ANALYSIS OF ATMOSPHERIC WATER VAPOR MEASUREMENTS USING A RAMAN LIDAR

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INTRODUCTION

An analysis of atmospheric water vapor profiles measured by a multiple wavelength Raman lidar system often shows a great deal of fine structure. In this paper the scales of this structure are examined with respect to both the temporal variability and the variation with respect to altitude. We have observed that the water vapor profiles exhibit structure on the order of the resolution of the lidar (75 m). Using two independent wavelengths this structure was verified. The study of temporal variations of water vapor on a fine scale are more difficult to quantify. In an effort to do this a model was created using minimum square error techniques and the deviations from this model are studied.

DESCRIPTION OF THE SYSTEM

The LAMP lidar system was built in 1990-91 at Penn State University and configured in a standard shipping container to serve as a field laboratory for upper atmospheric measurements. It has since been retrofitted for lower atmospheric measurements [Philbrick et al. 1992; Stevens, 1992]. Figure 1 shows a schematic of the LAMP lidar system. The transmitter is an Nd:YAG laser, operated in the zenith pointing mode, at the doubled (532 nm) and tripled (355 nm) frequencies with a pulse rate of 20 Hz. The output power per pulse is approximately 500 mJ at 532 nm and 200 mJ at 355 nm. The lidar system is monostatic and utilizes an f/15 Cassegrain telescope with a primary diameter of 40.6 cm. The backscattered light collected by the telescope is transferred to the detector box via an optical fiber with a diameter of 1 mm and a numerical aperture of 0.22. The LAMP detector system splits the returned signal into separate channels which include the 532 nm and 355 nm Rayleigh channels, the Raman nitrogen channels, and the Raman water vapor channels. The Raman channel filters have thermally stabilized narrowband filters with a bandpass of 0.3 nm in order to suppress both the background noise and the signal bleed through at the laser line. The rejection ratio of these filters at the laser wavelength is on the order of 10^{12}. The backscattered light is detected using cooled PMTs operating in the photon counting mode. The PMTs signals are then averaged by a set of CAMAC data acquisition modules before they are transferred to a 486 computer for storage.

According to the lidar equation [Measures, 1992], the Raman backscattered signal due to water vapor, at a given altitude and frequency is dependent on the species number density at that altitude. However, the signal strength is also proportional to the Raman backscatter cross-section, the atmospheric transmission at that altitude for both the transmitted and scattered wavelengths as well as system constants such as the laser power, telescope area, system optical efficiency etc. It is most convenient to express the water vapor mixing ratio, $w(z)$, which can be expressed as:

$$w(z) = \frac{n_{WV}(z)}{n_{dry\ air}(z)} \frac{M_{WV}}{M_{dry\ air}} = K \frac{S_{WV}(z)}{S_N(z)} \quad (1)$$

where M is the molecular weight, n is the number density and the subscript WV implies water vapor. Since nitrogen is a constant fraction of dry air, the water vapor mixing ratio can be estimated by taking the ratio of the Raman water vapor backscatter signal (S_{WV}) to the Raman nitrogen backscatter signal (S_N) in any altitude interval. Thus the mixing ratio can be expressed as the second part of equation 1, where K is a constant of proportionality. This constant is easily determined by calibrating the lidar measurement against information obtained from a radiosonde launched concurrently. By taking this ratio, we eliminate the dependence of the lidar's water vapor measurement on the system characteristics.

DISCUSSION

The data for this discussion were taken as part of the ground correlation measurements made during NASA's Lite campaign which extended from 9-17 September, 1994, and during the VOCAR campaign at Pt. Mugu, CA which was conducted in Summer and Fall of 1993.

Figure 1 shows an example of a typical water vapor mixing ratio profiles of a half hour integrated data set with 75 m vertical resolution, measured by both the visible and the UV channels on 8/18/93 at Pt. Mugu, CA. Upon visually comparing the two profiles we see that not only is there good agreement in the general profile, but that the fine structure also seems to match well. Correlating the shapes of the two profiles yields a correlation coefficient which is biased to the coarser features of the water vapor profiles. However, by correlating the vertical gradients, i.e. taking the change in the water vapor mixing ratio for the change in altitude between two data points, is equivalent to performing a high pass filter on the data. This serves to suppress the slowly varying features of the profile, and makes the correlation more sensitive to the finer vertical structure. Figure 2 shows the relation of the gradients of profiles measured by the visible and UV channels, for the example shown in Figure 1.

The water vapor profile used to study the temporal fine structure is shown in Figure 3. This data was taken on September 10, 1994 during the ground correlation experiments of the LITE campaign. Here the x-axis represents the universal time in hours, the y-axis the altitude and the color intensity represents the water vapor mixing ratio in g/kg. This figure shows the variations in the boundary layer with time. The general trend is that the nocturnal boundary layer height decreases with time [Stull, 1993] as seen. In addition in this particular example we see that there is an additional layer of moist air between 3000 m and 4000 m. We can see the layer descending and mixing with the layer below.

In order to quantify the small scale structure and variability, the water vapor distribution was modeled as a function of time and altitude. For each altitude we modeled the water vapor using a basic dc term, or constant on which were superimposed temporal variations.

$$w(z,t) = c_0(z) + c_1(z)\,t \qquad (2)$$

The night of September 10 was chosen since it was a relatively long and complete data set on a clear night. This makes the initial case study less complicated. The data was divided into slices with respect to height, each slice having the resolution of the lidar system. The data was then fit to the model using a minimum square error fit. The coefficients obtained for the fit are shown in Figure 4. As expected the term c_0 agrees fairly well with the average for the entire night. Future work will include using both radiosondes and microwave radiometer data in order to constrain the model.

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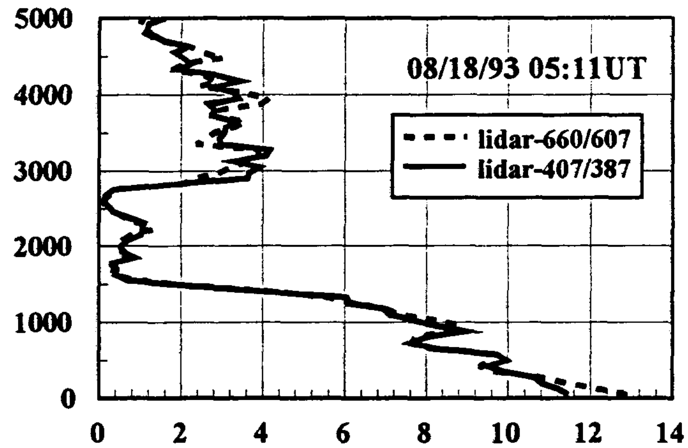

Figure 1

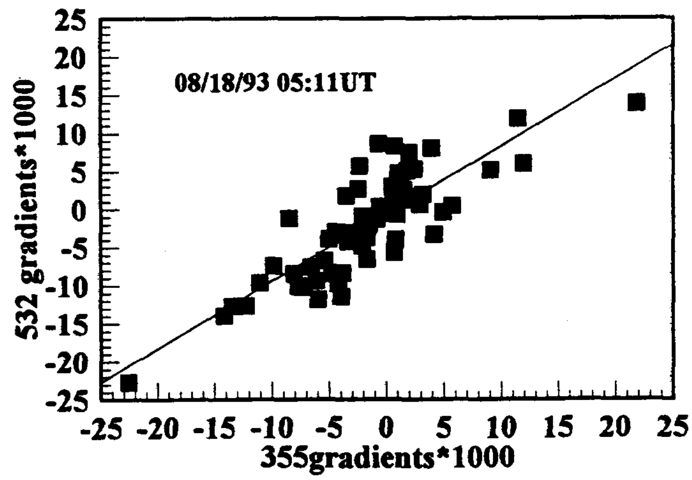

Figure 2

September 10, 1994

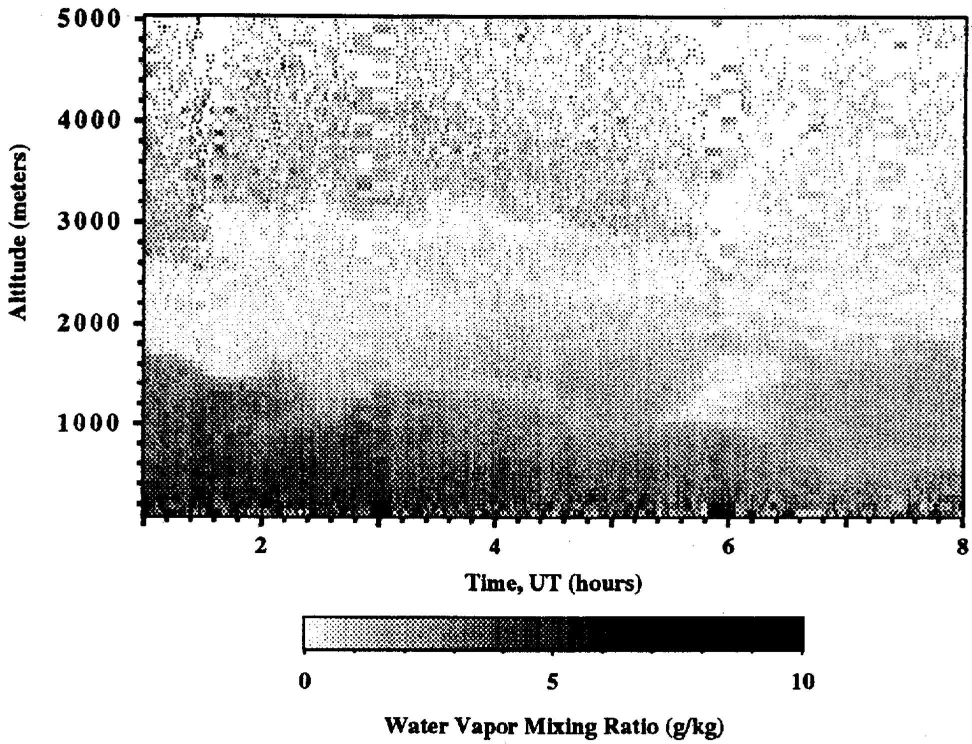

Figure 3

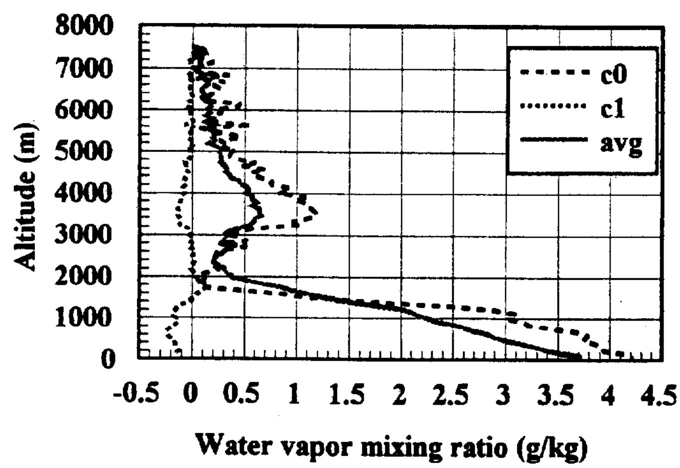

Figure 4