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Aerosol spectral optical depths and typical size distributions at a coastal urban location in India

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ABSTRACT

The ground-reaching direct solar flux measurements at 9 different wavelengths in the visible and near infrared region using a ground based multiwavelength radiometer have been used to study the spectral and temporal variation of aerosol optical depths and size distribution over Visakhapatnam (17.7°N, 83.3°E), a coastal industrial location on the east coast of India. The aerosol optical depths exhibit a typical spectral variation with summer maxima at all the 9 wavelengths. The inversion of the spectral optical depths following the constrained linear inversion algorithms yielded a typical bi-modal aerosol size distribution at Visakhapatnam with the primary mode centered around 0.1 μm and the secondary mode around 0.8 μm. The observed features, when examined along with the mesoscale meteorological data have indicated a strong control of the local sources and sinks on the aerosol populations of different sizes.

1. Introduction

A variety of experiments have been conducted for studies on atmospheric aerosol properties, of which the ground based sun photometer (solar radiometer) is a simple and direct passive instrument for the estimation of the spectral optical depths of aerosols (Shaw, 1973). The height-integrated aerosol size distribution functions in the particle size range 0.1 to 10 microns can be obtained from these spectral optical depths following the constrained linear inversion techniques (Quenzel, 1970; King et al., 1978; Krishna Moorthy et al., 1991; Mukai and Seno, 1993; Huene and Wendish, 1994 and numerous others). The inverse power law function for the aerosol size distribution, first introduced by Junge (1955) and later confirmed by many others, shows a monotonic decrease in aerosol optical depths with increase in wavelength. However, later measurements at different locations showed different types of size distributions like unimodal distribution (Quenzel, 1970; Twomey, 1976) which shows a negative curvature in spectral optical depth characteristic with wavelength and a 3rd type which is a combination of the Junge type (Small particle) and unimodal (large particle) for which the spectral optical depth characteristic showed a positive curvature. Recent results suggest multimodal form of size distributions for aerosols at several locations (King et al., 1978; Hoppel et al., 1985; Krishna Moorthy et al., 1991). The spatial and temporal changes in spectral optical depths and size distributions have been studied on the basis of their association with airmass type and weather conditions and it is established that the tropospheric aerosol is strongly controlled by the local production, removal, advection, stratification and mixing.

The importance of the aerosol spectral optical depths, phase functions and the size distribution functions in the earth's radiation budget, remote sensing and climate research studies point out the need for extensive measurements of spectral

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optical depths and turbidity parameters at as many locations on the globe as possible. Though extensive measurements on turbidity parameters have been made in India using single and 3-channel Volz-sun photometers (Mani and Chacko, 1963; Anna Mani et al., 1969; Chacko and Desigan, 1967; Muralikrishnan et al., 1993), the measurements of aerosol spectral optical depths and size distributions are very few. Realizing the need for such a study, a network of multiwavelength radiometers has been established in India under the Indian middle atmosphere programme (Krishna Moorthy et al., 1993). Visakhapatnam (17.7°N, 83.3°E) on the east coast of India, is one of the stations in the network which characterizes a typical coastal industrial location. This paper reports some characteristics of the aerosol optical depths and size distributions at this location during the years 1994–1995.

2. Experiment and methodology

A set of multiwavelength solar radiometers (MWR) based on the principle of filter wheel radiometers (Shaw et al., 1973) have been developed at the Space Physics Laboratories of the Vikram Sarabhai Space Centre, Trivandrum, India and one such unit is operational at the Physics Department, Andhra University, Visakhapatnam to obtain the characteristics of atmospheric aerosols typical of a coastal industrial environment. Visakhapatnam city is located on the coast of Bay of Bengal and is surrounded by sea on the eastern and southern side. The city's industrial belt is located to the south west of the observing site (see Fig. 1). The Kailasa hill ranges of the eastern Ghats are located to the north and north west of the observing site. The MWR which measures the ground reaching direct solar flux at different wavelengths as a function of solar zenith angle essentially consists of a field limited optics unit which is made to follow the diurnal trajectory of the Sun with the help of a mechanical mount. The full details of the system are available in Krishna Moorthy et al. (1989). The measurements are made at 9 different wavelengths namely 400, 450, 500, 600, 650, 750, 850, 940 and 1025 nm by employing narrow band interference filters mounted on a filter wheel disc sequentially bringing each filter into the field of view. The filters have a pass band of 5 nm (full-width at half-maximum) with peak transmittance less than 30% at the central wavelength and are blocked from X-rays and UV to far infra red with a transmittance less than 10^{-4} in the blocking range. As shown in Fig. 2, the wavelength selected radiation is received on a Photo detector after focusing it on a pinhole with the help of an achromatic doublet. The detector used is UDT 455 Photop of the United Detector Technology which incorporates a silicon photo-diode and low drift, low noise operational amplifier of adjustable gain. The device has an active area of 5.1 mm^2 and a spectral response covering the entire spectral range of interest. The detector is operated in photovoltaic mode where it is linear about nine decades of the input radiance level. The output of the detector is acquired on a digital panel meter which is interfaced with a seven column thermal printer for recording after multiplexing with the time of observation available from the system clock and the filter identification number.

The total optical depths at each of these wavelengths have been obtained by plotting the secant of the solar zenith angle against the natural logarithm of the system output voltage and by evaluating the slope of the regression line. From these total optical depths, the aerosol optical depths have been evaluated by subtracting the Rayleigh component corrected to the surface pressure and the molecular absorption component from the wavelength dependent absorption cross sections (Krishna Moorthy et al., 1993). The altitude profile of the neutral atmosphere for the calculation of the Rayleigh optical depth is taken from the mean model atmosphere generated using the rocket data for several years from Thumba, a nearby location to Visakhapatnam (Sasi, 1994).

3. Spectral and temporal variation of aerosol optical depths

Aerosol optical depths at different MWR wavelengths have been evaluated for each day of observation on all clear sky days. Care is taken to select the data points at 99.5% confidence level by editing the data to remove wild points (Bendat and Piersol, 1971) and an iterative procedure is used to evaluate the slopes of the Langley plots through linear regression by incorporating the

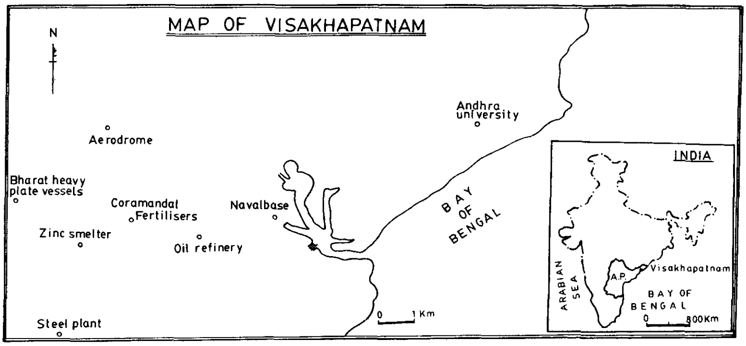

Fig. 1. Map showing the location of the observing station at Andhra University Campus in Visakhapatnam. Inset: India map showing the location of Visakhapatnam in the Andhra Pradesh (A. P.) state.

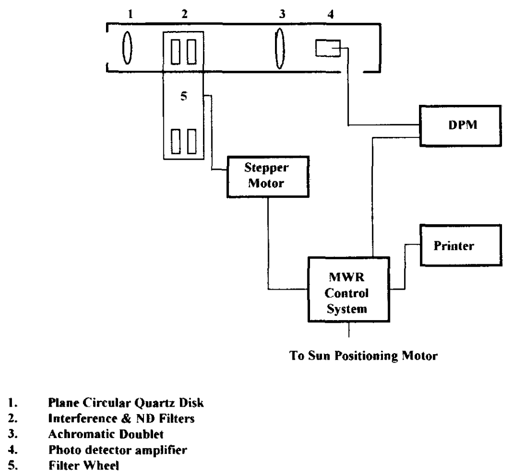

Fig. 2. The multiwavelength radiometer system block diagram.

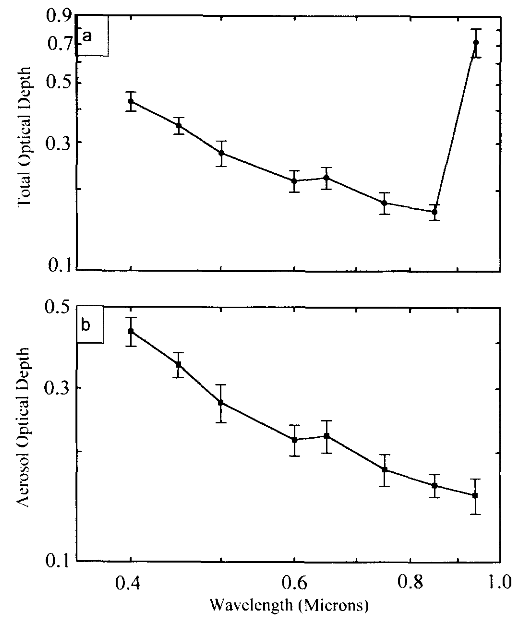

Fig. 3. Variation of aerosol optical depth as a function of wavelength (a) before correcting for water vapour absorption and (b) after correcting for water vapour absorption.

error estimates and corrections wherever necessary. Fig. 3a shows the spectral variation of aerosol optical depths for the month of January 1995 after correcting for Rayleigh optical depth and absorption due to ozone and before correcting for water vapour absorption. This shows a characteristic water vapour absorption at 940 nm, a wavelength close to the $\rho\sigma\tau$ band of water vapour absorption. The optical depths at 850, 940 and 1025 nm have been used to evaluate the contribution of optical depth due to water vapour for each day separately following the empirical transmission functions and the wavelength dependent mass absorption coefficients given by Leckner (1978). All the longer wavelengths have been corrected for water vapour absorption to arrive at the aerosol optical depths.

Fig. 3b shows the spectral variation of the aerosol optical depths after correcting for water vapour absorption. The aerosol optical depths gradually decrease from shorter wavelengths to longer wavelengths upto 600 nm. Then a small increase in optical depths is seen around 650 nm and thereafter the optical depths again decrease to a minimum at longer wavelengths. As per Junge's inverse power law distribution, there should be a gradual decrease in the aerosol optical depth with increasing wavelength. The observed spectral variation of aerosol optical depths does not show such a feature indicating that the aerosol size distribution does not follow the Junge's power law distribution at Visakhapatnam.

Fig. 4 shows the monthly mean variation of the aerosol optical depths during 1995 at three typical wavelengths namely 450, 650 and 850 nm. The seasonal variation at all the wavelengths is similar to the variation shown at these 3 wavelengths, with higher optical depths in summer months peaking around May. The optical depths are lower in winter and monsoon months. However, a small increase in the aerosol optical depths is seen around September, i.e., after the cessation of the south west monsoon and before the onset of the north east monsoon period. Table 1 gives the mean values of the aerosol optical depths for different months.

The spectral slope α (size co-efficient) and the turbidity co-efficient β are two of the few important optical parameters that characterize the shape

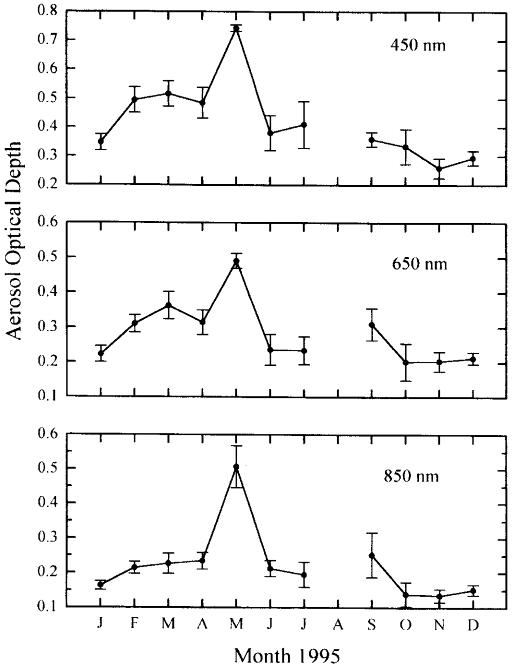

Fig. 4. Variation of the monthly mean aerosol optical depth along with standard error bars at three typical wavelengths namely 450, 650 and 850 nm.

and structure of the aerosols. α and β can be parameterised in the form of the Angstrom's power law $\tau_{p\lambda} = \beta\lambda^{\alpha}$ where $\tau_{p\lambda}$ is the aerosol optical depth at the wavelength λ. The parameters α and β have been evaluated by making a power law fit of the observed spectral optical depths for all the months and are shown in Table 1. The spectral slope α was around 1.1 during the winter and early summer, whereas it decreased suddenly during the month of May. During the monsoon period, it maintained a value around 0.8 excepting in the month of September when the south west monsoon activity is over and the north east monsoon activity is yet to start. It has been reported by Kumar (1984) that the month of May forms the most favourable conditions for the onset of sea breeze at Visakhapatnam and the sea breeze activity is seen in 80% of the days in May. As sea breeze is associated with maritime air masses, low value of α is observed in May (Huene and Wendisch, 1994). During monsoon months, when the sky conditions are clear, usually an elevated inversion layer is formed (Kumar, 1984) leading to accumulation of the urban industrial aerosol under the inversion heights. Hence α during these months is around 0.8. The turbidity co-efficient β is higher during the month of May showing higher pollution levels during the summer months as indicated by the aerosol spectral optical depths.

Large seasonal changes in the aerosol optical depths have been reported from various locations (Krishna Moorthy et al., 1989; Shiobora et al., 1991; Niranjan et al., 1995; Prabha and Krishna Moorthy 1995). The increase in the aerosol optical depths in summer with peak in May can be attributed to any of the following reasons: (1) increased aerosol input due to increased surface heating and resultant vertical mixing and dry surface conditions and wind blown dust which are important in increasing the back ground aerosol loading (2) high atmospheric water vapour content resulting in growth of particle size and high turbidities with airmasses originating from sea and blowing onshore due to mesoscale phenomena of sea breeze and (3) increased small particle loading depending on the local sources and mechanisms favourable for their transport.

Visakhapatnam, being a coastal industrial location, the aerosol optical depths are influenced by both the marine component as well as the industrial effluvia. The city's industrial belt located due

Table. 1. *Monthly mean values of aerosol optical depths and the angstrom turbidity parameters α and β at Visakhapatnam*

	Aerosol optical depth									
Month	400 nm	450 nm	500 nm	600 nm	650 nm	750 nm	850 nm	940 nm	α	β
Jan.	0.43	0.35	0.28	0.22	0.22	0.18	0.16	0.15	1.17	0.13
Feb.	0.54	0.50	0.38	0.30	0.31	0.23	0.22	0.21	1.19	0.18
Mar.	0.55	0.52	0.41	0.29	0.36	0.23	0.23	0.23	1.13	0.19
Apr.	0.57	0.49	0.38	0.27	0.32	0.25	0.24	0.22	1.08	0.19
May.	0.60	0.74	0.48	0.47	0.49	0.54	0.51	0.48	0.29	0.46
Jun.	0.42	0.38	0.24	0.20	0.24	0.21	0.21	0.22	0.75	0.18
Jul.	0.39	0.41	0.25	0.21	0.23	0.19	0.20	0.20	0.85	0.17
Sep.	0.31	0.36	0.30	0.30	0.31	0.22	0.25	0.29	0.30	0.25
Oct.	0.33	0.33	0.25	0.18	0.20	0.15	0.14	0.13	1.18	0.11
Nov.	0.24	0.26	0.21	0.16	0.21	0.14	0.14	0.13	0.83	0.12
Dec.	0.27	0.30	0.24	0.20	0.21	0.17	0.15	0.13	0.89	0.13

southwest of the observing site (Andhra University) consists of an oil refinery, a fertilizer factory, a zinc smelter, a polymer factory and a steel plant besides many other smaller units. Secondly, the location is about 500 m away from the coast of Bay of Bengal and is surrounded by sea both on the eastern and southern sides and hence is significantly effected by the land-sea air interactions. The Kailas hill ranges situated to the north and north west of the observing location act as a barrier thereby limiting the aerosol dispersion. In summer months, the surface wind speeds are highest at Visakhapatnam blowing due southwest, carrying extra small particle influx from the industrial area resulting in higher aerosol content. In addition, the high speed winds during summer may form white caps and surfs on the sea surface due to agitation resulting in sea spray. As the sea breeze, which is most probable in summer months at Visakhapatnam, is usually associated with a different type of airmass originating from sea with higher humidity, the optical depths increase due to the growth of the particle size in the humid conditions, in addition to the extra marine component brought in by the airmass.

The southwest monsoon sets in at Visakhapatnam in mid June and is effective till the end of August during which time considerable washout out takes place and hence lower extinctions are observed during the monsoon season. In addition, the station also receives significant rainfall during the northeast monsoon season (October and November) and the atmosphere is subjected to periodic cleansing during both the monsoon periods. However, during September, i.e., after the cessation of the southwest monsoon and before the north east monsoon sets in, the rainfall is usually very low and hence a small buildup in the aerosol content is observed as seen from a small increase in the aerosol spectral optical depths. Unlike in summer, the aerosol inputs due to sea spray and wind blown dust etc. are relatively weak in monsoon and winter and the aerosol size distribution is mainly governed by mixing, coagulation and sedimentation processes and hence lower optical depths are seen at all the wavelengths in winter.

4. Typical aerosol size distributions

The scattering and absorption caused by the aerosols are strongly dependent on the ratio of the aerosol size to wavelength of the radiation and the refractive index. Therefore, in order to understand the effects of aerosols on the incoming solar radiation and outgoing terrestrial radiation, it is important to characterize the aerosol size distribution. The aerosol spectral optical depths have been inverted following the constrained linear inversion method (King et al., 1978; Krishna Moorthy et al., 1991) to obtain the height-integrated columnar size distributions over Visakhapatnam. Considering the sources of aerosols around Visakhapatnam, the refractive indices have been taken from Shettle and Fenn (1979) for an aerosol composition of 20% background, 38% anthropogenic, 40% water soluble sea salts and 2% soot. A small amount of soot is added to take into account the exhausts from the oil refinery and the steel plant.

Figs. 5b, 6b and 7b show the typical aerosol size distributions for winter, summer and monsoon respectively. The top panel (a) in each of these Figs. 5, 6 and 7 shows the spectral variation of the re-estimated aerosol optical depths (solid line) along with the measured values (points with standard deviations). It may be observed that the aerosol size distribution over Visakhapatnam is consistently bi-modal in nature through out the year. The primary mode is generally centered around 0.1 μm characterizing the small particle population. The secondary mode is centered around 0.8 μm. This type of size distribution is seen all through the year excepting that the small particle mode shows a movement in the mode radius depending on the atmospheric humidity. It may also be observed that the small particle number density is more in summer compared to other seasons. Another interesting feature is the

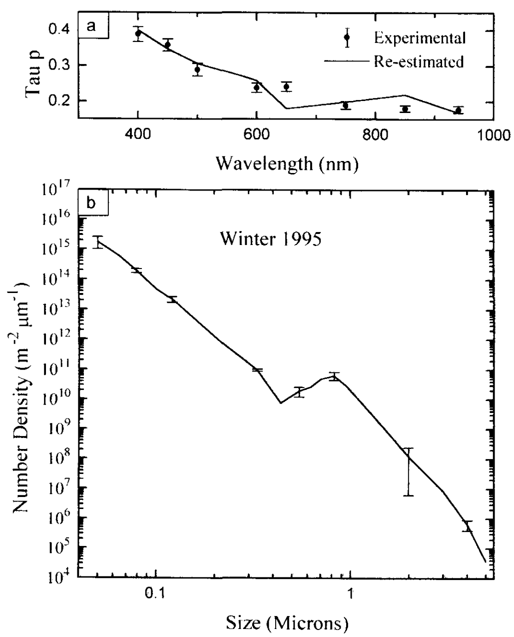

Fig. 5. Height-integrated columnar aerosol size distributions (panel b) for winter along with experimental (dots with error bars) and re-estimated (solid line) aerosol optical depths (τ p) in the top panel (a).

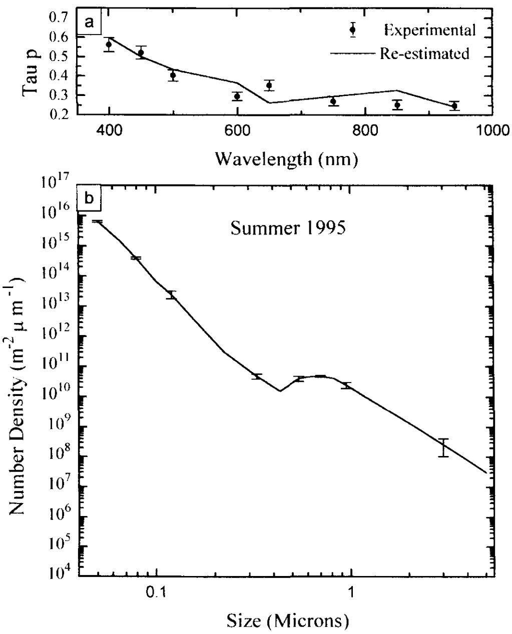

Fig. 6. Height-integrated columnar aerosol size distributions (panel b) for summer along with experimental (dots with error bars) and re-estimated (solid line) aerosol optical depths (τ p) in the top panel (a).

very slow decrease in the aerosol concentration after the secondary mode peak at 0.8 μm during summer showing a higher loading of the larger particles in this season.

The bi-modal structure of aerosol size distribution could be due to several reasons like mixing of 2 airmasses with very different aerosol populations (Hoppel et al., 1985), heterogeneous nucleation and growth of larger particles by condensation of gas phase reaction products and homogenous heteromolecular nucleation of new small particles in air initially deficient of particles. The small particles are generally produced by gas to particle conversion process and subsequent coagulation and nucleation while the larger particles are mostly generated by the bulk to particle conversion process such as sea spray and wind blown dust etc. (Prospero et al., 1983). As the present observing site is just 500 m away from the coast of Bay of Bengal, the maritime component characterizing the sea spray is always present showing up as the large particle mode in the size distribution. However, during summer, the sea breeze brings in a different airmass on shore with relatively very high humidities leading to the growth in the particle size. Thus, the secondary mode becomes much broader in summer months indicating the increase of the large particle population. Due to the proximity of the industrial area, large amounts of small particles are put into the atmosphere by the industrial effluvia by the condensation of the gas phase reaction products and hence a prominent primary mode peak at 0.1 microns. Thus a consistently bi-modal aerosol size distribution is seen at Visakhapatnam.

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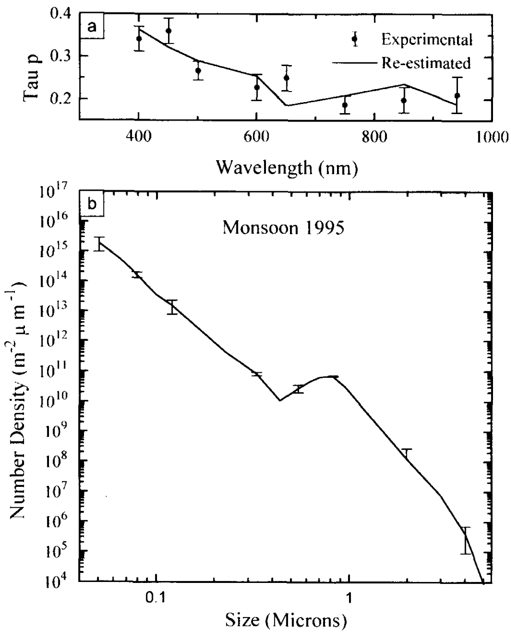

Fig. 7. Height-integrated columnar aerosol size distributions (panel b) for Monsoon along with experimental (dots with error bars) and re-estimated (solid line) aerosol optical depths (τ_p) in the top panel (a).

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