Scanning Raman Lidar Measurements of Atmospheric Water Vapor and Aerosols

R. A. Ferrare and K. D. Evans[(a)]
Hughes STX Corporation
Lanham, Maryland

S. H. Melfi and D. N. Whiteman
NASA/Goddard Space Flight Center
Greenbelt, Maryland

The principal objective of the Department of Energy's (DOE) Atmospheric Radiation Measurement Program (ARM) is to develop a better understanding of the atmospheric radiative balance in order to improve the parameterization of radiative processes in general circulation models (GCMs) which are used to study climate change. Meeting this objective requires detailed measurements of both water vapor and aerosols since these atmospheric constituents affect the radiation balance directly, through scattering and absorption of solar and infrared radiation, and indirectly, through their roles in cloud formation and dissipation.

Over the past several years, we have been investigating how the scanning Raman lidar developed at the NASA/Goddard Space Flight Center (GSFC) can provide the water vapor and aerosol measurements necessary for such modeling. The lidar system has provided frequent, high resolution profiles of atmospheric water vapor and aerosols in nighttime operations during two recent field experiments. The first experiment was ATMIS-II (Atmospheric Moisture Intercomparison Study) conducted in July-August 1992, and the second was the Convection and Moisture Experiment (CAMEX) conducted during September-October 1993. We present a brief description of the lidar system and examples of the water vapor and aerosol measurements acquired during these experiments.

(a) Under contract at the Goddard Space Flight Center, Greenbelt, Maryland.

System

The GSFC scanning Raman lidar is a trailer-based system which uses a XeF laser to transmit light at 351 nm. A steerable elliptical flat provides full 180 degree horizon-to-horizon scan capability within a single scan plane. The combined aerosol and molecular backscattered light at the laser wavelength is detected, as well as Raman scattered light from water vapor (403 nm), nitrogen (383 nm), and oxygen (372 nm) molecules. Profiles of the water vapor mixing ratio are computed from the ratio of the return signals due to Raman scattering by water vapor to Raman scattering by nitrogen. These profiles are calibrated using a weighted least squares regression of the lidar ratios to the water vapor mixing ratios measured by coincident radiosondes launched at the lidar site. For a 1-minute profile, the random error in these profiles is less than 10% for altitudes below 7.5-8.5 km. By averaging for longer periods of time and/or by reducing the vertical resolution, profiles above 8.5 km can be obtained. Profiles of the aerosol scattering ratio (defined as the ratio of the sum of aerosol+molecular scattering to molecular scattering) are derived from the Raman nitrogen return signal and the signal detected at the laser wavelength; the aerosol volume backscattering cross section can then computed from the scattering ratio and from the molecular volume backscatter cross section obtained from coincident radiosonde density data. The aerosol extinction cross section is computed from the derivative of the Raman nitrogen return signal with respect to range.

Water Vapor and Cirrus Clouds

During the CAMEX experiment, the Raman lidar was operated for 13 intensive observation periods for 58 hours without any downtime because of equipment failure. Making use of the large scanning mirror, the optical axis of the system was sequentially pointed at several different angles. At each angle, 1-minute profiles of water vapor and aerosols were obtained.

On several occasions during CAMEX, we simultaneously observed water vapor profiles and cirrus clouds. One such example is shown in Figures 1 and 2 for data acquired on September 23, 1993. The lidar water vapor profile shown in Figure 1 was derived by summing 55 one-minute profiles acquired while the lidar pointed vertically during this night; these vertical data were smoothed to an equivalent 300-m vertical resolution between 8- and 10-km altitude. These spatial and temporal methods were used to reduce the random error in the upper troposphere. The water vapor profiles measured by a Vaisala radiosonde at 03:45 UT, as well as the water vapor mixing ratios for constant relative humidities (over liquid water) of 20% and 100%, are also shown in Figure 1.

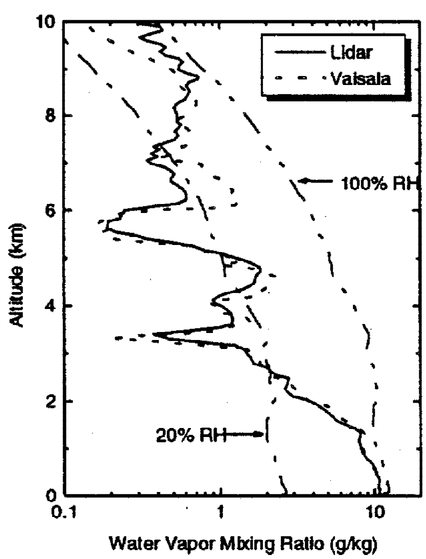

Figure 1. Lidar and radiosonde water vapor profiles measured at Wallops Island, Virginia, on September 23, 1993.

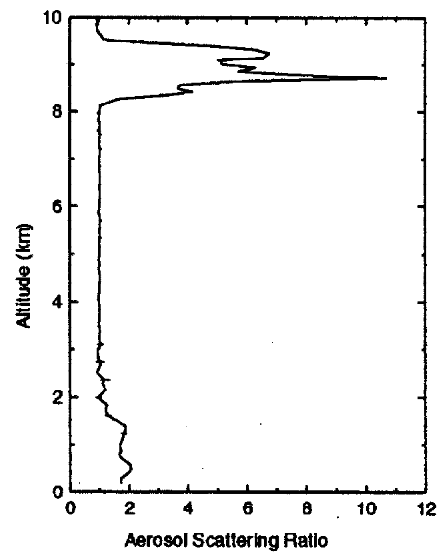

Figure 2. Aerosol scattering ratio profile measured by lidar at 03:45 UT at Wallops Island, Virginia, on September 23, 1993.

The aerosol scattering ratio measured by the lidar at 03:45 UT (shown in Figure 2) indicates cirrus clouds were present between altitudes of 8.2 and 9.6 km. Low-level aerosols extending up to about 1.5 km can also be seen in this figure. The unique capability of the Raman lidar to simultaneously observe upper tropospheric water vapor along with cirrus backscatter makes the technique very attractive for studying the pre-cirrus environment and conditions under which cirrus and/or contrails will form.

Aerosol Scattering and Extinction

By measuring high-resolution profiles of aerosol extinction and backscattering as well as simultaneous profiles of atmospheric water vapor, Raman lidar can provide information regarding the hygroscopic nature of aerosols. Such measurements of aerosol extinction, backscattering, extinction/backscatter ratio, water vapor mixing ratio, and relative humidity were made during the ATMIS-II experiment. Figure 3 shows the aerosol extinction as a

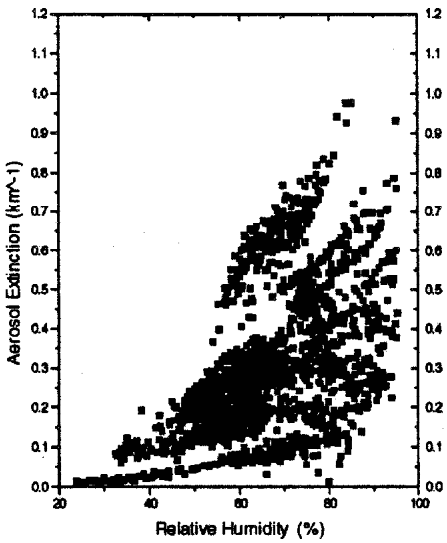

Figure 3. Lidar measurements of aerosol extinction cross section versus relative humidity for July 29-August 6, 1992 at Wallops Island, Virginia.

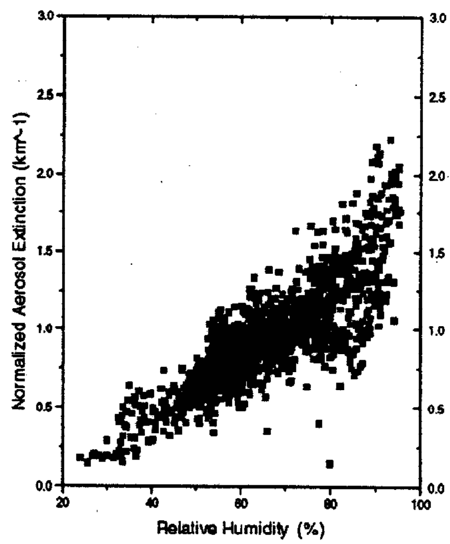

Figure 4. Same as Figure 3 except aerosol extinction is normalized to unity for a relative humidity of 70%.

function of relative humidity measured by the scanning Raman lidar. In an attempt to separate aerosols according to various air masses, we segregated the lidar data into layers using the measured water vapor mixing ratio, since the mixing ratio is conserved except for condensation and evaporation and can, therefore, act as a tracer of air motion. Data from 13 separate layers acquired on seven nights between July 29 and August 6 are shown in the figure. To reduce the dependence of aerosol extinction on aerosol number density, the data shown in Figure 3 were then normalized to an aerosol extinction value of unity at a relative humidity of 70%; the resulting normalized aerosol extinction values are plotted in Figure 4.

Since this normalization procedure does not completely remove the effects of changes in air mass, a unique relationship relating aerosol extinction and relative humidity for all types of aerosols cannot be defined. However, these data show that this lidar system is a valuable tool in studying how changes in water vapor affect the optical and physical characteristics of aerosols since these changes can be observed remotely throughout a large depth of the atmosphere.

Daytime Modifications

While used predominantly for nighttime measurements, this lidar system has also shown a limited ability to measure water vapor during the daytime. However, the solar background light has limited the range of these initial daytime water vapor and aerosol profiles. Since both daytime and nighttime measurements of water vapor and aerosols will be required to interpret the solar and infrared (IR) radiation measurements made at the Cloud and Radiation Testbed (CART) site, we are currently upgrading the daytime measurement capability of the GSFC Raman lidar. One method uses a narrow band/narrow field of view approach applied to the nighttime detection scheme. Reducing the field of view and the passbands of the Raman filters will reduce the solar background and should, therefore, increase the signal/noise ratio of the Raman return signals. We also plan to add analog-to-digital data acquisition hardware to the system to record the large signals expected for daytime measurements of water vapor and aerosols near the surface. Current system modeling indicates that the modifications should permit both vertical and horizontal daytime measurements of water vapor and aerosols to ranges of approximately 3-4 km.

Conclusion

The GSFC scanning Raman lidar briefly described here has provided profiles of atmospheric water vapor and aerosols with high temporal (1 minute) and high spatial (75 m) resolution during nighttime operation during several recent field experiments. These data are being used to study upper tropospheric water vapor, cirrus clouds and their relationship with atmospheric aerosols, and the validation/calibration of both ground-based and airborne microwave radiometers. Additional studies currently under way which use the scanning capability of the instrument include measurements of the spatial and temporal scales of water vapor and the relationship between the aerosol optical parameters measured by the lidar and the physical characteristics of these aerosols. Modifications and upgrades now being added to the lidar system should extend much of this nighttime measurement capability into the daytime.