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Aerosol optical properties at Nam Co, a remote site in central Tibetan Plateau

Zhiyuan Cong [a], Shichang Kang [a,b,*], Alexander Smirnov [c,d], Brent Holben [d]

[a] Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100085, China
[b] State Key Laboratory of Cryospheric Science, Chinese Academy of Sciences, Lanzhou 730000, China
[c] Science Systems and Applications, Inc., Lanham, MD 20706, United States
[d] Biospheric Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, MD 207771, United States

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ABSTRACT

To reduce uncertainties in the assessment of aerosol effects on regional climate and validate the satellite products, aerosol optical measurements were made at a remote site, Nam Co Station (AERONET) in central Tibetan Plateau, since August 2006. Very low aerosol optical values were observed with annual mean Aerosol Optical Depth (AOD) of 0.05 at 500 nm during August 2006 to July 2007. Angstrom parameters were also low with an average of 0.42±0.27. Angstrom parameter varies greatly over a narrow range of AOD, indicating the occurrence of different types of aerosol particles. The seasonal variation of the monthly average AOD shows maximum values in the spring (April, May) and remains high values in summer monsoon season (June, July, August, and September). The former corresponds to the prevalence of soil dust particle in spring and the later reflects the enhanced human activities in summer. The seasonal variation of columnar size distribution is also consistent with this result. Distinct seasonal variation of water vapor content was observed, with high that occurred in summer monsoon season. Nam Co appears to represent a clean continental background site for atmospheric composition investigation. This work could fill the gap which exists in our knowledge on the global aerosol distribution over the huge high elevation area (i.e. Tibetan Plateau).

1. Introduction

The Tibetan Plateau (TP) is one of the most imposing topographic features on the surface of the Earth. With an immense area (about 2,500,000 km^2) and mean elevation of more than 4000 m above sea level, TP plays a key role in Asia climatology and atmospheric circulation. Especially in summer, as an elevated heat source, the low pressure over TP induces a supply of moist, warm air from the Indian Oceans to the continent, affecting Asia summer monsoon circulation profoundly. Meanwhile, the atmosphere over the plateau is probably the least affected by human activities in the Asian continent due to the sparse population and minimal industries, providing a unique opportunity to describe atmospheric processes and changes.

In this context, several model simulation and satellite observation works have been carried out over the TP to elucidate the effects of aerosol on regional climate and water cycles. Lau et al. (2006) and Lau and Kim (2006) used the NASA finite-volume GCM to assess the possible impact of aerosol on the Asian summer monsoon over the TP and the adjacent area. Their results suggested that, on intra-seasonal to inter-annual time scales, absorbing aerosols such as dust and black carbon at southern and northern slopes of the TP at late spring may intensify India summer monsoon. Ramanathan et al. (2007) found atmospheric brown clouds widespread over Indian Ocean and Asia could lead to significant warming trends, which may account for the rapid retreat of Himalayan glaciers. Other model simulations and satellite observations have suggested that elevated aerosols and CO at high altitude over the TP may be due to the convective transport of South Asian pollution by summer monsoon (Li

* Corresponding author. Current address: Institute of Tibetan Plateau Research, Chinese Academy of Sciences. 18 Shuangqing Road, Haidian District, Beijing 100085, China.
E-mail address: Shichang.kang@itpcas.ac.cn (S. Kang).

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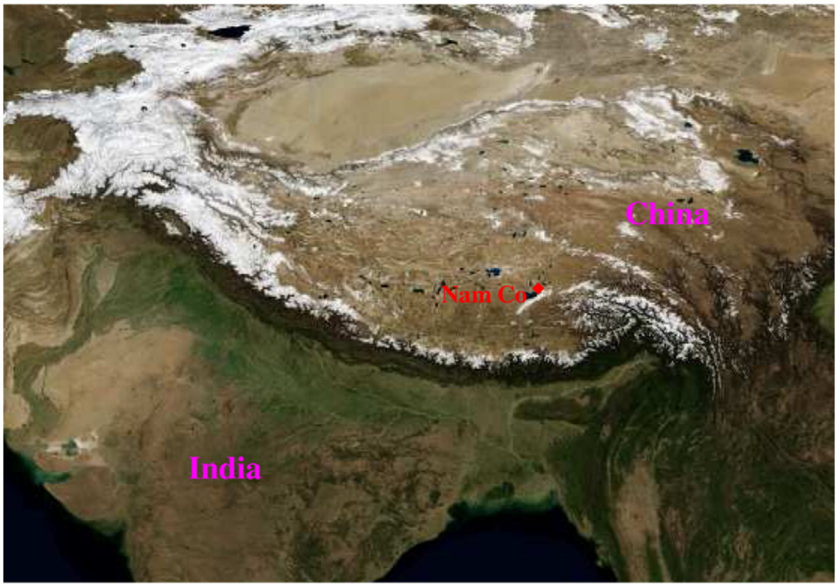

Fig. 1. Map of the Tibetan Plateau and the location of Nam Co Station.

et al., 2005). Jin (2006) investigated the seasonal and inter-annual variations of aerosols, clouds, water vapor and cirrus over the TP by MODIS observation, which closely related to large-scale hydrological cycle. Recently, the occurrence of summer dust aerosols over the northwestern TP detected from CALIPSO satellite were also reported (Huang et al., 2007). However, ground-based optical characterizations of aerosols are scarce at TP (Li and Lu, 1995; Zhang et al., 2000; Xin et al., 2007). Considering its huge area and essential role in the climate system, the lack of detailed knowledge of aerosol optical properties over TP leads to large uncertainties in climate modeling and assessments.

AERONET (Aerosol Robotic Network) is a worldwide aerosol characterization network with the automatic CIMEL Sun/sky radiometer as the principal instrument (Holben et al., 1998; Holben et al., 2001). Due to its significant advances on observation techniques and analysis methods (Dubovik et al., 2000), AERONET has been producing reliably and continuously

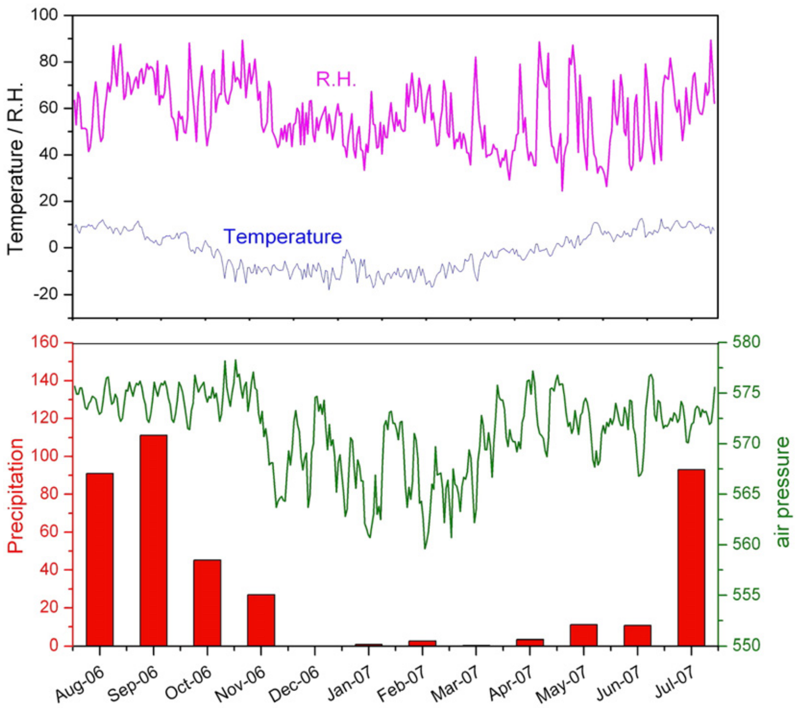

Fig. 2. Meteorological parameters recorded simultaneously by AWS at Nam Co Station during the sunphotometer observation period (August 2006–July 2007).

Table 1
Database summary for Nam Co Station (N30°46.44′, E90°59.31′, 4730 m a.s.l.), 2006–2007

	τ_a (500 nm)	σ	α	σ_α	WVC	σ	N
2006-Aug	0.06	0.02	0.90	0.32	0.70	0.15	16
2006-Sep	0.05	0.02	0.71	0.26	0.50	0.17	15
2006-Oct	0.03	0.01	0.68	0.32	0.19	0.07	5
2006-Nov	0.03	0.01	0.61	0.25	0.19	0.06	12
2006-Dec							
2007-Jan							
2007-Feb	0.04	0.02	0.32	0.33	0.09	0.04	16
2007-Mar	0.03	0.01	0.09	0.29	0.09	0.04	28
2007-Apr	0.06	0.03	0.17	0.19	0.16	0.09	21
2007-May	0.08	0.03	0.24	0.20	0.28	0.12	18
2007-Jun	0.06	0.03	0.25	0.28	0.41	0.11	22
2007-Jul	0.05	0.02	0.26	0.29	0.68	0.12	20
Year	0.05	0.02	0.42	0.27	0.33	0.10	125

detailed optical properties of various types of aerosols worldwide (Dubovik et al., 2002). In August 2006, an automatic sun and sky scanning radiometer (CIMEL) was established at Nam Co, central Tibetan Plateau as an AERONET site. This paper will focus on the optical properties (AOD, Angstrom parameter) and volume size distribution of aerosols in this poorly understood region based on the first-year (Aug 2006–Jul·2007) AERONET data. We expect such information can help to understand the atmosphere condition and interactive processes over the TP, validate the product of satellite measurements, and improve the initialization for climate models involving TP and the surrounding regions.

2. Site, measurement, and methodology

2.1. Site description

Nam Co is the largest lake in Tibet as well as the highest great lake in the world. Lying at the foot of Nyainqentanglha Mountain, it covers an area of 1961 km^2 at an elevation of 4720 m (Fig. 1). In 2005, Nam Co Monitoring and Research Station for Multispheric Interactions (briefly Nam Co Station, N30°46.44′, E90°59.31′, 4730 m a.s.l.) was established and maintained by Chinese Academy of Sciences and began to long-term monitor the environment in central TP (Cong et al., 2007). The annual average of temperature is 0 with a large seasonal and daily variation (Fig. 2). The minimum monthly mean temperature occurs in December and the maximum in July. The average annual air pressure is 571.2 hPa with minimum in January and maximum in September. There are four distinct seasons, winter (December to February), spring (March to May), summer (June to September) and autumn (October to November) (You et al., 2007). In spring, the dust episode occasionally impacts Nam Co from the upwind sandy regions (Fang et al., 2004). In summer, Nam Co is under the influence of the Indian summer monsoon, therefore, it is characterized by relatively higher temperature and humid weather and accounts for about 70% of annual precipitation (You et al., 2007). Autumn is generally characterized by cloudless sky and lower precipitation. Winter is very cold and the surrounding area was covered by snow, resulting in a clean environment.

The landscape in the Nam Co region mainly consists of high mountains, glaciers, lake and grassland, which are representative of most area of the TP and prone to be fragile related with the climate change. Due to the harsh climate, the local population in the Nam Co region is very limited. The local inhabitants mainly make a living by herding sheep and yaks, resulting scarcely atmospheric pollutants emission in the vicinity.

2.2. Measurements and methodology

The CIMEL Sun photometer makes direct solar radiation measurements with a 1.28 full field of view every 15 min at 340, 380, 440, 500, 675, 870, 940, and 1020 nm (nominal wavelengths). The direct Sun measurements take 8 s to scan all eight wavelengths, with a motor-driven filter wheel positioning each filter in front of the detector. These direct solar extinction measurements are then used to compute AOD

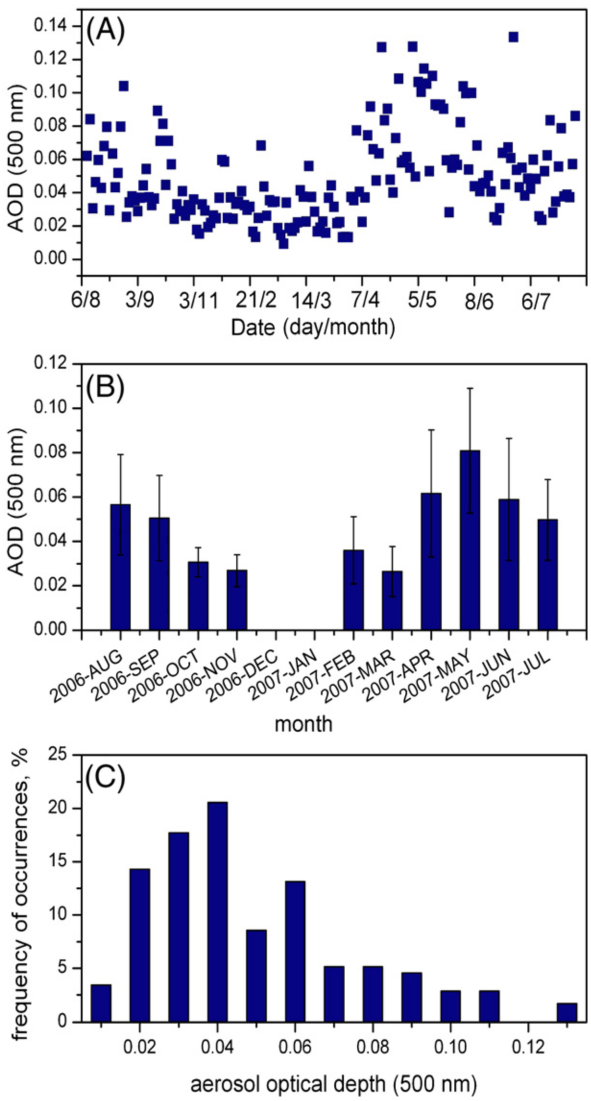

Fig. 3. Mean daily (A) and monthly (B) values of aerosol optical depth at the wavelength 500 nm for the one year measurements (the vertical bars represent one standard deviation), frequency of occurrence of aerosol optical depth (C).

at each wavelength except for the channel at 940 nm, which is used to retrieve water vapor content (WVC) in centimeters (Holben et al., 2001). The instrument calibration and derivation of AOD are discussed in detail by Holben et al. (1998). The accuracy of AOD was estimated to be 0.01–0.02 (Eck et al., 1999). Angstrom parameter was computed as the slope of the linear regression of ln(τ) and ln(λ), using the 440 and 870 nm data (τ means aerosol optical depth and λ is the wavelength). Sky radiance almucantar measurements at 440, 675, 870, and 1020 nm (nominal wavelengths) and direct sun measurements of AOD at the same wavelengths were used to retrieve columnar size distribution following the methodology of Dubovik and King (2000).

All data used in this paper are level 2.0 quality-assured data set (AERONET website, http://aeronet.gsfc.nasa.gov/), which have been pre- and post-calibrated, automatically cloud screened (Smirnov et al., 2000) and manually inspected. On account of the extremely low aerosol loading at Nam Co, we didn't consider the other optical and microphysical parameters like refractive index and single-scattering albedo in this study.

3. Results and discussion

3.1. Aerosol optical depth (AOD)

A summary of the aerosol observations at Nam Co is presented in Table 1. Daily mean values of AOD (Fig. 3A) show the spring peaks (maximum daily values of ~0.14). The seasonal variation of the monthly average AOD (Fig. 3B) shows maximum values in the spring (April and May) and remains high values in summer monsoon season (June, July, August, and September). This seasonal peak in spring is due to the snow covered Nam Co area began to melt and more loose ground surface expose to the windy condition, thereby more soil and dust particles were blown into the atmosphere. In summer, the high values of AOD may be resulted by the enhanced anthropogenic emissions from local region or south Asia which are transported by the Indian monsoon (Cong et al., 2007). The winter AOD minimum may be related to the snow cover existing in this region and therefore the air is expected to be cleaner. However, it should be noticed that the data in December 2006 and January 2007 are absent since Sun photometer didn't work at that time, thus current winter AOD data might be modified by further observations. The frequency histogram of τ_a (500 nm) peaks at 0.02–0.06 (Fig. 3C), which is typical for the background conditions (Holben et al., 2001).

The mean value of AOD for the whole year (0.05 at 500 nm) is relatively lower than or comparable to other continental background sites, representing one of the lowest values in the AERONET network. For example, Mauna Loa (3400 m a. s. l.) is located in mid-Pacific and acts as the calibration site of sun photometers in AERONET project due to the extremely low and stable AOD there. The annual average value of τ_a (500 nm) at Mauna Loa is 0.02, with seasonal peaks in spring (Holben et al., 2001). Six et al. (2005) have reported a mean AOD of 0.02 (440 nm) for clear sky conditions at Dome C, Antarctica. Annual mean AOD of 0.10 at a similar high elevation site (Issyk-Kul Lake) in central Asia was observed by Semenov et al. (2005). Therefore, Nam Co represents a very clean atmosphere environment and could be a perfect site for monitoring the continental background aerosol loading and anthropogenic impact on the atmosphere.

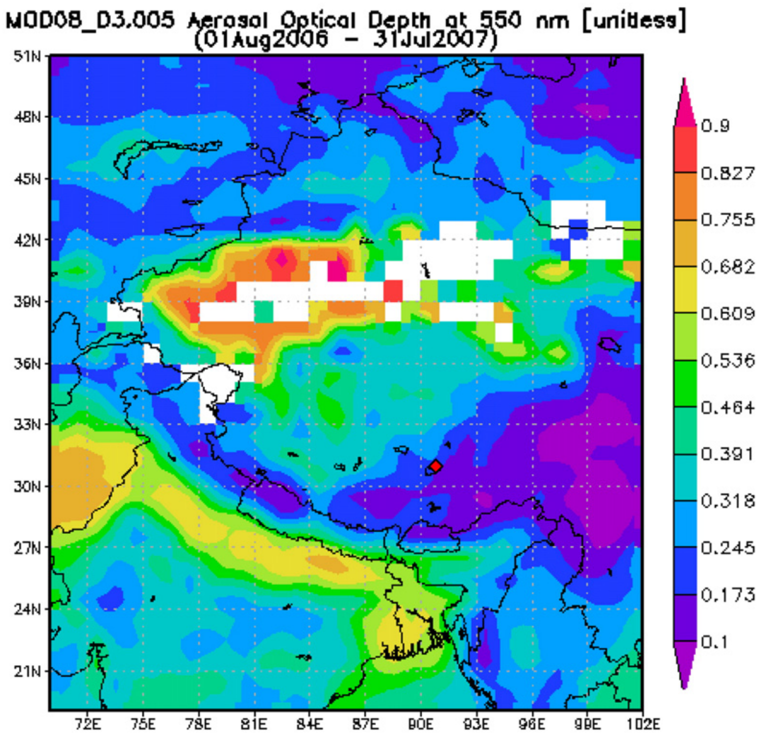

Fig. 4. Regional distribution of AOD over Tibetan Plateau derived from MODIS observation (Aug 2006–Jul 2007).

At Nam Co station, a TSP sampler was also set up and collected aerosol samples weekly during the AERONET observation (Cong et al., 2007). The range of TSP concentrations measured at Nam Co for the period of this study was 0.48–36.11 μg m^{-3} with the annual average of 6.74 μg m^{-3}, reflecting a background level. These values are generally comparable with those observed at other remote sites. For example, Mazzera et al. (2001) reported the average PM_{10} mass concentration measured at McMurdo (Hut Point), Antarctic during 1995/96 and 1996/97 austral summers was 3.4 μg m^{-3} with the maximum of 7.5 μg m^{-3}.

The Moderate Resolution Imaging Spectroradiometer (MODIS) has been providing high spatial resolution and global coverage of aerosol products. However, the accuracy of the MODIS aerosol products is still uncertain over TP due to the lack of validation by long-term ground-based observations. In this study, when compared with MODIS observation, the seasonality of AOD at Nam Co was generally consistent with that over the whole TP reported by Jin (2006), i.e. maximum occurs in spring and followed by summer. However, AOD produced by AREONET measurement in this study (annual mean value 0.05) is substantially lower than MODIS observation. The AOD retrieved from MODIS is generally larger than 0.1 in the same period (August 2006–July 2007) (Fig. 4). This discrepancy may be partly due to the significant overestimation of AOD over land, which originates primarily from inaccurate assumptions on land surface and aerosol types (Xia, 2006; Li et al., 2007). Then special care should be taken when we try to investigate the climatology of aerosol lover TP based on MODIS observation.

3.2. Angstrom parameter

The Angstrom parameter (α) determined from the spectral dependence of measured optical thickness is a good indicator of aerosol size characteristics (Eck et al., 1999). At Nam Co, the Angstrom parameter also has a clear seasonal variation with lower values in spring and higher values in summer (Fig. 5A). The high aerosol loading in spring accompanied with low α indicates that dust dominates the aerosol regime associated with loose ground surface and subsequent more soil dust in the aerosphere. In contrast, high AOD associated with high α in summer could be attributed to larger proportion of fine anthropogenic aerosols. In order to determine the occurrence and percentage of different aerosol types, twelve TSP samples (monthly) were also analyzed by scanning electron microscopy (SEM, PHILIPS XL 30 FEG) equipped with an energy-dispersive X-ray microanalysis (EDX). The results show the dominant aerosol particles are aluminosilicates in all seasons, which are typical crustal minerals and mainly exist in coarse mode. Especially in spring, the relative number concentration of aluminosilicates is about 61%. While in summer, the percentage of aluminosilicates decreased to 30% with increased amount of soot and tar ball (19% and 27%). Soot and tar ball were produced mainly from anthropogenic activities like fossil fuel and biomass burning and usually present in fine mode (Posfai et al., 2003). The annual average value of α computed from daily data is 0.42 ± 0.27 (Table 1). The frequency of occurrences histogram of α (Fig. 5B) displays a peak between 0.2 and 0.4 with a minimum near −0.4 and a maximum at 1.4. The Angstrom parameter varies greatly over a narrow range of AOD (Fig. 5C), implying a variety of aerosol types. It should be noted that the uncertainty in Angstrom parameter is high when the AOD is low, therefore very low and especially negative Angstrom parameters acquired in the low AOD conditions should be treated with caution.

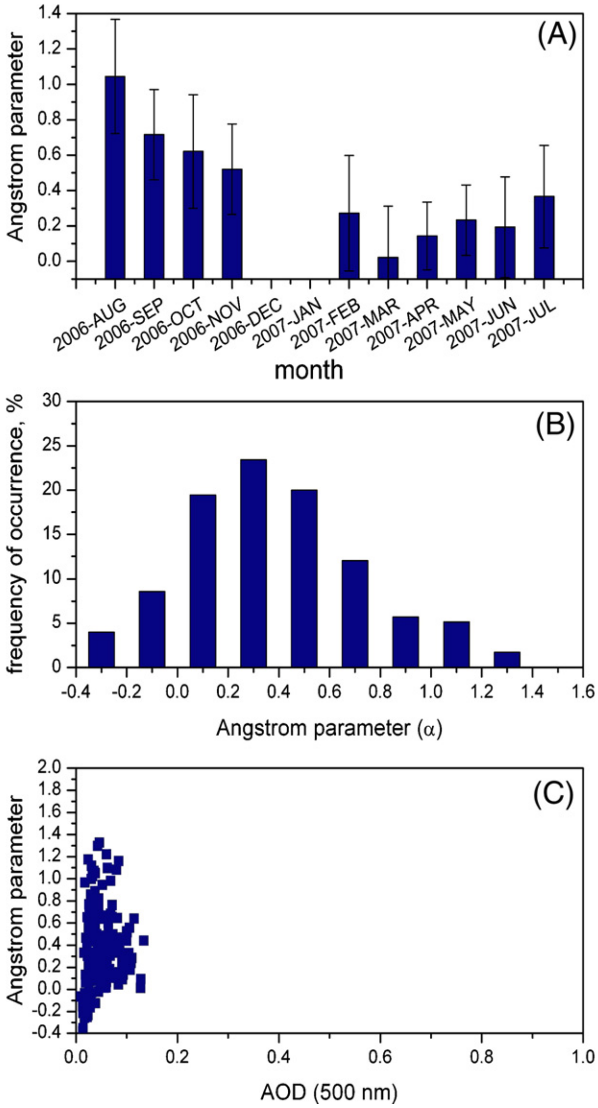

Fig. 5. Mean monthly values of Angstrom parameter (A), frequency of occurrence of Angstrom parameter (B), and scattergram of Angstrom parameter versus aerosol optical depth (C).

3.3. Water vapor content

Daily average water vapor content exhibits large variability, ranging from less than 0.04 to 1.03 cm. Distinct seasonal variation of water vapor content was clearly from Fig. 6A, with high values during the summer monsoon season, corresponding to the influence of the Indian summer monsoon in the Nam Co region. The water vapor content derived from the sun photometer in this study was generally consistent with the simultaneous relative humidity and precipitation observed by Automatic Weather Station (AWS) at the Nam Co Station. The minimum value of WVC that occurred in winter may be partly due to the extremely low temperature from December to February, reducing the capacity of the atmosphere to contain water (Holben et al., 2001).

AOD and Angstrom parameter had little correlation with water vapor content ($R<0.2$) (Fig. 6B and C). This is similar with some sites in AERONET (Holben et al., 2001; Smirnov et al., 2002; Xia et al., 2004), suggesting hygroscopic growth of aerosols is insignificant.

3.4. Aerosol size distribution

The average aerosol columnar volume size distributions (based on daily results) derived from the sky radiance for

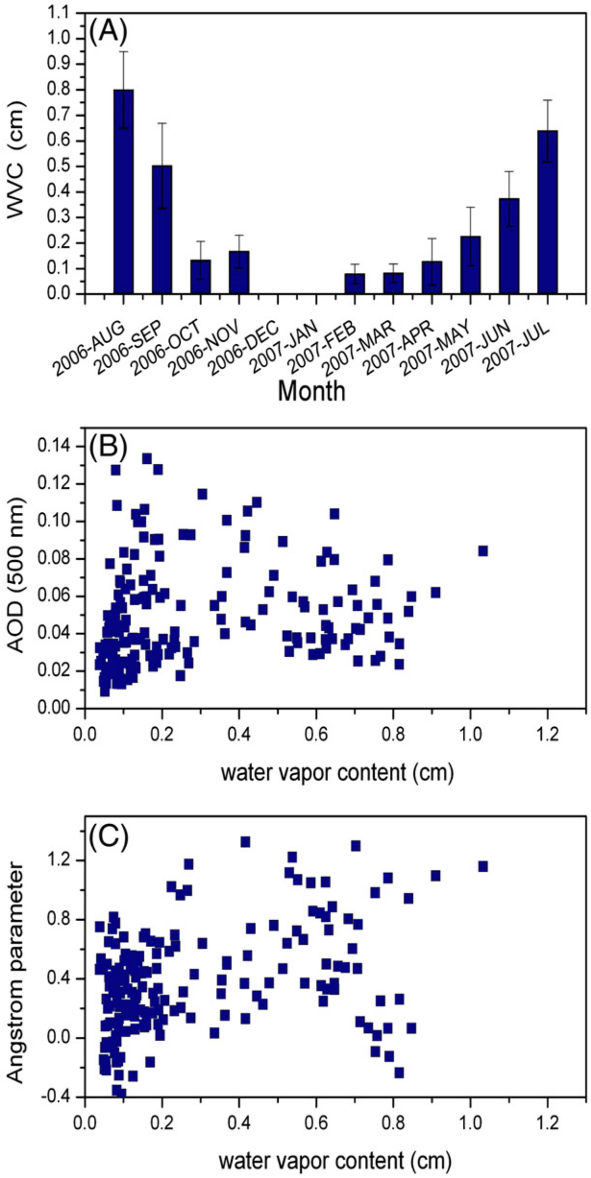

Fig. 6. Monthly mean values of water vapor content in the air (A), scattergram of AOD versus water vapor content (B), and scattergram of Angstrom parameter versus water vapor content.

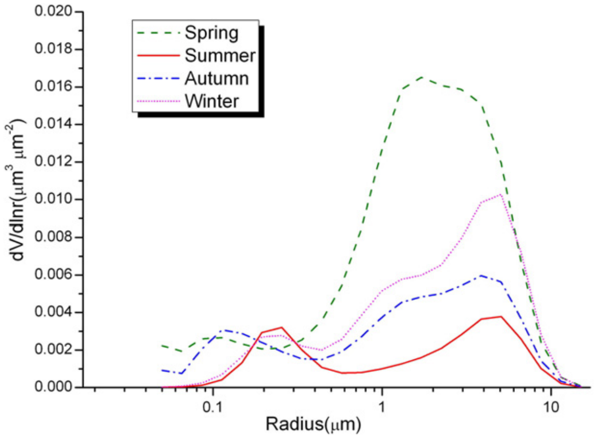

Fig. 7. Seasonal characteristics of volume size distribution derived from the sky radiances at Nam Co Station.

different seasons are presented in Fig. 7. Except for spring, the other seasons all show obvious bimodal aerosol volume size distribution, implying both fine and coarse particles exist. For autumn and winter, the size distribution curves exhibit an accumulation mode with radius 0.2–0.3 μm and a coarse mode around 5 μm, likely representing the background condition at Nam Co. Dramatic increase of volume size concentration for coarse particles during the spring (approaching 0.017 $\mu m^3\ \mu m^{-2}$) was due to the predominant contribution of soil dust particles, with a mode radius at 1–4 μm. In contrast, during summer a relative increase in the fine fraction presented with a decrease in the coarse fraction. The volume fraction of the fine mode ($r<0.6$ μm) was close to that of the coarse mode ($r>0.6$ μm), indicating the higher loading of anthropogenic particles and less of soil dust.

4. Conclusions

Measurements of aerosol optical properties were made with AERONET sun/sky radiometers at the Nam Co Station, a remote high elevation site in central TP from August 2006 to July 2007. Based on the one year observation, the general characteristics and seasonal variation of AOD, Angstrom parameter, water vapor content and volume size distribution were derived.

Predominant daily measurements of AOD (>95%) at Nam Co Station below the background level (τ_a 500 nm<0.1), representing one of the most pristine site in the AERONET network. In summer, some daily AOD (500 nm) were larger than 0.1, which may be associated to the increase of local vehicles or atmospheric pollutants transported by the Indian Monsoon during summer. However, considering the highest AOD values in the Nam Co region are less than 0.14 and just occurred on limited days, it appears that the influence by long-rang atmospheric transport from South Asia is insignificant. It was also found the AOD produced by AREONET measurement in this study (annual mean value 0.05) is significantly lower than simultaneous MODIS observation. This comparison could provide further insight into the improvement of satellite retrieval products in the future.

The WVC has a clear seasonal pattern with maximum values in summer and minimum values during autumn and winter, which is consistent with the meteorological record by AWS and reflects the reliability of the WVC retrieval method.

The volume size distribution of aerosols is bimodal except for spring. In spring, the aerosol loading was dominated by soil dust particles, while in summer, the ratio between fine and coarse fraction changes dramatically, accompanied with increasing contribution of anthropogenic aerosol and less influence of dust.

Generally speaking, Nam Co region could represent a clean continental background site for atmospheric composition investigation. This work could enhance our knowledge on the aerosol distribution over the TP and helpful for the modeling of climate change and validation of satellite remote sensing products.

Acknowledgments

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