent occur during March to July with values larger than 0.60 for AOD and less than 0.15 for Angstrom exponent. The maximum AOD occurs in April with value of 0.83 ± 0.41and the minimum Angstrom exponent occurs in May with a value of 0.09 ± 0.06. The AODs from November to January are less than 0.30 and the Angstrom exponent varies around 0.58 to 0.70, which indicates the aerosol loading during this period at Taklimakan Desert is low because of infrequent dust events and the coarse particles are less comparing with the period during March to July.

Diurnal Variation of AOD and Angstrom Exponent

The diurnal variation of AOD and Angstrom exponent is shown in Figs. 5 and 6, respectively. The mean values are based on the statistic of all the instantaneous data. The diurnal variation shows that AOD is higher in the morning and evening. AOD is ~ 0.50 before 9:00 (Local time) and decrease to ~ 0.40 until 18:00 and then increases to over 0.50 again from 19:00. The variation of Angstrom exponent is contrary to that of AOD. Angstrom exponent increases from ~0.15 to ~0.35 from 8:00 to 10:00 and varies very little until on 18:00 at afternoon. From 18:00, the Angstrom exponent decreases till to the minimum about 0.13 at 20:00.

The diurnal variation in this study is different from that of Gai *et al.* (2006), which could be due to the different

measurement period and processing method. The diurnal variation of AOD in this study is similar to that of scattering coefficient. Lu *et al.* (2010) measured the scattering coefficient (σ) by using M9003 nephenometer and also found diurnal variation of σ with the large values in the morning and evening. Tazhong is located in the middle of Taklimakan

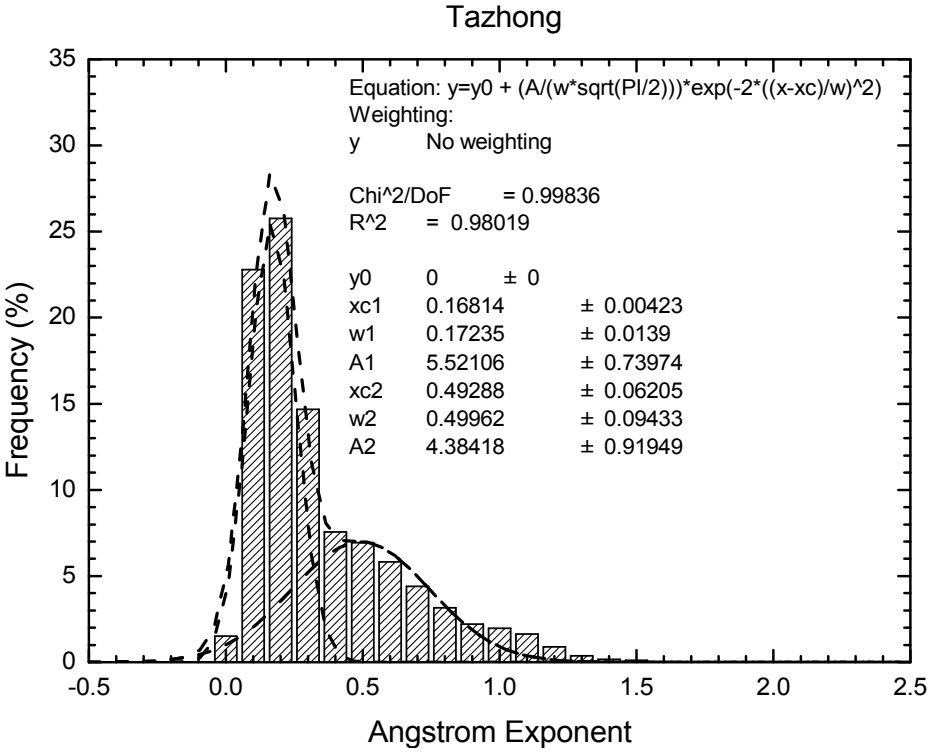

Fig. 2. Frequency of occurrences of Angstrom exponent between 440 nm and 870 nm at Tazhong. The Dash lines mean the Gauss fitting curves.

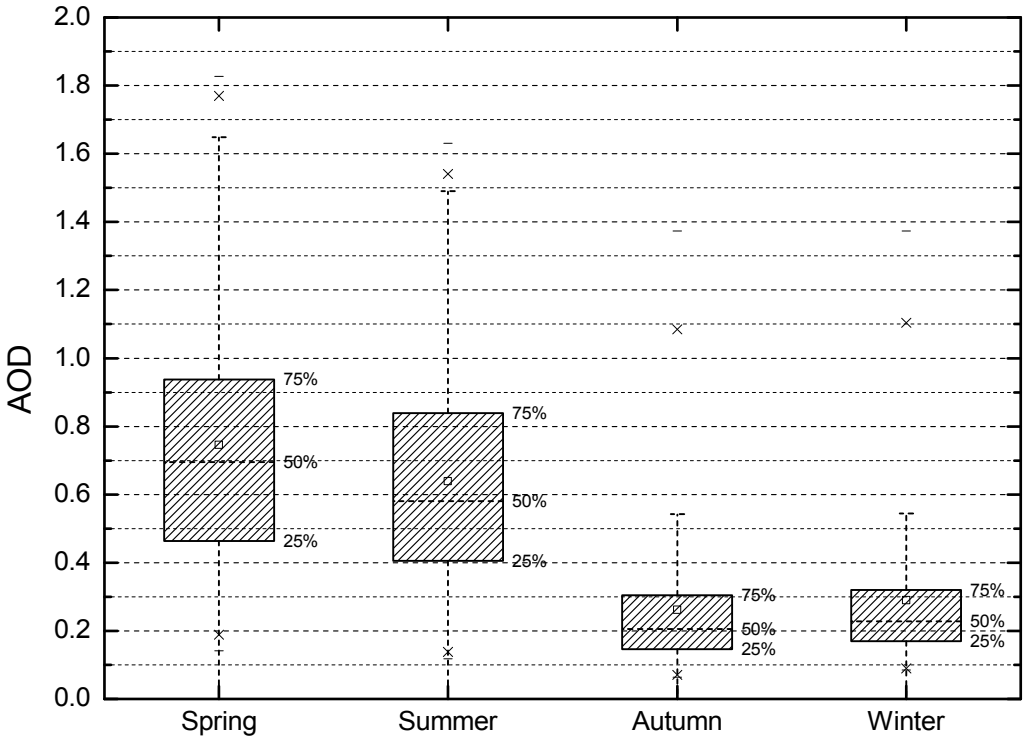

Fig. 3. Seasonal mean and standard deviation values of AOD at Tazhong (The extreme "–" means the maximum and minimum value; the "×" means 99% and 1% percentile value; the "□"means the mean value).

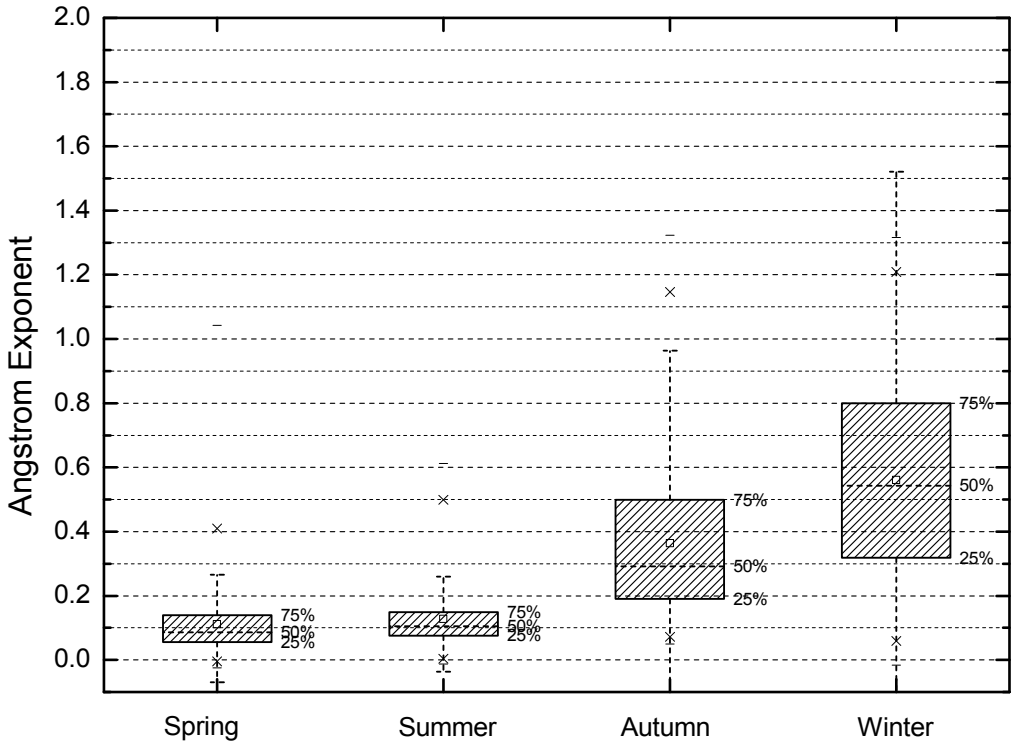

Fig. 4. Seasonal mean and standard deviation values of Angstrom exponent at Tazhong(The extreme "–" means the maximum and minimum value; the "×" means 99% and 1% percentile value; the "□"means the mean value).

Table 1. The monthly means of AOD and Angstrom exponent at Tazhong.

	AOD	Std (Δ)	Angstrom exponent	Std (Δ)	No. (days)
Jan	0.22	0.08	0.70	0.25	74
Feb	0.41	0.26	0.42	0.32	86
Mar	0.65	0.34	0.13	0.09	79
Apr	0.83	0.41	0.11	0.14	70
May	0.77	0.36	0.09	0.06	77
Jun	0.76	0.33	0.10	0.07	83
Jul	0.60	0.30	0.12	0.06	88
Aug	0.58	0.29	0.15	0.11	106
Sep	0.46	0.22	0.20	0.09	116
Oct	0.30	0.15	0.31	0.14	134
Nov	0.19	0.10	0.59	0.26	111
Dec	0.24	0.17	0.58	0.28	107

Desert with large temperature difference and affected mainly by mineral particles (Xue *et al.*, 2009). From Fig. 7, one can see the diurnal temperature and wind speed variations at Tazhong are very similar. Temperature and wind speed decrease continuously during middle night (00:00 local time) to early morning (08:00 local time) and increase rapidly from early morning about 08:00 to noon about 12:00. Inversion layer is easily formed in the morning, which is not in favor of the diffuse of aerosol particles. From evening about 18:00, both the temperature and wind speed begin to decrease rapidly. The near-surface atmosphere becomes stable because of the rapid temperature and wind speed decrease, which could block the diffuse of aerosol particles. However, during the daytime high temperature and wind speed could cause the turbulence exchange and convection very actively, and the aerosol particles are easily emitted into the atmosphere and diffused (Zhang *et al.*, 2008). This classic meteorological condition probably results in large AOD in the morning and evening but stable during daytime at Tazhong station.

The Angstrom exponent varies differently to that of AOD, which shows lower values in the morning and evening than daytime. This could probably because aerosol loading includes more coarse particles in the morning and evening. However, some coarse particles could be transported away with the strong turbulence exchange and convection during the daytime.

Relationship between AOD and Angstrom Exponent

The scatter gram of AOD versus Angstrom exponent is shown in Fig. 8. This representation often allows the physical

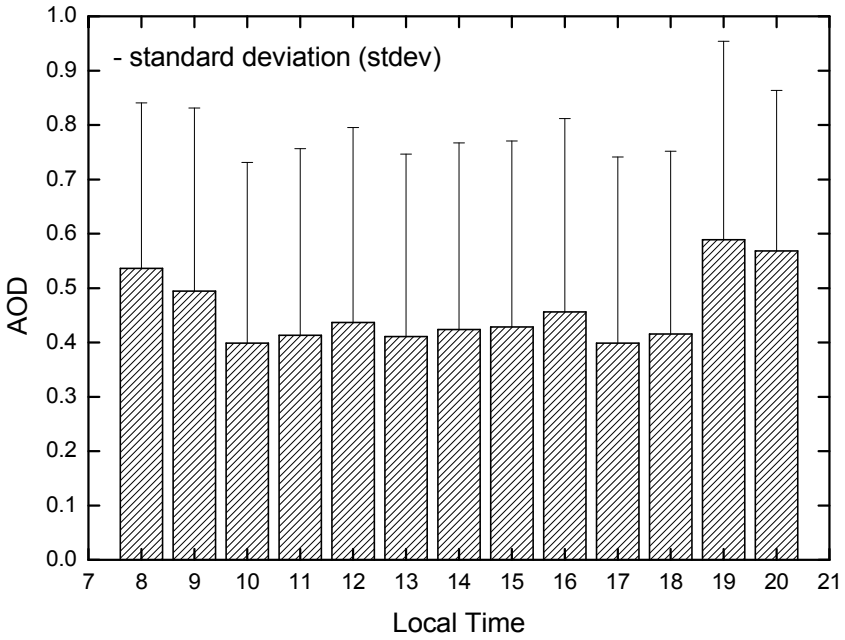

Fig. 5. Dural variation of AOD and standard deviation (stdev) at Tazhong.

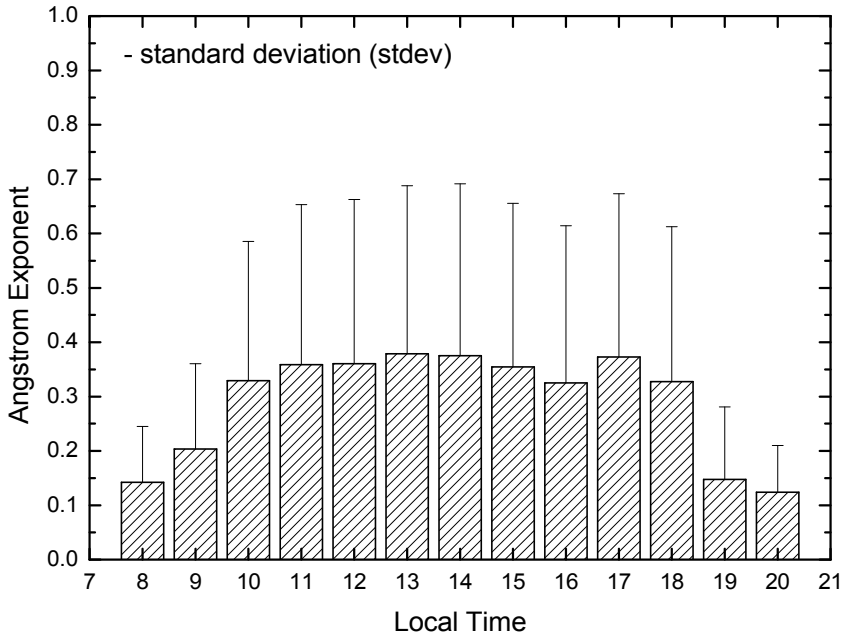

Fig. 6. Dural variation of Angstrom exponent between 440 nm and 870 nm and standard deviation (stdev) at Tazhong.

definition of interpretable cluster regions for different types of aerosols (Smirnov *et al.*, 2002). One can see that obviously there is a trend of increasing AOD with decreasing Angstrom exponent, which stands for large particles. Most likely, the origin of this type of aerosol is local or regional dust events. There are also some cases with AOD around 0.50 and Angstrom exponent around 1.0, which probably reflects the presence of some fine particles in the aerosol size distribution, such as sulfate and black carbon (Li *et al.*, 2010). In general, the relationship between AOD and Angstrom exponent can be well fitted by a power curve with the equation of $Y = 0.1055X^{-0.8568}$ with a R^2 about 0.55.

SUMMARY

It was found that seasonal variation of the optical properties was significant over Taklimakan Desert. The AOD increases from January to April and decreases until December while the Angstrom exponent shows an opposite trend from the AOD, with a minimum Angstrom exponent of 0.09 ± 0.06 in May. The maximum AOD occurs in April with a value of 0.83 ± 0.41. The dust aerosols in spring and summer are the major contributors to AOD and Angstrom exponent variations. AOD is lower in autumn and winter seasons than in spring and summer.

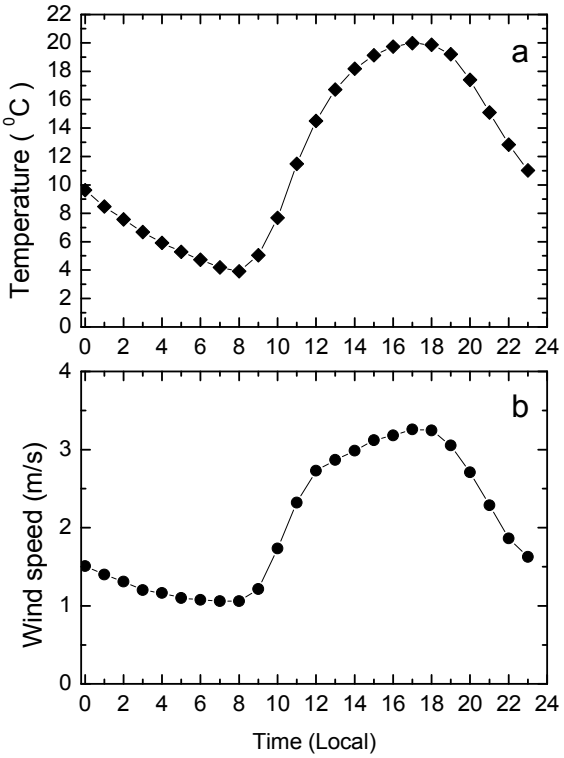

Fig. 7. Dural variation of temperature (a) and wind speed (b) at Tazhong.

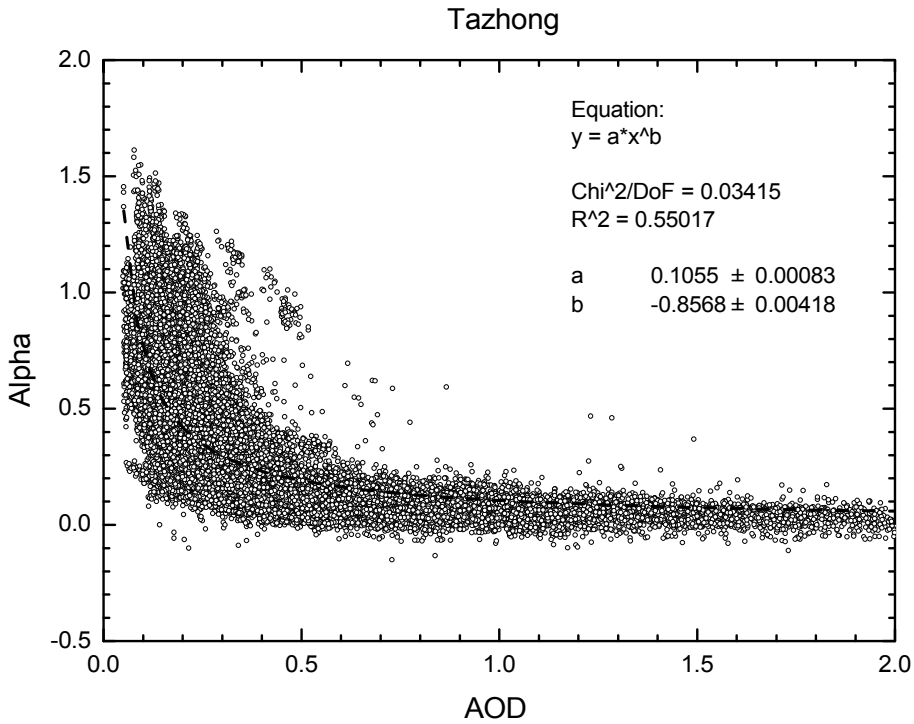

Fig. 8. Relationship between AOD and Angstrom exponent.

The diurnal variation shows that AOD (Angstrom exponent) is high (low) in the morning and evening and rather constant during the day. This pattern is linked to the meteorological conditions of Taklimakan Desert.

Relationship between AOD and Angstrom exponent shows that coarse particles are the major parts of aerosol in Taklimakan Desert. There is one peak probability distribution for the AOD and the Angstrom exponent. Both the AOD and Angstrom exponent distributions could be well fitted by a bi-mode normal distribution.

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