Lidar Measurements Describe Distribution of Airborne Particulate Matter

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ABSTRACT

Characterization of airborne particulate matter has been a major challenge to researchers involved in the field of atmospheric sciences. The variation of optical extinction associated with aerosols with respect to atmospheric conditions is useful in understanding the evolution of pollution events. Several cases of extinction measurements from the NARSTO-NE-OPS program in Philadelphia during summer 1998 and 1999 have been analyzed and compared with other measurements. Measurements were taken using the Lidar Atmospheric Profile Sensor (LAPS), which was developed at Penn State University as an operational prototype instrument. The measured Raman signals, which represent the molecular density, are directly analyzed to determine the optical extinction profiles. An algorithm for the telescope geometrical form factor was developed to aid in analyzing signals near the surface. Several data sets show that optical extinction is strongly correlated with relative humidity. Vertical profiles of optical scattering were obtained using a multi-wavelength Raman lidar to describe the distribution of airborne particulate matter to help determine particle density and size distribution. Scattering at optical wavelengths provides information on small airborne particles and corresponds well with the $PM_{2.5}$ particulate matter.

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1. Introduction

Knowledge of aerosol optical properties assumes significant importance in the wake of studies strongly correlating airborne particulate matter with adverse health effects. Studies have shown that tropospheric aerosols increase mortality, morbidity and respiratory problems, and pulmonary function decreases with increase in ambient particle mass concentrations [Hidy, 1998]. Fine particles are considered more likely than coarse particles to be responsible for respiratory health effects. Along with health issues, aerosol distributions have significant implications for natural environmental aesthetics and climatic change conditions. The combustion products from transportation and power sources produce most of the nucleation centers, which grow to aerosol sizes that change the visibility and radiative flux at the Earth's surface by optical scattering. Correlation between backscatter and extinction measurements provides a means of describing atmospheric aerosols and airborne particulate matter in the lower atmosphere. Analysis of extinction profiles during periods of atmospheric pollution events provides understanding of the characteristics and distribution of airborne particulate matter (PM).

2. Method

Lidar techniques have been used in remote sensing to measure the aerosol optical extinction from the particles in the atmosphere, as well as water vapor, temperature and ozone profiles. We have used Raman lidar and backscatter lidar techniques to measure the optical extinction and scattering properties as part of the NARSTO-NE-OPS (NorthEast-Oxidant and Particle Study) [Philbrick, 1998a] during the summers of 1998 and 1999. The signal profiles from Raman scatter signals at wavelengths of 607, 530 and 284 nm are directly analyzed to determine the optical extinction profiles. Vertical profiles of optical scattering were obtained using a multi-wavelength Raman lidar to describe the distribution of airborne particulate matter in the lower atmosphere. The Lidar Atmosphere Profile Sensor (LAPS) has been demonstrated for measurements of meteorological conditions and atmosphere properties during daytime and nighttime over an extensive range of weather conditions [Philbrick, 1998b]. Airborne particulate matter can be analyzed using the gradients in optical Raman scattering profiles to determine optical extinction which is used to describe changes in particle size and density as the function of time and altitude [Philbrick, 1998c]. Extinction is the total scattering and absorption of particles in the atmosphere. For the wavelengths selected, the extinction is predominantly by optical scattering by airborne particulate matter. A telescope form factor is used to aid in correcting and analyzing the surface level signals (up to an altitude 800 m) [Jenness,1997].

Extinction is calculated by first subtracting the background signal from the Raman backscattering raw photon count signal. It is then corrected for range and telescope form factor, and then extinction is determined from the change in signal strength. The particle extinction is determined using the basic lidar equation, assuming the absorption and multiple scattering are negligible over the interval. So extinction can be simply calculated using Beer-Lambert law:

$$a = -\frac{\ln(I_1 / I_2)}{2x_{12}}$$

where α is the extinction coefficient and x equals the range bin size in meters. I_1 and I_2 refer to the received signal power from the altitudes 1 and 2 respectively. [Measures,1992; Ansmann et al.,1992]

The telescope form factor is introduced to correct the received signal vertical profile at low altitudes where the out-of-focus ray bundle overfills the detector, which is generated by the near field effect below 800 meters. The form factor used in this analysis is calculated from the return signal curve obtained under clear weather conditions.

3. Results

Extinction shows a strong correlation with relative humidity. It has been conclusively established from a number of data sets that there is a sharp change in extinction at around a threshold relative humidity of 80%. In order for particles to be detected with lidar, the particle size must be within the accumulation mode. The accumulation mode is described by the accumulation of ultra fine particles (<0.1 μm) to form larger particles (>0.2μm). Typically, for particles to conglomerate, the relative humidity must be high, at least above the critical saturation ratio of the particle. Water vapor content and temperature are important factors in determining the optical extinction because of the humidity influence on the size distribution of the particulate matter, and thus influences the optical extinction. The comparison plots shown support this description. Ground level extinction from the 284nm channels for various periods was analyzed and compared to relative humidity to determine their correlation.

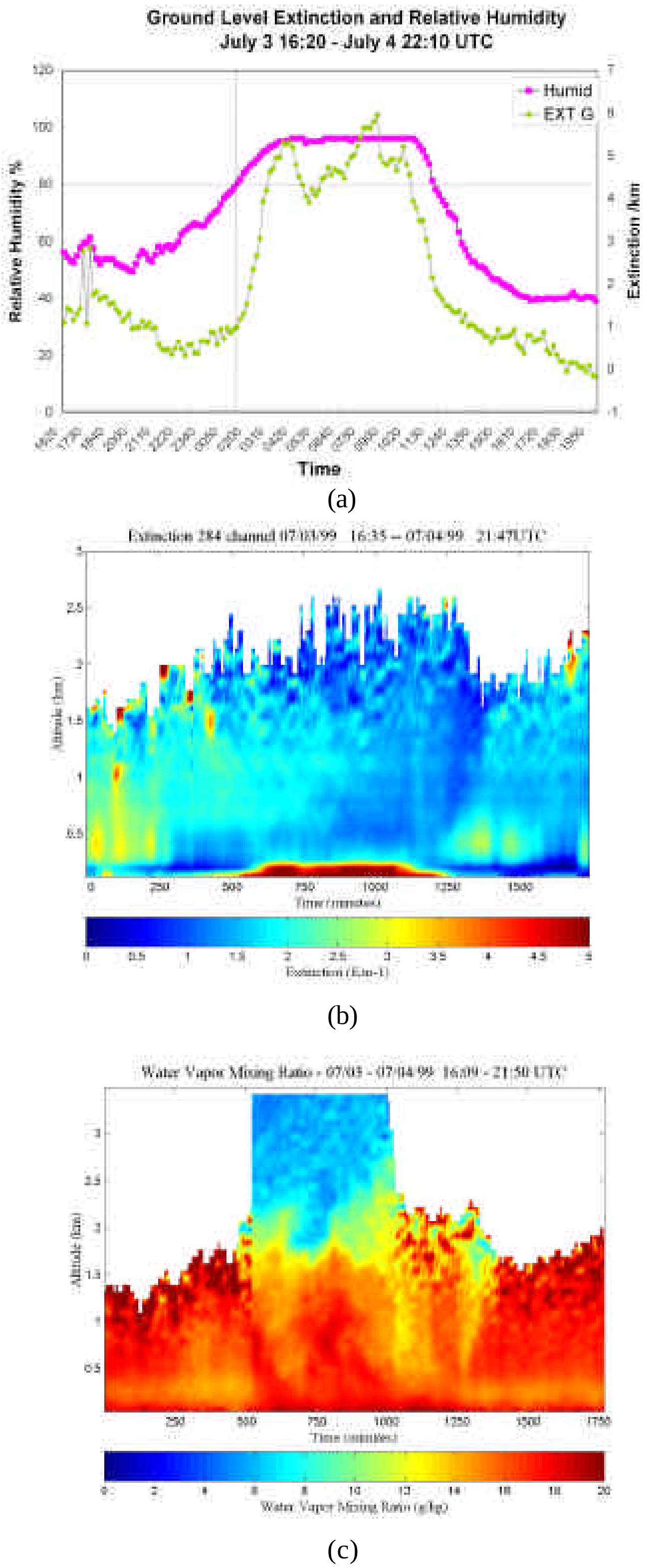
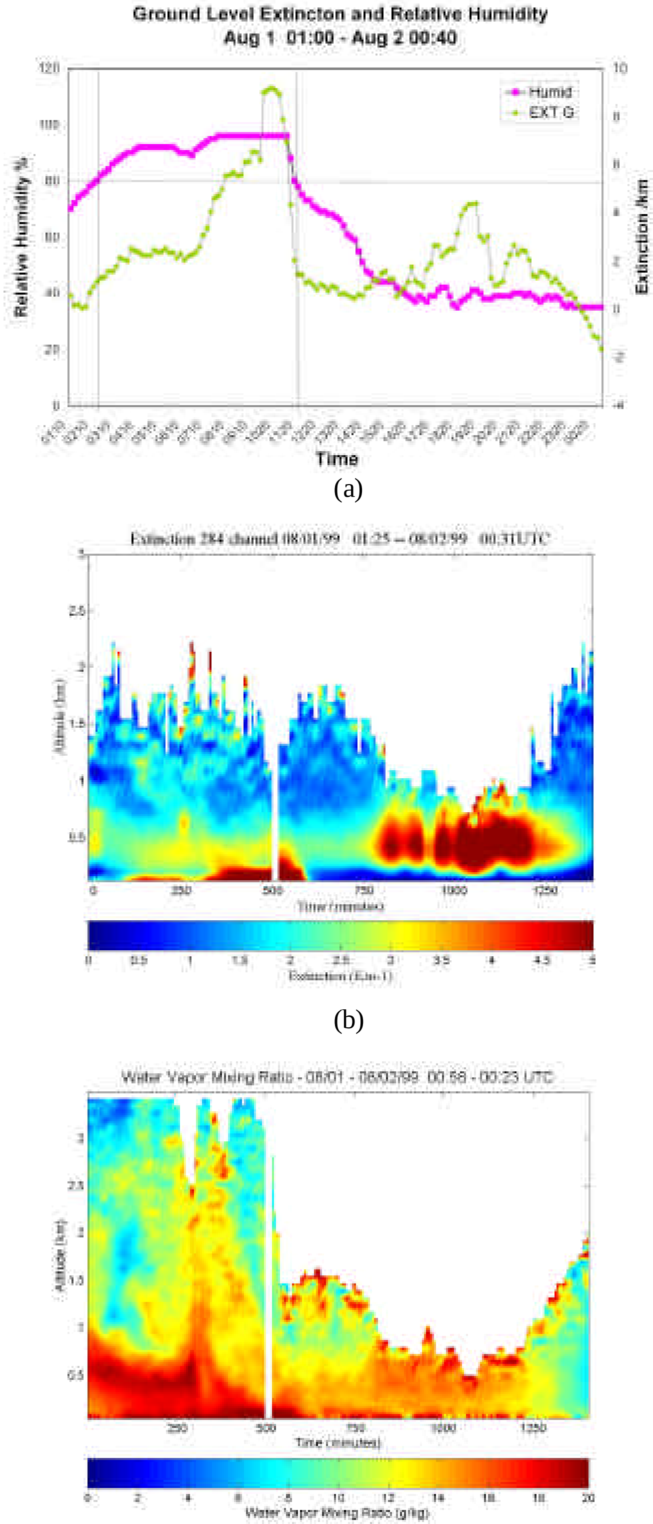


Fig. 1. (a) Ground level extinction and relative humidity, (b)Vertical extinction profile, and (c) Water vapor mixing ratio, for the time period 07/03/99 16:20– 07/04/99 22:00 UTC



(a)

(b)

(c)

Fig. 2. (a) Ground level extinction and relative humidity, (b)Vertical extinction profile, and (c) Water vapor mixing ratio, for the time period 08/01/99 01:10– 08/02/99 00:40 UTC

Fig. 1a shows the corresponding rise and fall in extinction when the relative humidity rises and falls relative to the threshold of 80 %, respectively. Fig. 1b and 1c show the vertical profiles of extinction and water vapor, respectively. In Fig. 1b we can see the corresponding rise in extinction which compares well to PM2.5. Another time period collaborating this observation is shown in Fig. 2. For both these time periods we can clearly see the strong correlation between extinction and relative humidity.

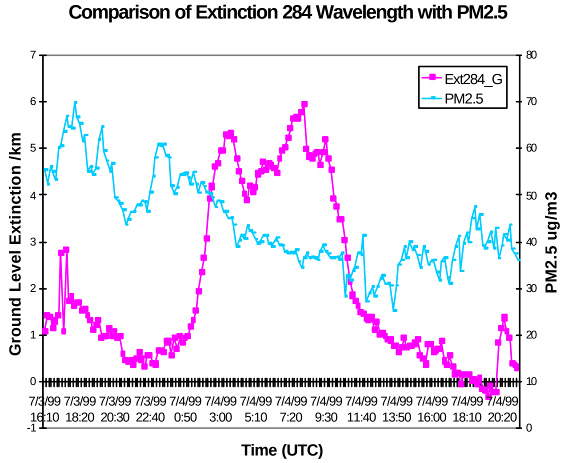


Fig. 3. Ground level Extinction at 284nm and PM2.5 for the time period corresponding to Fig. 1

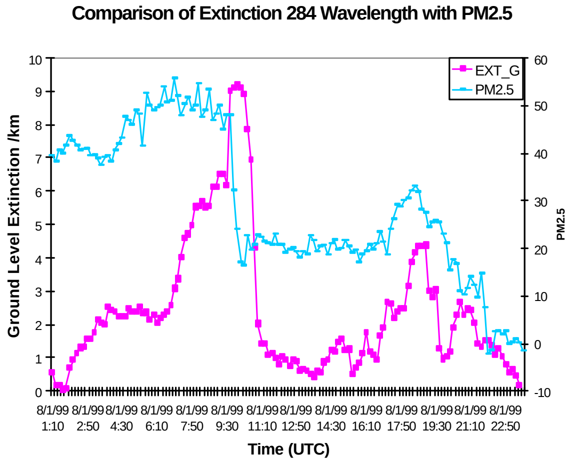


Fig. 4. Ground level Extinction at 284nm and PM2.5 for the time period corresponding to Fig. 2

Figures 3 and 4 show the corresponding PM2.5 measurements (provided by Dr. G. Allen from Harvard University) along with the extinction at ground level. Comparison with the humidity variation for the same time period shows that when humidity is above 80 %, there is more nucleation of particles and hence as the PM2.5 measurements show, a higher particulate matter density in the lower atmosphere.

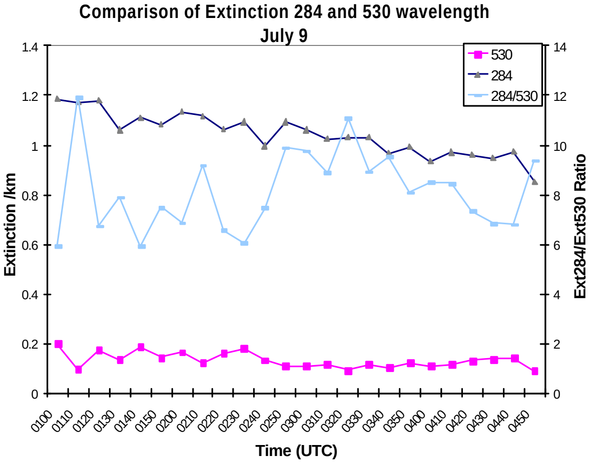


Fig. 5. Extinction at wavelengths 530nm and 284nm and the ratio of Ext_530 to Ext_284 at an altitude of 800m

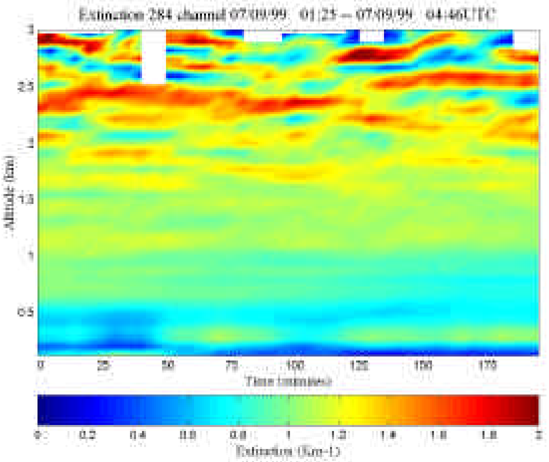


Fig. 6. Vertical Extinction profile corresponding to the time period of Fig. 3.

Fig. 5 shows a comparison of extinction being higher at shorter wavelengths. The molecular component of extinction at a given wavelength is inversely proportional to the fourth power of the wavelength. Hence we would expect to see a ratio of Ext_284 to Ext_530 to be in the range of around 12 for a clear day. For a cloudy/hazy day this ratio decreases and the Ext_530 approaches the Ext_284. Fig. 6 shows the vertical extinction profile for the same time period.

4. Conclusion

Optical extinction and hence particulate matter density shows a sharp increase when the relative humidity goes above 80 % and drops sharply when the humidity goes below 80 %. Optical extinction and relative humidity exhibit a strong correlation to each other. The wavelength dependent optical extinction can be used to describe changes in particle size as a function of time and altitude.

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