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Solar eclipse induced changes in aerosol extinction profiles: A case study of 11 Aug. 1999 solar eclipse using lidar at a tropical station Trivandrum, India

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An experiment has been conducted to understand the 11 Aug. 1999 solar eclipse induced changes in the aerosol extinction coefficient in the troposphere and the lower stratosphere using the multiwavelength lidar system designed and developed in-house at a tropical station Trivandrum (8° 33′N, 77° E). Results of the measurements reveal an increase in aerosol extinction coefficient in the troposphere and a decrease in the lower stratosphere compared to control day. Six high altitude balloon ascents with 1680 MHz radiosonde were conducted from Thumba to study the eclipse induced variations in winds and temperature of the lower atmosphere. The study clearly reveals the cooling of the entire tropospheric layers with maximum of 5° C occurring below 15 km altitude. The changes in the temperature and the relative humidity during the eclipse are the key factors contributed for the observed aerosol extinction coefficient.

1 Introduction

Atmospheric aerosols play an important role in many atmospheric processes. Although aerosols constitute only a very small percentage of the total contents of the atmosphere, they have strong influence on the radiation budget, air quality, clouds and precipitation as well as the chemistry of the troposphere and stratosphere. The important basic characteristics of the aerosols such as altitude profiles of concentration and size distribution are highly variable both in space and time. Also they are affected by various meteorological parameters, particularly, temperature, relative humidity, winds etc.[1,2] The temperature and ionization structure, chemical composition, dynamics of various regions of the atmosphere, etc. are controlled by the solar radiation flux. The physical and chemical properties of various atmospheric layers are strongly influenced by the solar radiation. During solar eclipse time the input solar radiation into the atmosphere is withdrawn in a very short time compared to the normal sunset condition. Sudden changes of radiation flux produced during eclipse will have effects on the behaviour of different layers. The response of the middle atmosphere comprising the troposphere and stratosphere to the changes in the radiation flux is believed to be characterized by the cooling of the troposphere and slight warming of the lower stratosphere towards the end of eclipse, probably, due to subsidence of the cooling from the upper region[3]. During the 24 Oct. 1995 eclipse time, Appu *et al.*[4] conducted balloon experiments to obtain vertical temperature structure, zonal and meridonal wind profiles at Trivandrum (8°33′N, 77°E), a coastal station. A delayed response of a very intense cooling of tropospheric layer with maximum 9°C at 14 km was observed after about 3 h of the eclipse. Stratospheric temperature in the 20-34 km layer has undergone a sharp increase with maximum of 8°C around 33 km during the end phase of the eclipse. These warming effects seem to remain at least for 3 h after the eclipse. Bansal *et al.*[5] also observed that the air temperature had fallen by about 5°C and relative humidity increased to 87% from 77%. They[5] had also studied the effects of these changes in the atmosphere on the aerosol characteristics. It was reported that there was an increase in aerosol concentration due to the observed variation of the relative humidity and air temperature. These measurements on aerosol concentration and atmospheric parameters were conducted at a height of about 9 m above the ground at Roorkee town in Northern India (77°55′ E, 29°52′ N, hamsl 267.70 m) where the totality of the solar eclipse was 90%.

Appu *et al.*[6] had conducted high altitude balloon ascents with 1680 MHz radiosonde to study the eclipse induced variation in winds and temperature of the lower atmosphere during the solar eclipse of 11 Aug. 1999 at Trivandrum. Though it was generally known that the changes in the atmosphere would affect the altitude structure of aerosol in the troposphere and lower stratosphere, no measurements were available to obtain the range-resolved measurements on the changes in the aerosol properties on a solar eclipse day. Lidar techniques offer powerful and unique means of measurements on the solar induced changes in the aerosol structure with very good temporal and spatial resolutions. In the present paper, a study has been conducted to understand the solar eclipse induced changes in the aerosol extinction profiles in the troposphere and lower stratosphere.

2 Lidar system description

As a part of major programme on the study of structure and dynamics of the atmosphere at a low latitude station, a multiwavelength lidar (MWL) system had been designed and developed[7] at the Space Physics Laboratory, Vikram Sarabhai Space Centre, Trivandrum. A Quantel (France) Model YG-581C-20 high power pulsed Nd: YAG laser, emitting the fundamental wavelength at 1064 nm in the near IR with pulse energy of 1200 mJ, is the main transmitting source in the MWL system. The laser pulse width is 10 ns and the laser can be operated up to a maximum pulse repetition frequency (PRF) of 20 Hz. To operate the system in the visible and UV regions, the second, third and fourth harmonics of the fundamental wavelength of the laser are used. The operating wavelengths at these harmonics are 532 nm, 355 nm and 266 nm with reduced pulse energy associated with the electro-optical crystals. The laser beam is transmitted vertically up into the atmosphere through a 45° diagonal mirror and a refracting telescope (only for higher altitude studies). Backscattered radiation from the atmosphere is collected by a 500-mm Cassegrain telescope. Using the post-processing optics system, the received signal is delivered to the photomultiplier tubes. Interference filter with bandwidth of 1 nm is used in the receiver optics to reduce the sky background noise. The receiver has three optical channels to cover different wavelength regions and two data acquisition modes. Photomultiplier tubes with S20 (EMI 9863 & EMI 9659) and S1 (EMI 9684) cathodes having built-in gating facility are used in appropriate channels. It is estimated that the dynamical range of the received backscattered signal from ground to 70 km can be as large as 10^6. As such two acquisition modes are used to cover the entire altitude range. The current mode of acquisition covers the altitude range up to about 30 km, whereas the photon-counting mode is used for studies above 30 km. A Pentium (II) personal computer- based two-step digitization scheme with 8 bit/100 MSPS and 14 bit/10 MSPS is configured for the data acquisition system (DAS) in the current mode. A 50 MHz multichannel counter is developed for the photon counting mode of acquisition and it is linked to the second PC through direct memory access (DMA) interface. The transmitter and receiver axes are aligned parallel using a laser alignment experimental set-up.

The MWL system is being used for the study of the long-term trend of various atmospheric parameters related to dynamics and structure with good altitude and time resolutions. Regular observations are conducted every month on atmospheric aerosols in the troposphere and lower stratosphere up to 30 km and on temperature structure to cover the entire range of 30-70 km. The schematic diagram of MWL system is shown in Fig. 1. The system details and other specifications of the MWL system are described elsewhere[8].

3 Data analysis

The basic single scattering equation for a monostatic pulsed lidar could be written as

$$P_r = P_o \, \frac{c\tau}{2} E \frac{\beta_r}{r^2} A \exp\left\{-2\int_o^r \alpha_r \, dr\right\} \qquad \ldots (1)$$

where,

P_r Power received from range r, where $r = C(t - t_o)/2$

P_o Transmitted power at time t_0

C Velocity of light

τ Pulse width

E Overall system efficiency

A Telescope aperture

β_r Volume backscatter function

α_r Volume extinction function

Defining a new signal variable $S(r) = \log\{r^2 P_r\}$, one can arrive at the following differential equation,

$$\frac{dS}{dr} = \frac{1}{\beta}\frac{d\beta}{dr} - 2\alpha \qquad \ldots (2)$$

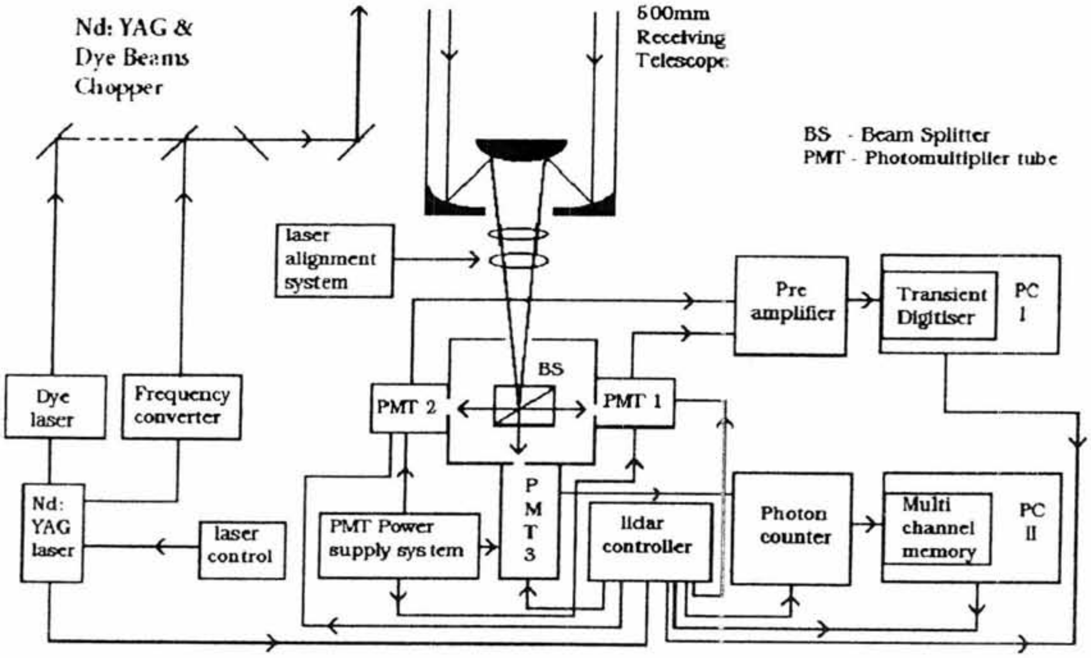

Fig. 1—Schematic diagram of multiwavelength lidar system

The above equation can be solved for α_r or β_r, if a relation of the form $\beta = D\alpha^k$ is assumed (k being a constant and depends on a lidar equation); where D and k are constants whose values depend on the aerosol characteristics and their relative number density with respect to gas molecule. Fenn[9] and Curcio *et al.*[10] had studied the validity of this relationship using experimental measurements under different visibility conditions as well as by the theoretical estimates using model values of aerosol and molecular density profiles. If the aerosols are non-absorptive and refractive index is close to 1.5, which is, in general, applicable for aerosols at 532 nm wavelength, the value of k is found to be close to unity[11]. Also the neutral density values obtained from the atmospheric model[12] derived from rocket-borne measurements at Trivandrum were used for calculating the molecular extinction coefficients in the analysis. A new inversion method has been developed in-house which incorporates the repetitive iterations to obtain the realistic values of k applicable to different regions of the atmosphere. This method divides the total height regions into different segments and assigns the applicable k values, which are obtained from observed lidar signal itself. This method, which is currently applied for lidar studies on aerosols, is under review.

The solution of the above equation [Eq. (2)] will depend on a boundary value for α_r or β_r at reference range r_m. Depending on whether the reference range r_m is at the near or far end of the lidar, two forms of solution exist. It was pointed out by Klett[13] that due to decreasing magnitude of the signal with increasing range the near end solution is unstable with respect to errors in the boundary value. The far end solution[14,15], which allows for a variable backscatter to extinction ratio for aerosol and includes the effects of background molecular scattering, is of the form

$$\alpha_r = \frac{\exp\left(\dfrac{S - S_m}{k}\right)}{\alpha_m^{-1} + \dfrac{2}{k}\displaystyle\int_{r_m}^{r} \exp\left(\dfrac{S - S_m}{k}\right) dr} \quad \ldots (3)$$

where, S_m is the value of $S(r)$ at the altitude of r_m and α_m is the molecular extinction at r_m. This top-to-bottom inversion procedure becomes an excellent choice for analysing lidar data, if backscatter signal can be measured well above the aerosol layers (35 km and above). Above 35 km the contribution from aerosol scattering to the total scattering can be neglected and α or β becomes Rayleigh backscattering coefficient at the maximum altitude, which can be readily computed. Klett[13] has shown that errors in the assumed value of α_m make only significant contribution to errors in α at lower altitudes. In Eq. (3), as r decreases from r_m, α is determined as the ratio of two numbers, each increasing progressively so that stability and accuracy are easily maintained. The denominator indicates that the dependence of the solution on α_m decreases with decreasing r and, thus, the solution at lower altitudes becomes relatively insensitive to errors in α_m.

4 Experimental observations during 11 Aug. 1999 solar eclipse

4.1 Lidar experiments

For the study of response of the aerosol characteristics due to changes in the meteorological parameters during eclipse time, the MWL system operating at 532 nm wavelength of the laser with pulse energy of 500 mJ was used. Backscattered signals were measured with a bin width of 200 ns corresponding to the altitude interval of 30 m. Background noise was estimated individually for each measurement from the signal received typically from 35-45 km range. This was based on the trial runs conducted just before obtaining the actual data used for the study. From the received trial data, it was clear that the altitude range above 30 km was practically aerosol free and corresponds to the sky background noise. The observations were taken on the day of the eclipse (11 Aug. 1999) as well as on the preceding (10 Aug. 1999) and succeeding days (12 Aug. 1999) from the early evening hours (1900 hrs LT) onwards. Data were analysed with 10s time integration corresponding to 100 laser pulses. Data obtained on 10 Aug. 1999 were not useful, as the sky was very cloudy and signal could be obtained up to a couple of kilometres only. Data obtained on 12 Aug. 1999 were relatively good and as such was used for further analysis presented in this study.

4.2 Balloon-borne radiosonde experiments

Six high altitude balloon ascents with 1680 MHz radiosonde were conducted from the same location (Thumba) to study the eclipse induced variation in winds and temperature of the lower atmosphere. The station was well outside the totality path of the eclipse and as such the location experienced only a partial eclipse with the first contact time at 11:48:57.5 hrs UT (17:18:57.5 hrs IST) and the maximum eclipse at 12:46:23.9 hrs UT (18:16:23.9 hrs IST). The eclipse magnitude was 0.689. Balloons were released at 1715 hrs and 1930 hrs IST on 10, 11 and 12 Aug. 1999. The ascents on 10 and 12 Aug. 1999 were planned to construct the reference height profiles of wind and temperature. Evening balloon data from meteorological centre, Trivandrum, 12 km away from Thumba, were also supplemented to the campaign to infer the pre-eclipse atmospheric conditions.

5 Results and discussion

Figure 2 shows the variation of aerosol extinction coefficient with altitude as measured by lidar on the two days using the method described in Sec.3. It can be seen that aerosol extinction coefficient profile obtained on the day of eclipse is distinctly different from the vertical profile obtained on the control day (12 Aug. 1999). The extinction values are higher on eclipse day by a factor of 2 compared to the values of 12 Aug. 1999 in the altitude range 4-13 km. In the altitude range 13-25 km, the extinction coefficient

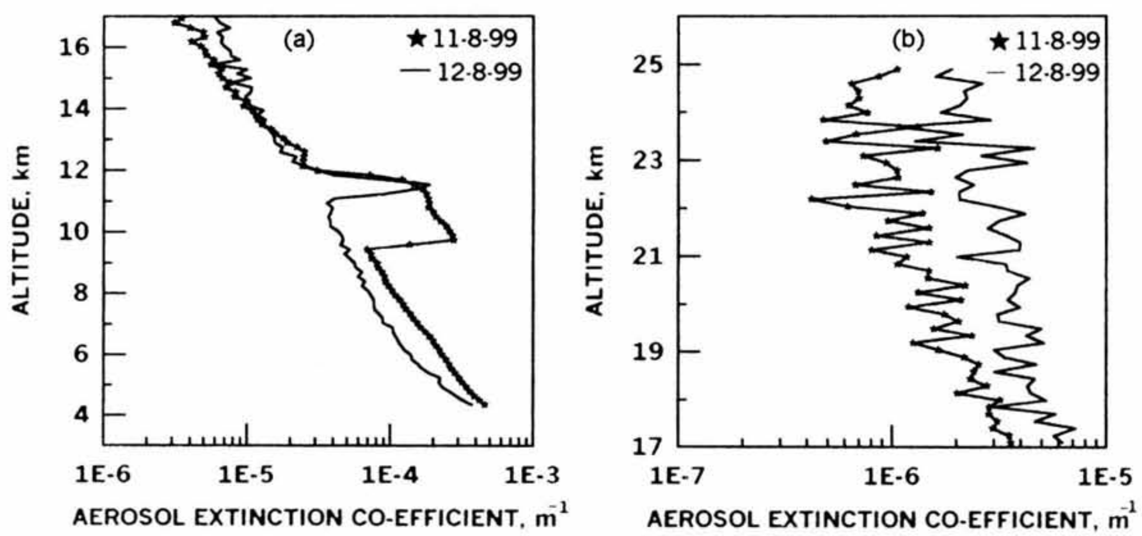

Fig. 2—Aerosol extinction coefficient profile obtained on solar eclipse day (11 Aug. 1999) and control day (12 Aug.1999) [(a) for troposphere and (b) for stratosphere]

values are lower on the day of eclipse compared to the values on 12 Aug. 1999 by a factor of 3. Apart from the observed changes due to eclipse it is seen that there is sudden enhancement of extinction values in the region of 9-11 km on both days. We believe that this is due to the presence of high altitude clouds particularly of cirrus type during the time of observation. Such layers were observed on most of the other days at this station. This observed feature of the cirrus, low level clouds and aerosol layers had been investigated extensively using the MWL system in the laboratory. The results on this will be reported separately. Another interesting feature, which can be seen from Fig. 2(a), is that the difference in the extinction values continued only up to 13 km, though we expect this to continue up to tropopause (15-17 km). This could be due to the presence of the cloud layers and their interaction with the local meteorological condition. This has been investigated separately and some of the results of the observed phenomena are being communicated. The observed higher and lower aerosol extinction coefficient in the troposphere and lower stratosphere could be explained on the basis of time variation of air temperature. Figure 3(a) shows the vertical temperature profiles obtained on the 10, 11 and 12 Aug. 1999 at 1930 hrs IST using 1680 MHz radiosonde conducted from Thumba. The measurements[6] showed the cooling of the entire tropospheric layer with maximum of 5°C occurring below the tropopause and warming in the stratosphere with a magnitude of 4°C at 23 km. This confirmed the earlier result on the observed decrease in temperature reported from Thumba and Hyderabad by Appu *et al.*[4] during the 24 Oct. 1995 solar eclipse. The occurrence of a slight warming of 2-3°C in the lower stratosphere was first noted at Wallops Island (38° N, 75° W) by Quiroz and Henry [3] during the total solar eclipse of 7 Mar. 1970 and was explained as due to subsidence as a result of the cooling of the upper layers. The average normal day-to-day variation of temperature in the troposphere and lower stratosphere are found to be ~ 2-3°C. This large scale cooling may be associated with the imbalance in the radiative cooling and heating of the water vapour and high altitude clouds. Tropopause height descended by about 1 km during the eclipse phase as observed by Appu *et al.*[6] Their analysis also showed the presence of short scale perturbations in troposphere temperature during the eclipse phase, which would be attributed to the non-uniform radiative processes taking place in this height regions. The height resolution in the temperature measurement by radiosonde is only 1 km in this range and as such the small-scale perturbations were not quantified precisely. The cooling effect in the troposphere lasted for more than two hours as seen in the Fig. 3(c). The eclipse-induced perturbation observed over Thumba would be of significance in delineating the various dynamical processes resulting from the blocking of solar radiation during a solar eclipse. This observed cooling effect in the troposphere could lead to condensation effect, which results in an increase in the aerosol extinction coefficient as seen in Fig. 2(a). The decrease in aerosol extinction coefficient in the altitude range 13-25 km obtained on eclipse day as seen in Fig. 2(b) might be due to the warming effect of the middle stratosphere as seen in Fig. 3(b). On 12 Aug. 1999,

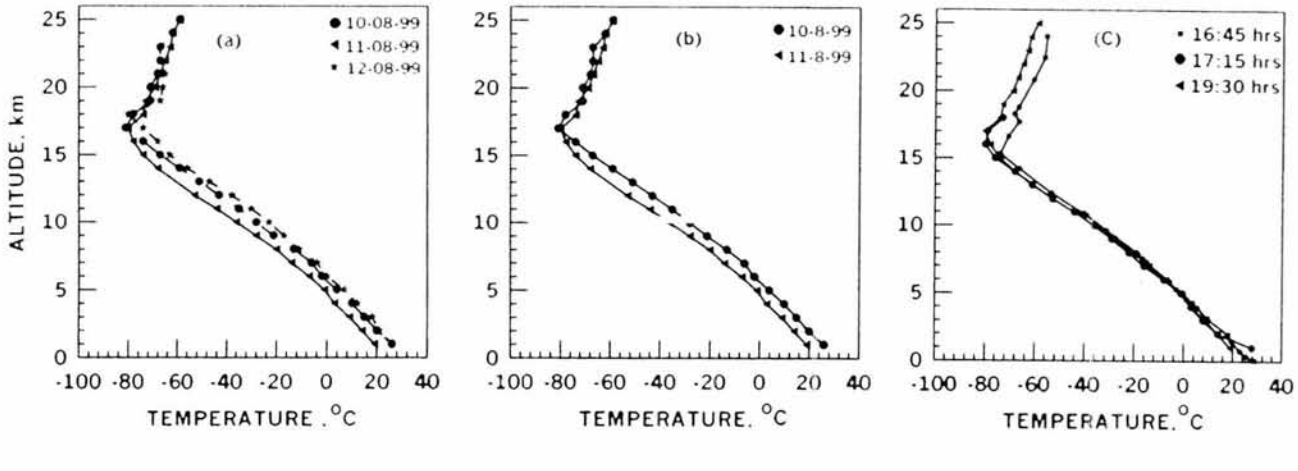

Fig. 3—Vertical temperature profile obtained on 10, 11 and 12 Aug. 1999 at 1930 hrs IST using radiosonde [(a) Profile obtained on three days, (b) Comparison between solar eclipse day (11 Aug. 1999) and control day (10 Aug. 1999) and (c) Temperature profiles of 11 Aug. 1999 corresponding to 1645, 1715 and 1930 hrs IST]

during balloon experiment at Thumba, the temperature data were obtained only up to 20 km due to some experimental limitations. For this purpose temperature data of 10 Aug. 1999, another control day, were used in this region. This was done knowingly that the profiles of 10 and 12 Aug. 1999 are practically same up to 21 km as seen in Fig. 3(a). Temperature data were, of course, available up to 35 km on 10 and 11 Aug. 1999, though the data were presented only for the altitude up to 25 km for one-to-one comparison.

6 Conclusions

The results of lidar observations on atmospheric aerosols at a tropical station, Trivandrum, show significant changes in extinction coefficient during solar eclipse period due to the changes in the meteorological parameters. The changes in the temperature and relative humidity during the eclipse are the key factors contributed for the observed increase in aerosol extinction coefficient. It is necessary to conduct multi-spectral measurements with lidar for understanding the contribution of the meteorological parameters on the size index and number density separately. Such a study has currently been undertaken by the present group using the multiwavelength capability of the MWL system.

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