Advances in Geosciences
Vol. 16: Atmospheric Science (2008)
Eds. Jai Ho Oh *et al.*

AEROSOL MEASUREMENTS OVER SOUTH AFRICA USING SATELLITE, SUN-PHOTOMETER AND LIDAR

VENKATARAMAN SIVAKUMAR*,†, MELAKU TESFAYE*,
WONDIMU ALEMU**, AMEETH SHARMA, CHRISTOPH BOLLIG
and GIZAW MENGISTU**
National Laser Centre, Council for Scientific and Industrial Research,
P.O. Box 395, Pretoria, South Africa
†*svenkataraman@csir.co.za*

**Department of Geography, Geoinformatics and Meteorology,*
University of Pretoria, Lynnwood Road 0002, South Africa

***Department of Physics, Addis Ababa University,*
P.O. Box 1176, Addis Ababa, Ethiopia

In this study, we present the climatological picture of aerosols over South Africa using 20 years of Stratosphere Aerosol and Gas Experiment (SAGE-II) satellite, 6–10 years of AErosol RObatic NETwork (AERONET) and ground based mobile LIDAR datasets The climatological variation of aerosol concentration indicate minimum during winter and maximum over September months. The satellite and ground based measurements are found to be in good agreement with each other. The study affirms the presence of fine and accumulation mode aerosols over industrial areas of South Africa.

1. Introduction

Aerosols (solid particles suspended in the air) play an important role in the global climate, the radiative forcing of the climate, and the Earth's radiative balance. The interaction between atmospheric aerosol and incoming solar radiation influences the radiative forcing which in turn affects temperature. Aerosols can also have a significant impact on visibility and air quality, with potential economic consequences for tourism, cloud formation, meteorology, and climate. Aerosol particles are a largely natural, though highly variable component of our atmosphere. This is due to widely varying aerosols microphysical properties, such as their sources, sinks and loading, composition, size distribution, chemical interaction, life time and diurnal variation in space and time. Atmospheric aerosols originate from anthropogenic (human) activities such as biomass burning and industrial pollution as well as from natural processes, such as wind generated dust and sea spray, volcanic eruptions and smoke from natural forest fires, etc.

The knowledge of aerosol characteristics at a local and global scale, their temporal change interrelations with other atmospheric parameters and with solar radiation is of great importance for atmospheric research. Improved aerosol climatology may enable more accurate estimations of the direct and indirect aerosol forcing [1, 2]. The aerosol optical depth (AOD), which is an indicator of the aerosol loading in the vertical column of the atmosphere, constitutes the main parameter to assess the aerosol radiative forcing and its impact on the climate. The rationale for analyzing the Angstrom exponent (α) which is important in the interpretation of these datasets and in providing further information on the particle size. The values of both parameters exhibit strong depends on the amount of aerosols of different sizes and number concentration — their chemical composition and the wavelength of the incident radiation. It is critical that scientists continue to gather information about aerosols, especially in the Southern hemisphere regions [3]. In and around Southern Africa, major cities produce large amounts of aerosols as a result of industrial activities and automobile emissions, in addition to the natural bio-mass burning, volcanic eruptions and desert dust (Sahara in North Africa).

In this paper, we present our results over Southern Africa regions based on ground based and space borne datasets. It includes the data obtained from (a) Stratosphere Aerosol Gas Experiment (SAGEII), (b) Sun-Photometer measurements through AEROsol NETwork (AERONET) programme and (c) mobile LIDAR (LIght Detection And Ranging) system operational at the Council for Scientific and Industrial Research (CSIR) National Laser Centre (NLC), Pretoria (25°5°S; 28°2°E), South Africa.

2. Data

2.1. *SAGE-II data*

SAGE-II was launched into orbit aboard the Earth Radiation Budget Satellite in October 1984. The SAGE-II instrument vertically scans the limb of the atmosphere during sunsets and sunrises (15 observations) each day. During each sunrise and sunset encountered by the orbiting spacecraft, the instrument uses the solar occultation technique to measure attenuated solar radiation through the Earth's limb in seven channels centered at wavelengths ranging from 0.385 to 1.02 μm. The exo-atmospheric solar irradiance is also measured in each channel during each event for use as a reference in determining limb transmittances. The transmittance measurements are inverted using the "onion-peel" approach to yield 1 km vertical resolution profiles of aerosol extinction, ozone, nitrogen dioxide, and water vapour [4, 5]. The SAGE-II instrument has collected vertical profiles of stratospheric and troposphere aerosol extinction at four wavelengths (0.385, 0.453, 0.525, and 1.02 μm) with high resolution since the program's inception in October 1984. Near-global coverage 80°S to 80°N was achieved over time spans of about 1 month. The instrument mission was terminated on 8 September 2005. For clear geographical observation of the trend of aerosols, we have extracted the aerosol parameter; the aerosol extinction coefficients derived from version 6.20 series of 21 years (1984–2005) of data over southern Africa region (Latitude, 15°S to 40°S and 10°E to 40°E and Longitude).

2.2. *Aeronet*

Aerosol Robotic Network (AERONET) is a federation of ground-based remote sensing aerosol network which provides a long-term, continuous and readily accessible public domain database of aerosol optical, microphysical and radiative properties for aerosol research and characterization, validation of satellite retrievals, and synergism with other databases (www.aeronet.gsfc.nasa.gov). Basically, it uses the sun-photometer at different wavelengths to obtain aerosol microphysical and radiative properties. AERONET collaboration provides globally distributed observations of spectral AOD, Angstrom exponent, inversion products, and perceptible water in diverse aerosol regimes [6, 7]. The present study examines the climatology of aerosols over South Africa (three sites) for a longer period of data (see Table 1) over selected locations characterized by differing environments, and influenced by various air masses, anthropogenic activities and natural sources. From seven South African AERONET sites

Table 1. Quantity of data used in three selected South African AERONET sites.

Site and Location	Data used
Skukuza (24 S, 31 E)	January 1998–December 2008
Johannesburg (26 S, 28 E)	January 2002–December 2008
Bethlehem (28 S, 28 E)	January 1996–December 2001

selection of three stations were based on the criterion of the availability of enough (6–10 years) cloud-screened and quality-assured (level 2.0) aerosol data.

2.3. *LIDAR*

CSIR-NLC mobile LIDAR is also used for the present study. A neodymium-doped yttrium aluminium garnet (Nd:YAG) laser, which is presently employed at the second harmonic (532 nm), is used for transmission at a repetition rate of 10 Hz. The receiver system employs a Newtonian telescope configuration with a 406 mm diameter primary mirror. The backscattered signal is subjected to fall on the primary mirror of the telescope and is then focused toward a plane mirror kept at an angle of 45 degrees. It is detected by the Photo-Multiplier Tube (PMT) and the PMT output signal is transmitted to the transient digitizer and PC for analysis and archiving. The data acquisition is performed by a transient recorder which communicates with a host computer for storage and offline processing of data. More details about the system are available in the literature [3, 8, 9]. The LIDAR inversion technique is then applied to the signal returns in order to obtain the aerosol backscatter and extinction co-efficient. Retrieve aerosol extinction coefficients are used to determine the optical depth with SAGE-II satellite measurement and are being compared with AERONET results.

3. Results and Discussion

3.1. *SAGE-II aerosol extinction measurements*

The SAGE-II provides a height profile of aerosol extinction coefficient for the height region from 0.5 km to 40 km. We have grouped the SAGE-II retrieved profiles in terms of months to obtain the individual monthly mean aerosol-extinction profiles for the height region from 0.5 km to 40 km. The monthly mean aerosol extinction profile obtained for Southern Africa region is shown in Fig. 1. We have considered the SAGE-II profile as far as possible above 3–4 km, keeping in mind that the lower height region measurements are inaccurate due to a low signal to noise ratio (SNR) [10]. Figure 1 shows a larger extinction values during late summer periods but the accuracy of the satellite measurement is questionable at lower height regions. Relatively, it is found that the larger values below 5 km might be due to aerosol loading in the lower troposphere. The variations show a moderate value during winter

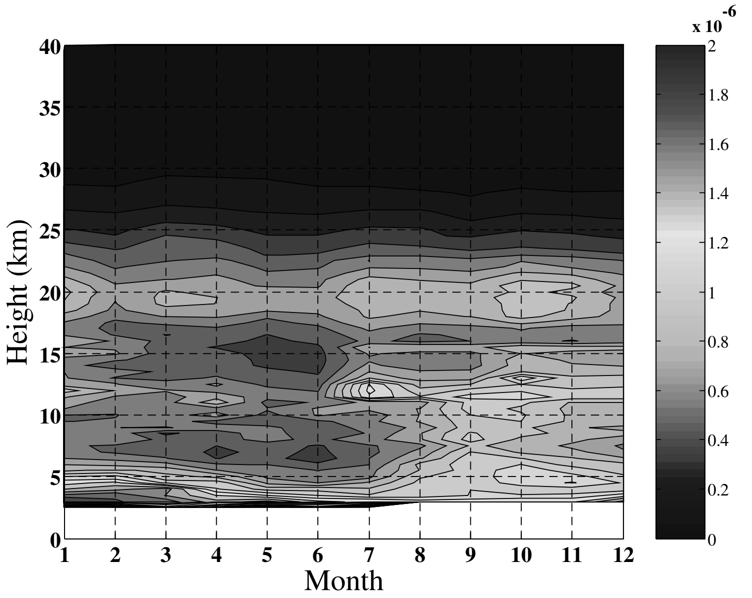

Fig. 1. Monthly variation of aerosol extinction coefficient for Southern Region of Africa, for = 525 μm.

period and enhanced values during the September month. In addition, the lower stratosphere at approximately 20 km, shows an aerosol layer (Junge layer) which is in general dominated by liquid sulfate aerosols and soot particles. This illustrates a semi-annual oscillation (SAO) with peaks during March and October months.

Aerosols at any given location in the tropics are subject to large variations by day, month and year. In order to observe the inter-annual variability of aerosols, we have studied the long-term variations in aerosol concentration based on the above 20 years of data. Figure 2 shows the lower stratosphere (18 km–21 km) aerosol extinction measured at 525 nm using SAGE-II data. Here, we have used the every-year-individual-monthly-mean datasets. Though, there are some data gaps (less than 2 months over year), we have plotted a running average on the measured data sets (solid-line). The data gaps are partly due to the satellite coverage periodicity which is generally about two months. The figure illustrates a clear annual oscillation of the aerosol concentration with a maximum during summer months (Nov–Jan) for most of the years. It also shows aerosol concentration

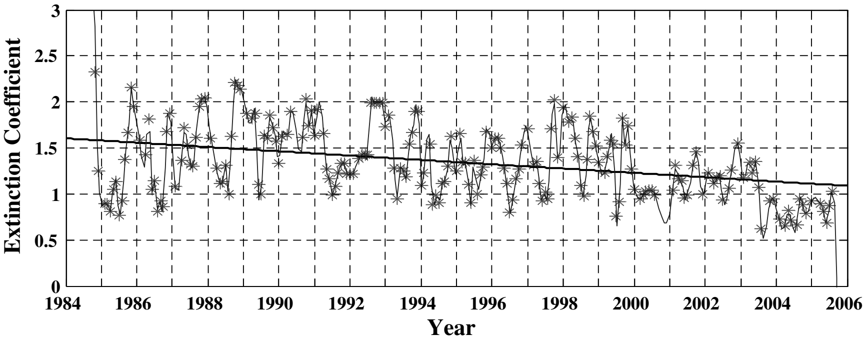

Fig. 2. Temporal evolution of lower stratosphere aerosol extinction at 525 nm over Southern Africa region and measured by SAGE-II.

has decreased in the lower stratosphere height region of ~15% over the 20-year period which indirectly reflects the loading of the aerosol concentration in the troposphere. The initial increase in aerosol concentration might due to the Pinatubo volcanic eruptions.

3.2. *AERONET — Sun photometer measurements*

In this study, we investigate the climatology of aerosols over South Africa using the monthly average AOD and Angstrom exponent (α). The AOD is obtained from direct-beam irradiance measurements measured by the AERONET sun photometer at 500 nm wavelength and the Angstrom exponent, determined from the spectral dependence of the measured optical depth, indicator of the aerosol size and its variations. Values of α approaches zero correspond to coarse-mode aerosols (sea spray and desert dust), while values of α above 1.5 indicate significant presence of fine-mode particles (mainly smoke or urban aerosols) and α is greater than 2, for very small particles in the Rayleigh limit [11].

The monthly average variation of the AOD_{500} (AOD at 500 nm) and $\alpha_{440-675}$ (Angstrom exponent (α) in the wavelength band 440 nm–675 nm) are presented in Figs. 3 and 4 for all three sites. Johannesburg and Skukuza show a clear annual oscillation (AO) with maximum values during summer (October–March) and minimum during the winter (May–July). On the other hand, the Bethlehem site illustrates a semiannual oscillation (SAO) with two maxima during March and October and minimum values during the winter period. In comparison to the three sites, Skukuza shows a larger

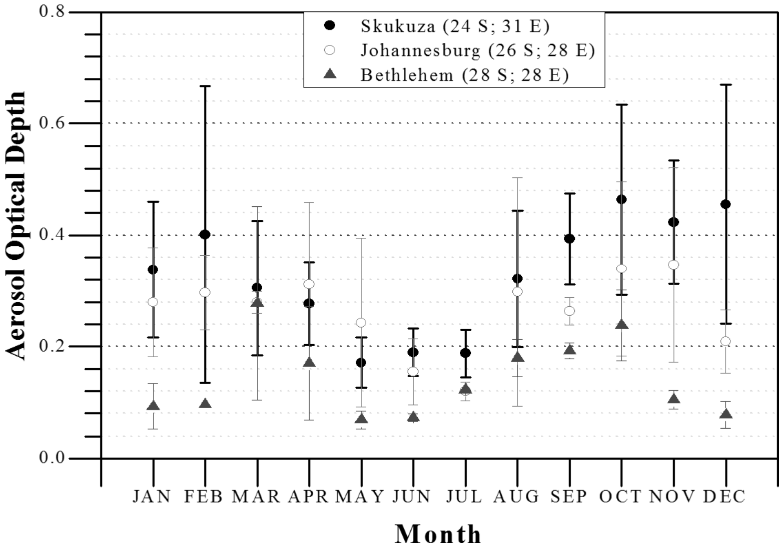

Fig. 3. A six-year's monthly average AOD_{500} over selected South Africa AERONET sites.

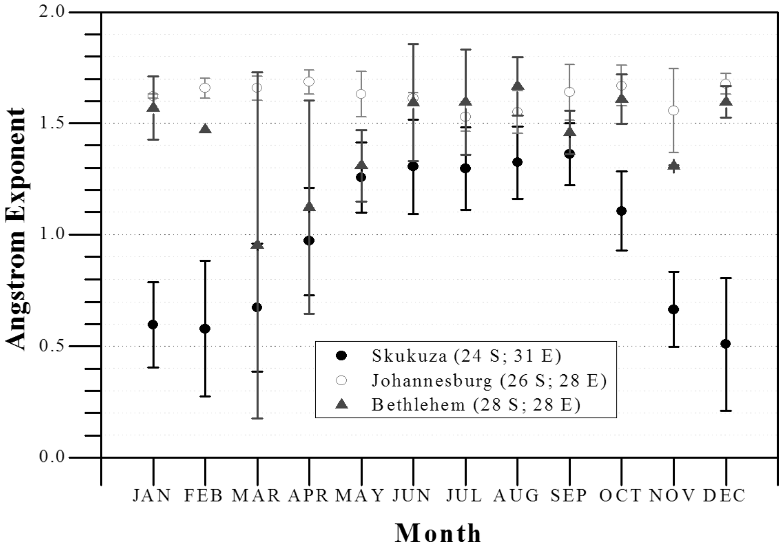

Fig. 4. Same as Fig. 3 but for Angstrom exponent for 440 nm to 675 nm wavelength regions.

AOD values, this might due to biomass burning [10, 12]. The individual monthly variations (measured interms of standard deviation) show a higher variability for Johannesburg and Skukuza than Bethlehem.

The interesting result from the determination of the Angstrom exponent in the selected wavelength regions (Fig. 4, Bethlehem and Johannesburg regions), indicates that the relative influence of fine and accumulation-mode aerosols in the VIS band is much more sensitive to scattering and/or absorption of solar and terrestrial radiation than coarse-mode aerosol particles. Furthermore, the interpretation of the information contained in monthly mean values of $\alpha_{440-675}$ based on a reported studies [11, 13] shows a higher α value in the longer wavelengths which illustrates anthropogenic combustion processes mainly resourced from the fossil fuels or urban/industrial aerosols. This explains the dominance of fine and accumulation mode particles over those regions. At the Skukuza site, the Angstrom exponent value is less than 1 which indicates the significant presence of coarse-mode particles. Short and long-range transport hygroscopic aerosols, combustion processes and their interaction with atmospheric moisture results in dominant coarse-mode particles.

3.3. *LIDAR measurements*

The extinction profile was derived from the LIDAR and compared/validated using ground based and satellite borne instruments. Figure 5 presents the height profile of the extinction coefficient derived from the LIDAR data taken during the nights of 23 February 2008. The profiles are overlapped by the Stratosphere Aerosol Gas Experiment (SAGE-II) extinction data at 525 nm collected over southern Africa regions. Here, we have used the corresponding monthly-mean extinction profiles (February). The extinction profiles derived from LIDAR and SAGE-II are in close agreement with respect to trend and magnitude. The LIDAR profile has been terminated above 4 km due to thick cloud passage. One is able to observe the boundary layer peak at ∼2.5 km which is considered an important parameter for model and atmosphere mixing (including pollutants). The presence of a cloud results in a sharp enhancement in the extinction and backscatter co-efficient to a high value making the detection quite unambiguous.

The above mentioned height profile of aerosol extinction coefficients obtained using the LIDAR and SAGE-II satellite data are integrated appropriately to get the aerosol optical depth. Generally, we considered

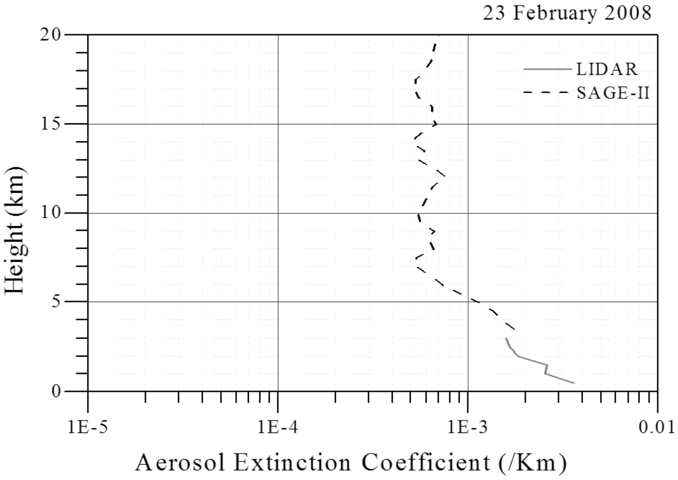

Fig. 5. Height profile of aerosol extinction derived from LIDAR signal returns and SAGE-II satellite data.

the LIDAR profile for the lower height region with respect to the SNR and at higher altitudes from the SAGE-II data. We found the value for February months is around ∼0.224 and for April about 0.3227 which is in good agreement with AOD measured by the photometer over Johannesburg. The values are within the variations of the AOD reported (February: 0.2966 ± 0.06668 and April: 0.31234 ± 0.14707).

4. Future Perspectives and Concluding Remarks

The monthly variations of aerosol concentration over South Africa are moderate during the winter period and enhanced during the September month. The annual average values of AOD and Angstrom exponent climatology indicate that the urban/industrial areas of South Africa are dominantly loaded by fine and accumulation-mode aerosols produced from urban/industrial or biomass-burning activities. The measured aerosol optical depth by combined LIDAR and SAGE-II satellite are in good accordance with the value measured by sun-photometer.

Long-term observations from satellite remote sensors, complemented by LIDAR and *in-situ* measurements, significantly improve our understanding of the climatology of stratospheric and troposphere aerosols over Southern Africa regions.

Acknowledgments

The authors are also grateful to the different South African funding agencies: Council for Scientific and Industrial Research-National Laser Centre (CSIR-NLC), Department of Science and Technology (DST), National Research Foundation (NRF) (Grant no: 65086) and the African Laser Centre (ALC). We also express our thanks to SAGE-II, AERONET and radiosonde data centres for providing access to the required data.

References

1. Y. J. Kaufman, D. Tanrè, L. Remer, E. Vermote, A. Chu and B. N. Holben, *J. Geophys. Res.* **102** (1997) 17051.
2. M. Masmoudi, M. Chaabane, D. Tanré, P. Gouloup, L. Blarel and F. Elleuch, *Atmos. Res.* **66** (2003) 1.
3. V. Sivakumar, M. Tesfaye, W. Alemu, D. Moema, A. Sharma, C. Bollig and G. Mengistu, *South African J. Science* (2010), in press.
4. W. Chu, M. McCormick, J. Lenoble, *J. Geophys. Res.* **94** (1989) 8339.
5. L. Thomason, L. Poole and C. Randall, *Atmos. Chem. Phys.* **7** (2007) 1423.
6. B. N. Holben, T. F. Eck, I. Slutsker, D. Tanré, J. P. Buis, A. Setzer, E. Vermote, J. A. Reagan and Y. A. Kaufman, *Rem. Sens. Environ.* **66** (1998) 1.
7. B. N. Holben, D. Tanre, A. Smirnov, T. F. Eck, I. Slutsker, N. Abuhassen, W. W. Newcomb, J. Schafer, B. Chatenet, F. Lavenue, Y. J. Kaufman, J. Vande Castle, A. Setzer, B. Markham, D. Clark, R. Frouin, R. Halthore, A. Karnieli, N. T. O'Neill, C. Pietras, R. T. Pinker, K. Voss and G. Zibordi, *J. Geophys. Res.* **106** (2001) 12067.
8. A. Sharma, V. Sivakumar, C. Bollig, C. Van der Westhuizen and D. Moema, *South Africa J. Science* (2010), in press.
9. V. Sivakumar, A. Sharma, D. Moema, C. Bollig, C. Van der Westhuizen and H. van Wyk, *Proc. 24th Int. Laser Radar Conf.*, Boulder, Vol. 99 (2008).
10. P. Formenti, H. Winkler, P. Fourie, S. Piketh, B. Makgopa, G. Helas and M. O. Andreae, *Atmos. Res.* **62** (2002) 11.
11. T. F. Eck, B. N. Holben, D. E. Ward, O. Dubovic, J. S. Reid, A. Smirnov, M. M. Mukelabai, N. C. Hsu, N. T. O' Neil and I. Slutsker, *J. Geophys. Res.* **106** (2001) 3425.
12. S. Generoso, F.-M. Breon, Y. Balkanski, O. Boucher and M. Schulz, *Atmos. Chem. Phys.* **3** (2003) 1211.
13. J. S. Reid, T. F. Eck, S. A. Christopher, P. V. Hobbs and B. N. Holben, *J. Geophys. Res.* **104** (1999) 27473.