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Diurnal variability of dust aerosol optical thickness and Angström exponent over dust source regions in China

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[1] Using 22 months of Sunphotometer Aerosol Optical Thickness (AOT) data collected near the Taklamakan and Gobi dust source regions (Dunhuang, 40.09°N, 94.41°E) in China; we examine the diurnal and seasonal change of dust aerosol properties. Most dust events are during the spring through early summer months with a season-invariant diurnal change of more than ±10% for AOT and ±30% for Angström exponent, with larger AOT and smaller Angström exponent values late in the afternoon. These values are much larger when compared to recent studies that have reported a much smaller (±5%) diurnal variability of dust AOT over various AERONET sites where dust is a major contributor to AOT. The differences are largely due to the geographical locations and meteorological conditions and such large diurnal changes of aerosol properties at or near dust source regions may be significant enough for consideration in regional radiative forcing, air quality and numerical modeling studies. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 3360 Meteorology and Atmospheric Dynamics: Remote sensing. **Citation:** Wang, J., X. Xia, P. Wang, and S. A. Christopher (2004), Diurnal variability of dust aerosol optical thickness and Angström exponent over dust source regions in China, *Geophys. Res. Lett.*, *31*, L08107, doi:10.1029/2004GL019580.

1. Introduction

[2] The effect of aerosols on climate is one of the largest uncertainties in current global climate models [*Hansen et al.*, 1997]. Current understanding of the radiative forcing of dust aerosols is limited, especially over dust source regions where ground observations are sparse and polar orbiting, multi-spectral satellite retrievals at visible to near-infrared wavelengths are often difficult due to the high surface albedo [*Kaufman et al.*, 2002]. While several studies and field experiments were conducted to study Saharan dust aerosols [*Tanré et al.*, 2003], the widely prevalent dust events (“yellow sand”) from the Taklamakan and Gobi deserts in Northwest China, have only gained attention recently [e.g., *Husar et al.*, 2001]. In addition, recent experiments such as ACE-Asia [*Huebert et al.*, 2003] examined aerosol properties thousands of kilometers downwind from the Taklamakan and Gobi deserts. To our knowledge, no long-term systematic observations of dust radiative properties at or near dust source regions over China have been presented.

[3] Using AOT data from the Aerosol Robotic Network (AERONET) [*Holben et al.*, 2001], recent studies have indicated that the diurnal variability of dust AOT is small (<±5%) over various observation sites such as Cape Verde [*Kaufman et al.*, 2000; *Smirnov et al.*, 2002] that is several hundred kilometers downwind from the Saharan dust source region. On the other hand, several cases studies from both ground observations [e.g., *Levin et al.*, 1980] and geostationary satellite retrievals [e.g., *Wang et al.*, 2003] reported that the diurnal variation of dust aerosols could be relatively larger (>15%) and are important for dust radiative forcing calculations [*Christopher et al.*, 2003]. Our current study is different from previous research since we use Sunphotometer-derived aerosol optical thickness (SP AOT) collected near the Chinese dust source regions over a two-year time period to analyze the diurnal and seasonal variations of dust properties.

2. Data

[4] Twenty-two months of AOT (from 1999 and 2000) inferred from a Sunphotometer (Model Pom-01, Prede Inc.) located at Dunhuang airport (40.09°N, 94.41°E), was used to study the wavelength-dependent optical and temporal characteristics of dust aerosols (Table 1). The observation site is located at the eastern edge of the Taklamakan desert (35°N ~ 40°N, 80°E ~ 90°E), southwestern edge of the Gobi desert (about 40°N ~ 45°N, 90°E ~ 110°E), and the western edge of Hexi corridor in Gansu province (Figure 1). Due to the location of the Gobi and Taklamakan desert along 40°N, most Chinese dust storms are located in a horizontal zone (35°N ~ 45°N, 80°E ~ 110°E) and is one of the major dust source regions in the east Asian region [*Sun et al.*, 2001]. This zone is bounded by several mountains with elevations higher than 3000 m and usually, the lofted dust aerosols in this zone are transported eastward, affecting the eastern part of China and other countries such as Japan and Korea. At other times, cold high-pressure systems from Siberia could entrain the dust aerosols westward, to an elevation greater than 5000 m, and then further northward to 50°N, where ultimately dust would be transported by the westerly jet stream to the North Pacific Ocean [*Sun et al.*, 2001]. In either case, Dunhuang is affected by these dust storms. The elevation of Dunhuang city is about 1400 m above sea level, the annual relative humidity is about 40%, and annual precipitation is less than 16 mm. Such geographical and meteorological characteristics of the Dunhuang observation site are different when compared with Cape Verde (16.72°N, 22.93°W) that is commonly used to study Saharan dust properties.

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Table 1. Monthly Mean Statistics of AOT (τ) and Angström Exponent (α) at Dunghuan Observation Site in 1999 and 2000[a]

Year	Month	τ_{MaxIns}	τ_{MinIns}	τ_{Max}	τ_{Min}	τ_{Mean}	τ_{std}	α_{Mean}	α_{std}	D_{used}	D_{dust}	α_{dust}
1999	Jan.	1.173	0.058	0.608	0.074	0.305	0.138	0.149	0.124	27	3	0.053
	Feb.	0.934	0.032	0.663	0.089	0.298	0.156	0.010	0.114	18	2	−0.031
	Mar.	0.771	0.086	0.661	0.138	0.345	0.122	0.129	0.110	20	1	0.111
	Apr.	0.820	0.168	0.619	0.227	0.423	0.114	0.138	0.061	20	6	0.111
	May	0.834	0.069	0.683	0.112	0.278	0.145	0.335	0.374	24	2	0.171
	Jun.	0.916	0.067	0.749	0.137	0.294	0.138	0.159	0.092	25	2	0.045
	Jul.	1.835	0.037	0.648	0.082	0.269	0.142	0.220	0.172	26	1	0.000
	Aug.	0.585	0.067	0.539	0.111	0.221	0.117	0.274	0.114	25	2	0.246
	Sep.	0.589	0.023	0.390	0.051	0.180	0.099	0.007	0.183	18	–[b]	–
	Oct.	0.585	0.014	0.514	0.064	0.211	0.107	0.252	0.237	30	1	0.068
	Nov.	0.717	0.034	0.519	0.066	0.218	0.120	0.143	0.179	29	1	−0.096
	Dec.	0.830	0.047	0.672	0.091	0.262	0.148	0.077	0.120	26	2	0.019
2000	Jan.	0.355	0.048	0.321	0.102	0.183	0.055	0.372	0.113	18	0	–
	Feb.	0.549	0.036	0.396	0.098	0.218	0.096	0.395	0.133	19	0	–
	Mar.	1.525	0.081	0.737	0.145	0.286	0.134	0.196	0.073	21	1	0.078
	Apr.	1.542	0.080	0.875	0.148	0.289	0.186	0.234	0.162	15	1	0.057
	May	2.490	0.041	1.477	0.071	0.351	0.337	0.110	0.150	17	3	−0.067
	Jun.	2.427	0.051	1.561	0.082	0.349	0.361	0.282	0.279	17	3	0.014
	Jul.	0.712	0.030	0.511	0.047	0.216	0.162	0.529	0.251	16	1	0.239
	Aug.	0.545	0.019	0.350	0.048	0.150	0.083	0.573	0.333	21	–	–
	Sep.	0.574	0.125	0.368	0.170	0.253	0.086	0.236	0.095	7	–	–
	Nov.	0.230	0.063	0.134	0.097	0.117	0.013	0.466	0.176	8	–	–

[a] The monthly statistics are calculated from the daily mean values which are computed from the instantaneous Sunphotometer AOT values on each day. Subscript Mean and Std. denote mean and standard deviation. τ_{MaxIns}, τ_{MinIns} τ_{Max}, and τ_{Min} are the maximum and minimum instantaneous AOT and daily mean AOT in each month. For each month, the number of days used in the calculations (D_{used}), the number of dust days that has daily mean AOT larger than 0.5 (D_{dust}) and the averaged α in these dust days (α_{dust}) are also shown in the table.

[b] No data.

[5] The Sunphotometer (SP) measures the direct solar radiation centered at 315, 400, 500, 675, 870, 940, 1020 nm and AOT is calculated based on the Beer-Lambert-Bouguer law. Included in the calculation is a correction for Rayleigh scattering, the change of sun-earth distance, and ozone optical depth based on Total Ozone Mapping Spectrometer (TOMS) data. The instrument has been calibrated more than 300 times using a modified Langley plot approach [*Nakajima et al.*, 1996] over the two year time period. The random errors in calibration during each time step were filtered by using techniques outlined by *Harrison and Michalsky* [1994], and diurnal stability checks were performed according to the method outlined by *Smirnov et al.* [2000]. Additionally, the measurements with the largest deviation (>0.02) from a second order $\ln\tau$ versus $\ln\lambda$ (λ is the wavelength) polynomial fit were rejected according to procedures outlined by *Eck et al.* [1999]. A second order polynominal fit between AOT and wavelength in logarithmic space gave excellent agreement with differences of the same order as the measurement uncertainty of AOT (~0.01–0.02) [*Eck et al.*, 1999]. Manual cloud screening for questionable data was also performed with the help of weather observations obtained at the Dunhuang Meteorological Observatory. This dataset is unique not only because the AOT measurements in the Chinese dust source region is very sparse [*Holben et al.*, 2001], but also because of its relatively long-term continuous observations.

3. Results and Discussion

[6] To enable comparison with previous studies [e.g., *Smirnov et al.*, 2002], the aerosol wavelength-dependent properties is characterized by two parameters: AOT (τ) at 0.5 μm, and the Angström exponent (α), derived from a multi-spectral (λ ranging from $0.50 \sim 0.87$ μm) log linear fit to the Angström exponent equation $\tau \sim \lambda^{-\alpha}$. Generally, α provides information on the aerosol size distributions, with values greater than 2.0 corresponding to accumulation mode particles such as fresh biomass burning smoke and values closer to zero for coarse mode particles such as dust. *Eck et al* [1999] showed that for large particles, α has small variations in the $\ln\tau \sim \ln\lambda$ domain over the visible and near infrared wavelengths, and can be used as a first-order indicator of the spectral behavior of dust aerosols.

[7] The histogram of daily mean AOT and α for different seasons is presented in Figure 2 and relevant statistics are shown in Table 1. The intense dust storms (instantaneous AOT > 1.5 and daily mean AOT > 0.4) are during the spring (February–April) and summer (May–July) months

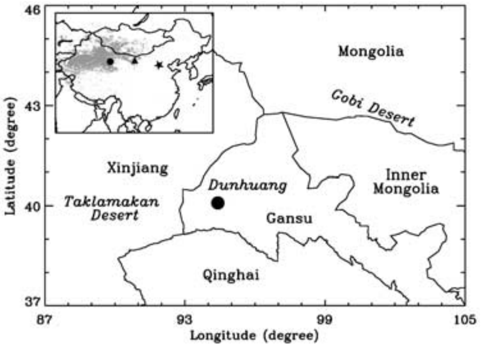

Figure 1. Map of the observation site Duhuang (denoted as filled circle) and its vicinity. The inset shows the map of eastern Asia. The shaded area in the inset is the location of Taklamakan desert and Gobi desert (based on the on the ecosystem database from USGS). The five-point star denotes the location of Beijing, and triangle denotes the AERONET site at Dalanzadgad, Inner Mongolia.

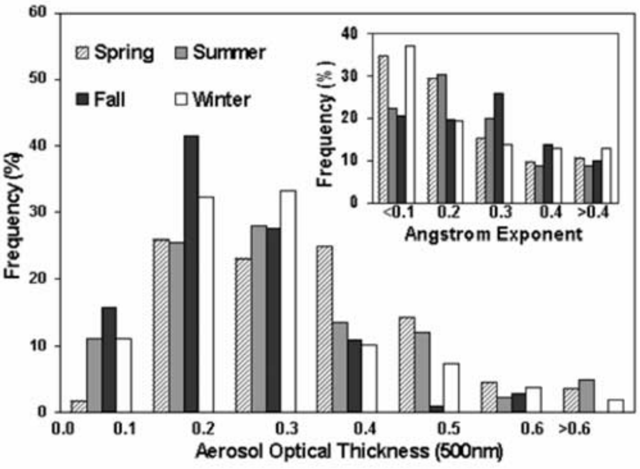

Figure 2. Seasonal frequency distribution of aerosol optical thickness and Angström exponent for different seasons in Dunhuang.

that is consistent with the TOMS analysis [*Prospero et al.*, 2002]. In both years, the monthly mean AOT is larger during spring and summer (mean AOT around 0.3), with smaller values (around 0.2) during the fall (August–October) and winter (November–January) seasons. Generally, the monthly mean standard deviation of AOT is proportional to the monthly mean AOT, since large AOT variations are usually associated with intense dust storms. The monthly mean α is generally less than 0.35 with slight seasonal variations, and over 20% of daily mean α are less than 0.1 in all seasons (inset in Figure 2). This feature implies that the aerosols in this region are dominated by coarse mode particles that are different when compared with urban conditions [*Holben et al.*, 2001].

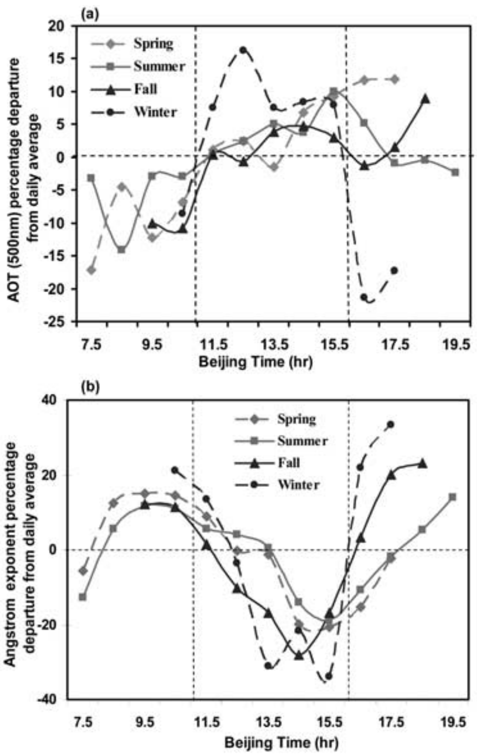

Figure 3. Diurnal variations expressed in terms of percentage departure from the daily mean for different seasons a) aerosol optical thickness at 500 nm b) Angström exponent.

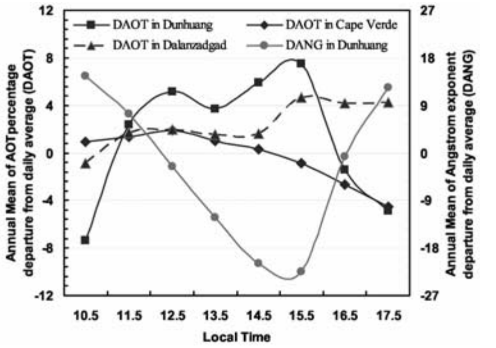

Figure 4. Diurnal variations expressed in terms of percentage departure from daily mean for aerosol optical depth and Angström exponent at several sites where dust is a major contributor.

[8] To calculate the hourly statistics for different seasons, all individual AOT and Angström exponent values in a day are expressed as a percentage difference from the daily mean. The computed percentages are then averaged in hourly intervals for four seasons. This procedure is similar with previous studies [e.g., *Peterson et al.*, 1981; *Smirnov et al.*, 2002], thereby enabling comparison and examination of systematic diurnal trends. The diurnal variations of AOT and α for four seasons are shown in Figures 3a and 3b, respectively. The AOT (α) is smaller (larger) in the morning (8 ~ 11 a.m. local time) and larger (smaller) during afternoon (12 ~ 4 p.m. local time). In all seasons, the diurnal change of dust AOT is usually more than ±10% (equivalent to a change of dust AOT about 0.05), and the change in α is about ±30%. Such differences have not been reported previously because AERONET locations lack a long-term observation site in the Chinese dust source region. The variations of both AOT and α in one hour could as be as large as 5% of the daily mean. For instance, during the fall season, the AOT departure from daily mean at 2 p.m. is about −1% and increases to about 5% one hour later at 3 p.m. Another interesting pattern is that the Angström exponent shows a consistent season-invariant increase in the late afternoon (after 4 p.m., Figure 3b), although the AOT changes do not show any consistent change patterns at this time (Figure 3a). Depending on different seasons, in the last 2 ~ 3 hours before the sunset, the departure of Angström exponent from daily mean could change rapidly from daily minimum values below zero to near zero or daily maximum. Further meteorological data sets are needed to study such rapid changes.

[9] Using 7 years of AOT data collected from various AERONET observation sites around the globe, *Kaufman et al.* [2000] showed that the maximum diurnal variation in an individual site is 11% for AOT and 20% for Angström exponent. *Smirnov et al.* [2002] further showed that diurnal variability of AOT generally is less than ±5% over the AERONET sites where dust is a major contributor to AOT. However the diurnal variability showed in these studies are multi-year averaged quantities, and therefore they are expected to be smaller than the maximum variations showed

in terms of different seasons. To compare with these studies, we also computed a 22-month averaged diurnal change of AOT and Angström exponent for daytime data for all seasons. Compared to diurnal variations of Saharan dust AOT at Cape Verde and Asian dust at Dalanzadgad found by *Smirnov et al.* [2002], Figure 4 shows that the dust aerosols from Takalamakan and Gobi desert have a larger daily variation of AOT (about ±8%) and a much larger variation of Angström exponent ($-25\% \sim 15\%$). One possible reason might be the distance of the observation site from the dust source regions. Cape Verde Island is several hundred kilometers away from the Saharan desert, and Dalanzadgad in Inner Mongolia is close to the south-eastern edge of Gobi desert (Figure 1). Compared to these two AERONET sites, the observation site in Dunhuang is much closer to the desert source region, and is affected by dust from both Gobi desert and Taklamakan desert depending on the meteorological conditions. We also note that our analysis is based on 22-months of daytime data in cloud-free conditions, which could have some bias due to the limited sampling and intra-annual variability. For instance, Angström exponent in July and August, 2000 is above 0.5, that is substantially higher than the same time period in 1999 (Table 1). The sudden 30% drop of AOT from 3 p.m. to 5 p.m. in winter in Figure 3a could also due to our limited observations points during this time period. Recent numerical modeling studies have also shown that the largest dust emissions could be during the night near the early morning hours [*Ginoux and Torres*, 2003]. Therefore long-term systematic observation of aerosol optical properties both during day and night coupled with meteorological observations is necessary.

[10] The relatively large seasonal and diurnal variations of dust AOT and Angström found in this study has several important implications. Recent remote sensing sensors such as MISR and TOMS provide an opportunity to analyze large scale dust AOT and radiative forcing over the desert area. However, the impact of diurnal change of dust optical properties on the satellite retrieval accuracy and the validation process is still unknown, and need to be carefully examined over the different desert regions. Furthermore, polar orbiting satellite measurements can only provide instantaneous dust AOT and dust forcing [*Zhang and Christopher*, 2003; *Hsu et al.*, 2000]. To apply satellite-based estimation of AOT to calculate the mean radiative forcing of dust aerosols, the diurnal change of dust AOT and other radiative properties should be carefully considered, especially in the dust source regions. The larger diurnal variations of dust AOT could also pose challenges for forecast of air quality and visibility where high temporal resolution products are needed, especially for aviation and military purposes. From this perspective, the current and future generation of geostationary satellites could play an important role in capturing the large diurnal variations of aerosol properties over a large spatial domain.

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