Study of aerosol optical depth and precipitable water vapour content
at Rajkot, a tropical semi-arid station

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Aerosol optical depth (AOD) at 1020 nm for the period July 2004 - July 2005 and at six different wavelengths ranging from 380 nm to 1020 nm for March-June 2005 is studied. The measurements are being made at the tropical semi-arid location Rajkot (22°18′ N, 70°44′ E, 142 m above sea level) using a hand-held microprocessor-based sun photometer, MICROTOPS-II under the aegis of ISRO’s Geosphere Biosphere Programme (IGBP). Precipitable water vapour is estimated from the measurements of solar intensity at 936 nm and 1020 nm. The AOD shows seasonal variation with high values (0.41) in summer and low values (0.11) in winter. Angstrom wavelength exponent $\alpha$ has been found to be high (0.59) during March, indicating relative dominance of accumulation-mode particles. During summer season, low value (0.25) of Angstrom wavelength exponent $\alpha$ indicates relative dominance of coarse-mode particles. The changes in the column water vapour have been found to be correlated with the changes in AOD. This is supported by the observed increase of AOD with relative humidity at high humidity values.

Keywords: Aerosol, Aerosol optical depth, Water vapour content, Tropical semi-arid station

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1 Introduction

Aerosols are tiny particles in solid or liquid phase suspended in the air. Some occur naturally, originating from volcanoes, wind blown dust, forest and grassland fires, living vegetation and sea spray. They occur over a wide range of sizes extending from $10^{-2}$µm to about $10^{2}$µm. Aerosol particles larger than about 1 µm in size are produced by wind blown dust and sea salt from spray and bursting bubbles. Aerosols smaller than 1 µm are mostly formed by condensation processes such as conversion of sulphur dioxide (SO$_2$) gas (released from volcanic eruptions) to sulphate particles and by formation of soot and smoke during burning processes. After formation, the aerosols are mixed and transported by atmospheric motions and are primarily removed by cloud and precipitation processes. Mitchell$^1$ reported that aerosols in the size range 0.1-1 µm are most effective in attenuating sunlight. Spectral attenuation due to aerosols has been studied by multiwavelength solar radiometer technique in the wavelength range of 0.1-1.0 µm at several locations in India to cover different types of environments, e.g. rural, urban, coastal, marine, etc. under IMAP programme and IGBP programme.$^{2,6}$

Rajkot (22°18′ N, 70°44′ E and 142 m above sea level) is a semi-arid suburban region near the Arabian Sea and there are no AOD measurements reported so far from this location. Probably the local aerosols are a good mixture of aerosols originating from wind blown dust, vehicular and industrial emission of smoke particles and marine aerosols. It is important to monitor the AOD at this site to delineate the aerosol characteristics. Hence, a project to study aerosols was initiated under ISRO-GBP programme in 2004 at Saurashtra University, Rajkot. The paper reports the initial results of this study.

2 Present measurements and study at Rajkot

Aerosols interact both directly and indirectly with the earth’s radiation budget and climate. They scatter and absorb optical radiation depending upon their size distribution, refractive index and total atmospheric loading. This results in attenuation (or extinction) of solar radiation reaching the earth’s surface. The attenuation can be characterized by the parameter, aerosol optical depth (AOD), which is measured here using MICROTOPS-II sunphotometer at the wavelength 1020 nm from July 2004 and at six wavelengths ranging from 380 to 1020 nm using the
same instrument from March 2005 under ISRO-GBP project. Daily monitoring of AOD estimates the variation in column concentration of aerosols over the measurement site.

3 Meteorological conditions over Rajkot during June 2004-September 2005

The variation in observed monthly mean relative humidity RH (collected from the site ‘wunderground.com’ through internet) for the period June 2004-September 2005 is shown in Fig. 1. The monthly mean RH shows peak value of about 81% in the month of August 2004. Daily data show that RH reached 98% and above, on a few days in the month of July and August 2004, when the summer monsoon is active over Rajkot. Monthly mean RH value starts decreasing after August and continuously decreases till November. In December, it shows a small increment and afterwards follows, more or less, increasing trend and regains the previous values in respective months.

Variation in monthly average surface wind speed and direction starting from July 2004 to August 2005 over this location is shown in Fig. 2. The wind speed is maximum with a value of about 6-8 m/s during months of July and August, blowing from southwest, whereas it is minimum with value of about 3-4 m/s in November and December blowing almost from east. Sometimes the wind speed reached up to 10-12 m/s in the month of May and June 2005. Monthly mean wind speed showed an almost constant standard deviation of about 2.5 m/s.

4 Instrument, experimental method and data analysis

The measurements of AOD and water vapour are being carried out using MICROTOPS-II which is a five-channel hand-held microprocessor-based sun photometer with a full field of view of 2.5°. Estimated values of AOD at different wavelengths and column thickness of precipitable water vapour are directly obtained from this instrument. It has five optical collimators aligned to aim in the same direction. A narrow band interference filter and a photodiode suitable for the particular wavelength range are fitted with every channel. All the channels face directly the solar disc simultaneously, when the image of the sun is centered at the cross hairs of the sun target. When the radiation captured by the collimators falls on to the photodiodes, it produces an electrical current which is amplified and converted into digital form in a high-resolution A/D converter. Signals are processed in a series of 20 conversions per second. The complete details of the sunphotometer and measuring technique have been already described by Morys².

The amount of precipitable water vapour is estimated based on the solar intensity measurement at 936 nm (water absorption peak) and 1020 nm (no absorption by water) in cm (integrated columnar water vapour thickness).

The AOD at 1020 nm is computed based on Beer-Lambert relation expressed as

\[ I = I_0 \exp(-\delta m) \]  

\[ \quad \cdots \quad (1) \]

where \( I \) is the solar intensity measured at the earth’s surface, \( I_0 \) the solar intensity at the top of the
atmosphere, $\delta$ the total optical depth of the atmosphere and $m$ the secant of the solar zenith angle. The value of $I_0$ is estimated using Langley plot [$\ln(I)$ versus secant of solar zenith angle] at that wavelength corrected for sun-earth distance and the value of $I$ at 1020 nm and the value of solar zenith angle are collected from this instrument. The data are processed inside the instrument by microprocessor and the AOD values are available on the display unit of the instrument. Observations are taken for both the filters (for water vapour measurements) at an average interval of one hour starting from 0930 hrs IST till 1730 hrs IST on each cloud free day from July 2004 to July 2005. A second instrument with five different filters with passband centred at the wavelengths 380, 440, 500, 675, 870 nm has been also used from March to June 2005 over Rajkot (22°18' N, 70°44' E). Due to large number of cloudy days, only limited observations could be made in the months of August 2004 September 2004 and July 2005. The results are presented in this paper.

5 Result and discussion

5.1 Month-to-month variation of mean AOD and precipitable water vapour

Variations of monthly mean AOD at 1020 nm and precipitable water vapour for the period July 2004-July 2005 are shown in Figs 3 and 4, respectively. It can be seen from the Fig. 3 that the mean values of AOD are high during the summer months of June-July; the mean AOD values go on decreasing to reach the lowest in January 2005 and thereafter increasing trend is seen. The minimum in January may be due to weak generation mechanisms and gas-to-particle conversion processes. Low value in winter, a global feature, is attributed to the removal of aerosols due to monsoon rains and decreased aerosol input due to colder ground surface. The less possibility of hygroscopic growth of aerosols due to low water vapour content may also contribute. High AOD is observed during July and has been attributed to increased aerosol input due to increased surface heating and resultant vertical mixing, dry surface conditions and wind blown dust. The wind directional pattern shown in Fig. 2 indicates that during summer, wind is blowing almost southwesterly. So, over this location, the effect of marine aerosols may be significant. The cloud contamination may be one of the reasons for higher AODs during June-July. Seasonal variations in AOD of present study are in good agreement with the variations observed in other places in India$^{9,10}$. It can be also seen from the Fig. 4 that the highest value of the mean water vapour (reaching a value 3.89 cm) is in the monsoon months (June, July, August and September) as expected. During winter season, its value is appreciably low. The water vapour tends to follow the variation in AOD (see Figs 3 and 4). The water vapour is observed to be higher during the periods when the AOD is also higher indicating the possibility of hygroscopic growth of aerosols. Such trends were also reported by Pandey$^{11}$, Gupta$^{12}$ and Krishnamoorthy$^{13}$.

The optical depth values obtained from November 2004 to January 2005 are, more or less, the lowest in the present data set. This is in qualitative agreement with the results at other Indian stations$^{14,15}$ wherein AOD values have been found to be the lowest from October to December and increases thereafter until summer. The lowest AODs from October to December attribute to the washing down of the aerosols by rain during the monsoon months.

Concurrently higher values of total water vapour and the AOD at 1020 nm are suggestive of the possibility that aerosols of sizes $\approx$1020 nm act as
condensation nuclei for the water vapour. As the droplets grow in size, and when a threshold size of the droplets is reached, precipitation occurs. Following the downpour, the down loading of the aerosols results in the decrease of AOD.

5.2 Spectral dependence of AOD

Figure 5 shows the spectral dependence of mean aerosol optical depth in the wavelength region 380-1020 nm for the period March-June 2005. The general trend shows that the AOD values are higher for smaller wavelength and lower for larger wavelengths. The spectral dependence of AOD is mainly controlled by the aerosol columnar size distribution. Higher value of AOD for lower wavelength shows that, at the observing site, the number of smaller size particles dominate. The gradual decrease of AOD with increasing wavelength suggests that the aerosol size distribution at this site is of Junge’s inverse power-law distribution type as follows

\[ \frac{dn}{dr} = Cr^{-\nu} \quad \ldots \ (2) \]

where \( C \) is a constant depending on the total number of particles.

It is further observed that during the months of March, April and May the spectral dependence follows the above pattern. But during the month of June, there are three peaks at 440, 500 and 870 nm suggesting multi-modal aerosol size distribution over the observing site (not shown here). During the month of June the observed spectral variation of AOD shows that the estimated value of \( \nu \) is comparatively very small. High AOD has been observed at 380 nm suggesting high accumulation-mode particle loading over this site. Similar spectral variation was reported from other Indian stations\(^{16-18}\).

5.3 Angstrom coefficients \( \alpha \) and \( \beta \)

Many studies of AOD and its spectral (wavelength) dependence rely on the Angstrom wavelength exponent \( \alpha \) to quantify this spectral dependence. Angstrom suggested the following empirical expression

\[ \delta = \beta \lambda^{-\alpha} \quad \ldots \ (3) \]

where \( \lambda \) is the wavelength in microns of the corresponding AOD values (\( \delta \)), \( \beta \) the Angstrom turbidity coefficient and \( \alpha \) the Angstrom wavelength exponent. Recent studies\(^ {19-21}\) have shown useful application of \( \alpha \) measurements for characterization of aerosol physical and radiative properties.

In view of the above, from the average AOD values at six wavelengths and using Eq. (3), wavelength exponent \( \alpha \) and turbidity coefficient \( \beta \) are computed for the observation site. Figure 6 shows the variation of wavelength exponent \( \alpha \) and turbidity coefficient \( \beta \) with months. The value of \( \alpha \) is relatively small (0.25) during the month of May and high (0.59) during the month of March 2005, while the value of \( \beta \) increases from March to June 2005. Typical values of \( \alpha \) range from a value greater than 2 for fresh smoke particles (which is dominated by accumulation-mode aerosols) to nearly zero value for high optical thickness [Sahelian/Saharan desert cases (dominated by coarse mode aerosols)\(^ {19-21}\)]. Latha et al.\(^ {22}\) pointed out that large value of \( \alpha \) indicates relatively high ratio of small particles to large particles. When aerosol particle size approaches the size of air molecules, \( \alpha \) should approach 4 and for very large particles it should approach 0. Thus, the larger value of \( \alpha \) in March shows that relatively small size particles dominate during March. Turbidity coefficient \( \beta \) gives an

Fig. 5—Spectral dependence of mean AOD in the wavelength region 0.38 \( \mu m \) –1.020 \( \mu m \) for the period March-June 2005 over Rajkot

Fig. 6—Variation of wavelength exponent \( \alpha \) and turbidity coefficient \( \beta \) with months over Rajkot
estimate of aerosol loading over a site. From Fig. 6 it is also seen that the value of $\beta$ shows a slight increase from March to June 2005. The increasing values of $\beta$ and decreasing value of $\alpha$ indicate that aerosol loading of coarse particle increases from March to June 2005. This is also consistent with the result shown in Fig. 3.

Figure 7 shows the diurnal variation of mean AOD at different wavelengths for the month of March 2005. It is seen that the afternoon values of AOD are comparatively larger than the forenoon values. This trend is consistently seen at all wavelengths.

6 Summary and Conclusion

At 1020 nm, mean AOD values over the study area gradually decreased for the period July 2004-January 2005 and then increased up to July 2005. Spectral variation of AOD values at six different wavelengths showed decreasing trend of AOD with increasing wavelength in accordance with Junge’s inverse power-law, except in the month of June. Angstrom wavelength exponent $\alpha$ followed decreasing trend from March 2005 to May 2005 and then slightly increased in the month of June 2005, but turbidity coefficient $\beta$ followed slightly increasing trend from March 2005 to June 2005 indicating relatively increasing dominance of coarse particles from March to June.

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