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Aerosol radiative properties in the semiarid Western United States

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Abstract

Characterization of aerosol optical properties, such as aerosol optical depth, Angstrom exponent, and volume size distribution at the semiarid site of Tombstone Arizona (31°23′ N, 110°05′ W, 1408 m) will be presented for one annual cycle. In this region, extensive observations of selected optical parameters such as aerosol optical depth (AOD) have been made in the past and reported on in the literature. Less is known about other optical characteristics that are important in climate modeling and remote sensing. New observational techniques and inversion methods allow for the expansion of the earlier information. Observations have been taken with a state of the art sun photometer for a 1-year period and their analysis will be presented here. Monthly mean AODs at 500 nm were found to be in the range of 0.03–0.12; the monthly mean Angstrom exponent ranged from 0.9 to 1.6, being higher in spring and summer and lower in late fall and winter. Volume size distributions exhibit clear dominance of smaller particles, with a gradual increase in size from winter to spring and into summer. Annual variation of the radii of the smaller and the larger particles ranged between 0.05–0.4 and 4–8 μm, respectively. Radiance measurements at 940 nm were used to estimate precipitable water. The retrieved values compared within limits of uncertainty with independently derived estimates from the National Center for Environmental Prediction (NCEP) regional weather forecast model. An interesting outcome from

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this study was the consistency found in aerosol optical depths as observed in this study and those derived about two decades ago.

Keywords: Aerosols; Aerosols in semiarid region

1. Introduction

Tropospheric aerosols have an important effect on climate and there is a need to represent them realistically in climate models. They scatter and absorb the irradiance (direct effect) and can enhance or inhibit cloud formation (indirect effect; Vogelmann et al., 2003). Their radiative effects are frequently compared to the more widely available estimates of the radiative forcing of greenhouse gases (IPCC, 1996). At present, most of the information on aerosol properties comes from sparse ground observations. Satellite observations are well suited for retrieval of aerosol optical properties, and many such attempts have proven to be feasible over the oceans (Husar et al., 1997; Stowe et al., 1997; Nakajima and Higurashi, 1998; King et al., 1999). Over land, the retrieval problem is more difficult due to the large signal from the land surface, when compared to the atmospheric aerosol signal, and the large spatial variability of the aerosols. Observations from current satellite missions, such as MODIS (King et al., 2003), which is part of the EOS TERRA and AQUA missions, are expected to be useful for deriving such information over land (Chu et al., 2002; Gatebe et al., 2001; Remer et al., 2002). Ground truth on the seasonal and annual variation of aerosol optical characteristics over different environments is needed for evaluation of satellite retrievals: for ensuring realistic representation in climate models and for the assessment of anthropogenic impacts. The objective of this study was to obtain such information for an entire annual cycle for a semiarid region, which serves as a validation site for many national research efforts (Goodrich et al., 2000; Pinker et al., 2000).

2. Experimental site and instrumentation

An automatic sun-tracking sky radiometer of the CIMEL type (Model CE 318) was set-up during 1997 at the USDA-Agricultural Research Service Walnut Gulch Experimental Watershed (Goodrich and Simanton, 1995) near Tombstone, Arizona and was integrated into the AERONET network. The CIMEL sky radiometer is capable of measuring both sun and sky radiance at eight spectral channels, providing information needed to derive aerosol optical properties and total column water vapor. The sensor head is equipped with 2 collimators for the measurement of solar and sky radiance, and eight ion-assisted deposition filters centered at wavelengths 340, 380, 440, 500, 670, 870, 940, 1020 nm are located in a filter wheel which is driven by a stepper motor. The observation routine, radiometer precision, calibration procedures, data transmission and processing methods are described in Holben et al. (1998, 2001).

Tombstone was a focal point of the Semi-Arid Land–Surface–Atmosphere (SALSA) activity which was a multiagency, multinational global change effort that seeks to evaluate the consequences of natural and human-induced changes in semiarid environments (Kustas and Goodrich, 1994; Moran et al., 1994; Janetos, 1997; Pinker et al., 2000; Goodrich et al., 2000). SALSA was also associated with various remote sensing technology development Programs, such as NASA-EOS, ASTER, ERS-2, SPOT4, ADEOS and MODIS. Observations from these platforms are being used to develop methodologies to accurately represent surface energy fluxes from local to regional scales in order to learn how LANDSAT thematic mapper (TM), and radar (ERS-2 SAR) measurements can be combined to improve regional estimates of surface soil properties; and how satellite-sensed surface thermal data can be assimilated into atmospheric models to improve partitioning of surface energy fluxes. It is also anticipated that the SALSA-related activities will play a major role in several larger programs, such as the GEWEX Continental-Scale International Project (GCIP) and the Climate Variability and Predictability (CLIVAR) programs, aimed at a better understanding of the American Monsoon and its relation to global climate. Therefore, information on the optical characteristics of aerosols in this region is of considerable relevance to the various programs.

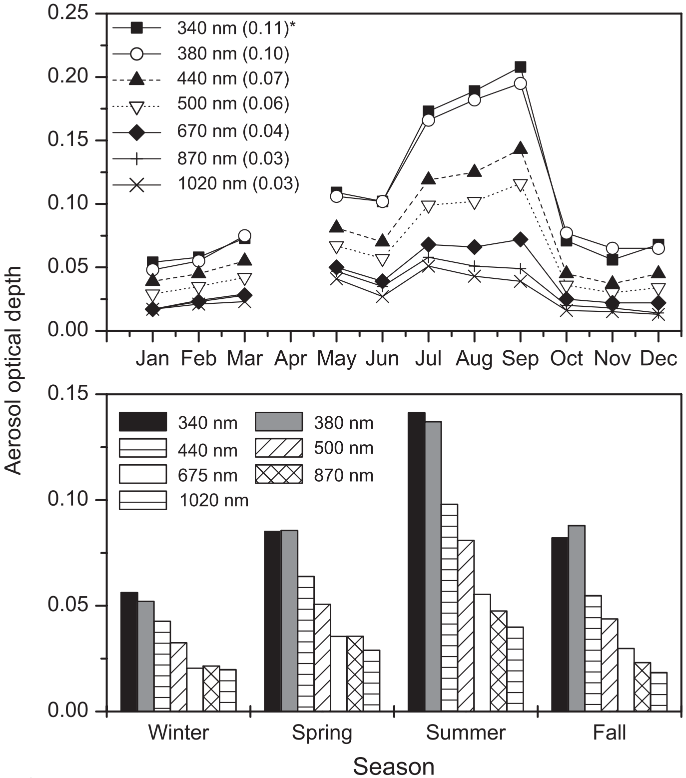
3. Data and analysis

Measurements from about 227 days of direct and diffuse sky radiances from January to December of 1997 are used in the present study (instrumental problems occurred in April). Data were cloud screened and quality controlled beyond the routine operational cloud screening protocol of AERONET (Smirnov et al., 2000). Detailed information on measurement protocol, radiometric precision, calibration procedures and processing methods are described in Holben et al. (1998). Spectral dependence of aerosol optical depth (AOD) contains information about the size of the particles (Junge, 1955; Remer et al., 1999). The volume size distribution was retrieved from the direct solar and diffuse sky radiance measurements as discussed in Dubovik and King (2000). Briefly, in the aerosol scattering model used in the retrieval algorithm, it is assumed that the aerosols are composed of spherical and homogeneous particles, scattering is simulated using Mie formulation and multiple scattering effects are also accounted for. In the retrieval procedure, the radiative properties of the atmosphere are determined by the particle size distribution of the aerosol in the total atmospheric column and the complex index of refraction. The inversion of measured radiance to particle size and index of refraction by the scattering model is done as a simultaneous search for the best fit of sun radiance and the angular distribution of sky radiances measured at four wavelengths (0.44, 0.67, 0.87 and 1.02 μm). Assessment of retrieval accuracy of the aerosol optical properties from sun and sky radiance measurements by this method can be found in Dubovik et al. (2000a).

4. Results and discussion

4.1. Monthly variation of aerosol optical depth

Monthly and seasonal variations in AOD are illustrated in Fig. 1, indicating high values during summer and lower values during the winter months. Values in parentheses indicate annual mean AOD observed over Tombstone. It was found that AODs increase during spring and summer and decrease during fall and winter. Chemical characterization of aerosols near the experimental station (Mt. Lemmon, Arizona) were made by Ohta et al. (1996) who reported high sulfate, ammonia and gaseous HNO_3 concentrations during summer which would explain the observed high AODs during this season. Moreover, during summer, winds blow from the west and the air is hot and dry, thus inhibiting cloud and rainstorm development (Badandangon et al., 1991). The total uncertainty in AOD retrievals for a well-calibrated instrument is stated to be <0.01 for l >440 nm and <0.02 for shorter wavelengths (Holben et al., 1998). Observed AODs were compared with historic data obtained during 1975–77 over Tucson, Arizona (King et al., 1980) at three nearby wavelengths (Fig. 2). At Tombstone, at the Walnut Gulch Watershed, located about 75



* Annual Means

Fig. 1. Monthly (upper) and seasonal (lower) variation in spectral aerosol optical depths (AODs) as observed with a CIMEL sky radiometer at Tombstone, Arizona during 1997.

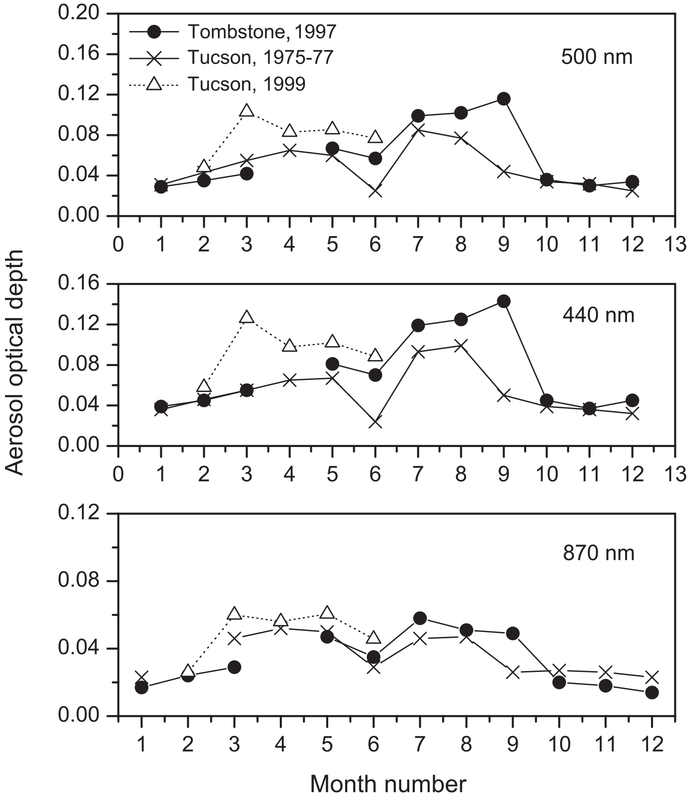


Fig. 2. Comparison of spectral AODs over Tombstone with measurements made in Tucson, Arizona.

miles southeast from Tucson, in a sparsely populated area, the mean annual temperature is 17.6 °C, mean annual precipitation is approximately 330 mm and the elevation is about 1350 m. At Tucson, the average annual temperature is 19.9 °C, the average annual precipitation is 290 mm at an elevation of 790 m.

4.2. Angstrom exponent

The spectral dependence of aerosol optical thickness is represented by the Angstrom exponent (Angstrom, 1964; Eck et al., 1999; Reid et al., 1999) as:

$$\tau_a(\lambda) = K\lambda^{-\alpha}$$

where $\tau_a(\lambda)$ is the spectral aerosol optical thickness, λ is the wavelength, K is called the turbidity coefficient and α is the Angstrom exponent. The Angstrom exponent is a rough measure of particle size. The greater its magnitude, the greater the contribution of smaller particles to the overall particle distribution. The α parameter was computed for each observation by fitting a power-law to the AOD as a function of wavelength. Monthly means of the Angstrom exponent are illustrated in Fig. 3. They exhibit higher values

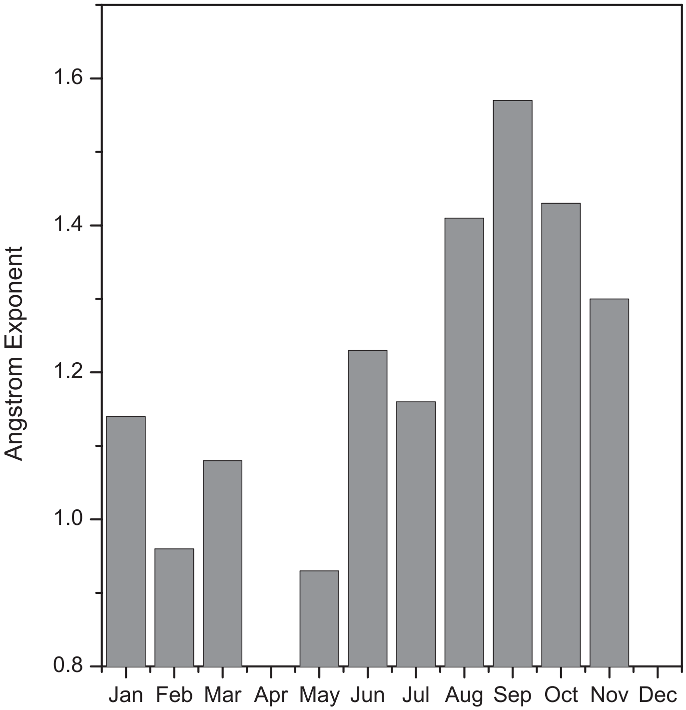


Fig. 3. Monthly mean variation in the Angstrom exponent as observed at Tombstone, Arizona.

during the summer months, which suggests an abundance of submicron-sized particles which can be clearly observed from the monthly mean volume size distribution retrieved from direct and diffuse sky measurements (Fig. 4).

4.3. Monthly variation in size distribution

Volume size distributions were retrieved from sun/sky radiance using the method developed by Dubovik and King (2000) and are grouped into monthly means (Fig. 4). The inversion algorithm of Dubovik and King (2000) allows the simultaneous retrieval of the particle size distribution and complex refractive index from spectral optical thickness measurements combined with the angular distribution of sky radiance measured at different wavelengths. The size distributions [both accumulation (0.1–1.0 μm) and coarse (1.0–100 μm) modes] are lower during November–December and then grow consistently and peak during July–August. A shift in the accumulation mode radius from 0.3 (November) to 0.05 (May) μm is also noticed. In a previous study over Mt. Lemmon, Arizona by Ohta et al. (1996), it was reported that the monthly mean total particulate mass (TPM) ranged from 0.64 to 3.49 μg m^{-3}, with high values in spring and summer and low values during fall and winter. They also reported monthly mean concentrations of individual species such as elemental carbon, organics, SO_4^{2-}, Cl^-, NO_3^-, NH_4^+ which clearly explains the increase in accumulation mode particles observed during spring and

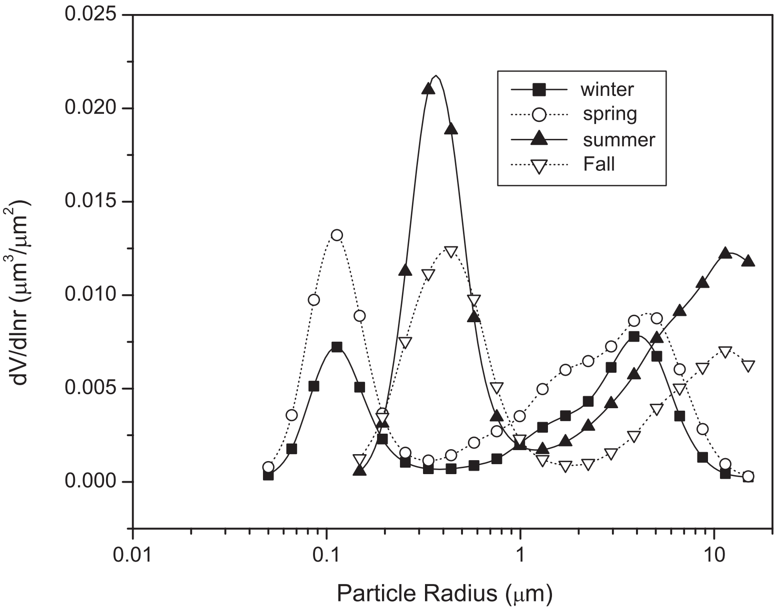


Fig. 4. Monthly mean size distributions retrieved with Dubovik and King (2000).

summer. It should be noted that the effective radius of accumulation mode particle increased with increasing AOD (Remer and Kaufman, 1998), an important information to consider for building a semiarid aerosol model for use in remote sensing. Accuracy assessments of the inversion code used are presented in Dubovik et al. (2000). Briefly, the effects of both random measurement errors and possible systematic offset originating from instrument degradation or calibration uncertainty was tested for several optically distinct aerosol models. For example, for desert aerosols dominated by coarse particles, it is reported that the volume size distribution given as $dV(r)/d\ln r$ has an error of 15–25% for $r \geq 0.5$ μm.

4.4. Precipitable water vapor

Precipitable water vapor was retrieved using direct solar measurements obtained at the water vapor absorption band (940 nm) and an adjacent nonabsorbing band (870 nm), using a modified Langley technique (Reagan et al., 1992; Bruegge et al., 1992). The physical principle of this approach is based on the concept of differential solar transmission between the two bands (Reagan et al., 1992). The stated accuracy of these methods is about 10% (Reagan et al., 1995). Monthly mean values of precipitable water vapor retrieved from the CIMEL data show high values during summer (JJA) of about 1.52 cm and low values during winter (DJF) of about 0.50 cm, and intermediate values in (0.67 cm) and autumn (0.92 cm). The retrieved water vapor from the CIMEL observations was compared with the NOAA/NCEP Eta model forecast values, the only independent estimates that were available at this site (Fig. 5). In experiments designated to evaluate the

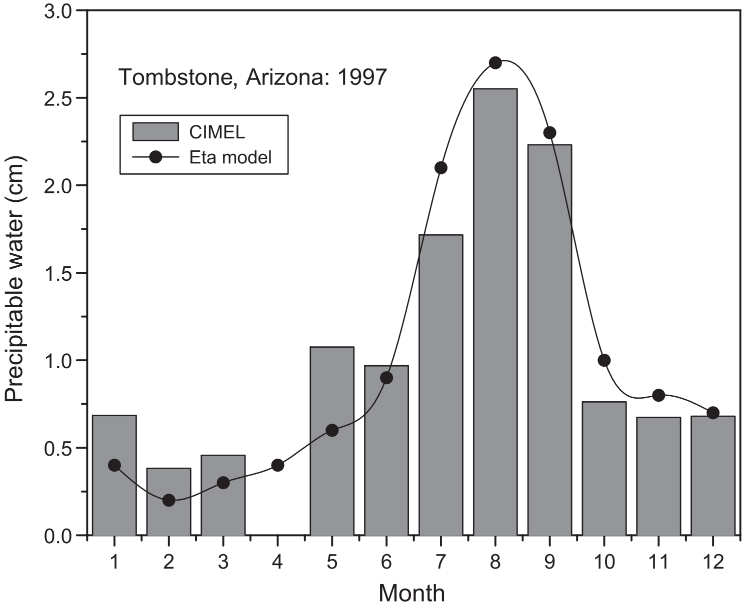


Fig. 5. Monthly mean variations in CIMEL-derived precipitable water vapor over Tombstone, Arizona and Greenbelt, Maryland. Comparison with NCEP Eta model values (●) is also presented.

accuracy of the sun photometer capabilities to retrieve precipitable water, use is made of radiosonde soundings or microwave radiometers (Michalsky et al., 1995).

5. Summary

(1) Annual means of spectral AOD are found to be low over this semiarid region and they agree well with historic data collected two decades ago at a nearby location.
(2) Significant month-to-month variations in volume size distribution, and, in particular, considerable variation in accumulation mode particles is evident.
(3) Monthly means of the Angstrom exponent are found to be higher during summer, suggesting an abundance of submicron-sized particles.
(4) Precipitable water vapor retrieved from the 940-nm channel showed a minimum of ~0.4 cm in February and a maximum of 2.5 cm in August. These values were compared with NOAA/NCEP Eta model forecast values and found to be in good agreement.

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