Laser Reviews

Study of Atmospheric Water Vapor Using a Raman Lidar

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Water vapor is one of the most important constituents in the Earth's atmosphere. It fuels storm development and is the most infra-red active atmospheric molecule. It plays a major role in dynamics and radiative transfer. The Raman lidar development at NASA Goddard is able to measure water vapor profiles, at night, from near the surface to ranges of 9-10 km along any elevation angle from horizon to horizon in a single plane. The lidar has been used in a number of field studies since its first deployment in the fall of 1991. Comparisons of lidar derived moisture profiles with radio-sonde measurements have shown good agreement for warm moist conditions. Consistent disagreement has been noted for sondes using carbon hygrometers when the relative humidity is below about 20%

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1. Introduction

Water vapor is one of the most important constituents in the Earth's atmosphere. It plays a crucial role in the heat and radiation balance of the Earth-Atmosphere system, from heat transfer at the surface to the radiative effects of clouds. Water vapor is the most infra-red active molecule in the atmosphere and thus will be a major player in any global warming scenario¹⁾.

In addition water in all its forms contributes significantly to the character of our weather. The evaporation of water at the surface tempers the otherwise wide diurnal swings of temperature we see over dry deserts. The accumulation of water vapor in the boundary layer provides fuel for severe storm development. The gradient of water vapor with altitude determines the convective stability of the troposphere which when unstable can trigger deep convection. Water vapor and the clouds which result from its convergence represent the two largest uncertainties in the global models which are used to predict global change²⁾.

At present, water vapor is measured routinely over a world-wide network of radio-sonde launch sites. The radiosondes are widely spaced (about

every 400 km in the USA and Western Europe) over the continents missing most of the atmosphere over the oceans. In addition, the moisture sensors on the balloons have limitations especially when the atmosphere is cold (less than -40°C) and dry (less than 20% relative humidity)³⁾. Passive infra-red and microwave sensors onboard orbiting satellites are able to observe upwelling radiation associated with atmospheric moisture. At most, the present satellite instruments are limited to total integrated measurements. Advanced satellite sensors which will have profiling capability are planned for the EOS (NASA's Earth Observing System) era in the early part of the next century.

High quality research measurements of water vapor and its variability are required to gain a better understanding of the atmospheric processes involving moisture such as: surface evaporation, convective stability, boundary layer growth, cloud formation and precipitation. Instrumented aircraft and research quality balloons have been used for these studies. They are limited to measurements along their line of flight and therefore may miss important structure in their vicinity. Continuous measurements at multiple levels on a meteorological tower have been used very effectively to study

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rapidly evolving phenomena but are limited to observations between the surface and the top of the tower which may be only a few hundred meters. A Raman lidar which is able to provide continuous measurements at many altitude levels up to 8-9 km is an ideal tool to measure moisture profiles and its variability.

This paper will give a brief review of the Raman lidar technique, then a description of the lidar developed at Goddard. This will be followed by examples of the lidar data which will demonstrate the comparison with standard radio-sondes and the remarkable variability of atmospheric moisture. Finally, we will summarize some of the advantages of Raman lidar.

2. Raman Technique

Raman scattering is weak scattering by molecules. The scattered radiation is shifted in wavelength from the exciting radiation by an amount which is unique to the scattering molecule. In Raman scattering, the scattering molecule absorbs the incident photon then immediately emits a photon of slightly different energy in the transition to a vibrational or rotational excited state. The probability for the molecule ending up in one of these excited states is very low generally more than three orders of magnitude less than the probability of the molecule ending up in the original state (Rayleigh scattering). Because of the weak nature of Raman scattering our lidar has been optimized for night-time operations. Raman scattering in the atmosphere has been under study since the late 1960's. The ratio of Raman scattering by atmospheric water vapor to scattering from nitrogen is proportional to water-vapor-mixing-ratio⁴). Water-vapor-mixing-ratio is defined as the mass of water vapor to the mass of dry air and is a conserved quantity for all atmospheric processes except condensation and evaporation.

3. Raman Lidar

The Raman lidar developed at the NASA Goddard Space Flight Center consists of a 76 cm diameter Dall-Kirkham telescope aligned with a XeF excimer laser. The laser and telescope are housed in an environmentally controlled van and point out the rear of the van toward a large flat mirror which can be rotated so that the lidar can make atmospheric measurements along any elevation angle in a plane which is perpendicular to the long axis of the van. The laser puts out an average power of 12 watts firing at 400 Hz. The output of the telescope is divided by di-chroic beamsplitters into four wavelength

channels: one at the laser wavelength(351 nm), and the others at the Raman wavelength's for oxygen (372 nm), nitrogen(382 nm) and water vapor (402 nm). Each wavelength channel is further divided into a low (5 %) and a high sensitivity (95 %) detector allowing unsaturated measurements to be made from near the surface up to the maximum altitude. The output of each of the eight detectors is amplified and applied to individual accumulating photon counters. Typically, counts are accumulated for 23,000 shots (one minute) in 0.5 micro-second bins which correspond to an altitude resolution of 75 meters.

4. Water Vapor Measurements

The Goddard Raman lidar has been used in a number of field missions since it's first deployment in the Spectral Radiation Experiment (SPECTRE) conducted during November and December, 1991 at Coffeyville, KS. Data from SPECTRE and the Clouds and moisture Experiment (CAMEX) conducted during September and October, 1993 at Wallops Island, VA will be shown to demonstrate the capabilities of the lidar. A vertical profile of water-vapor-mixing-ratio measured by the lidar compared with an independent measure of water vapor from a radio-sonde is shown in Fig. 1. The lidar ratio was calibrated to a number of coincidentally launched radio-sondes from the entire experiment period using only relative humidities above 30 % between the

Fig. 1 A comparison of water-vapor-mixing-ratio obtained with the Raman lidar and a radio-sonde. Also shown is the mixing-ratio for a constant 20 % relative humidity. The data were acquired on Dec. 6, 1991 in Coffeyville, KS during the SPECTRE field campaign.

Fig. 2 A time- height image of atmospheric water vapor on December 6, 1991.

Fig. 3 A Fast Fourier Transform of the temporal variation of atmospheric moisture over an altitude range of 750 m centered at 1 km acquired on the night of Dec 6, 1991.

Fig. 4 A comparison of water- vapor- mixing- ratio obtained with the Raman lidar and two radiosondes carried aloft on the same balloon. Also shown is the mixing- ratio for a constant 20% relative humidity. The data were acquired on Oct. 5, 1993 at Wallops Island, VA during the CAMEX field campaign.

surface and cloud base when clouds were present⁵⁾. Note from the figure the good agreement between the lidar data and the sonde data up to an altitude of 2.5km and again from 7 to 10 km. The disagreement between 2.5 and 7 km is due primarily to the sondes limitations in reporting measurements less than 20 % relative humidity⁶⁾. The figure shows that the sonde output tends to parallel the 20% relative curve also shown in the figure. Measurements like that shown in Fig. 1 were acquired once per minute over the 12 hour observation period on December

Fig. 5 Time- height images of the variation of atmospheric vapor acquired during the operational period of Oct. 5, 1993. The three images (left, center, right) were constructed using data acquired while the lidar was pointed 45 degree off vertical toward the west, on the vertical, and 45 degrees off vertical toward the east.

6, 1991.

These data have been combined together and color coded to provide a measure of the time-height variation of water vapor during the period and is shown in Fig 2. Figure 2 shows a moistening of the first kilometer of the atmosphere over the eleven hours of operation.

Above this lowest layer the moisture is seen to decrease with altitude. The subsiding layer whose base starts at 8-9 km and decreases with time to about 6km at the end of the observation period was associated with cirrus clouds. Data from any altitude level can be studied in more detail. Figure 3 shows a Fast Fourier Transform of the time dependent water vapor distribution at an altitude of 1km acquired on Dec. 6, 1991.

The figure shows that the logarithm of the spectral energy density falls off linearly with the logarithm of frequency. This shape is commonly referred to as a power-law distribution. The spectra is compared with a straight line of slope of -1.8. Spectra of water vapor at other altitudes and acquired at other locations tend to show power-law distributions with slopes around -2.0. This spectral shape is most likely due to the mixing of the atmosphere by ubiquitous gravity waves.

A comparison of water vapor acquired by the Raman lidar and two radio-sondes launched on the same balloon is shown in Fig. 4. The comparison shows good agreement between the lidar and the Vaisala sonde which does not have the 20 % relative humidity floor. The AIR sonde shows its inability to accurately report low relative humidities at altitudes above 5 km. Water vapor data were acquired over a 4.5 hr. period on October 5, 1993. The three panels of data acquired during the operation period are shown in Fig. 5. During this observation period the pointing capability of the lidar was utilized. Through the use of the large rotatable mirror the lidar was sequentially pointed on the vertical to ac-

quire one minute of data then toward the east 45 degree off the vertical for one minute then on the vertical and next toward the west 45 degrees off the vertical.

This sequence was repeated throughout the observation period. The center panel of Fig. 3 shows the time-height structure of the water vapor while the lidar was pointing on the vertical. The right and left panels shows the time-height structure of the water vapor while the lidar was pointing 45 degrees off the vertical in the east and west direction respectively. One can note from the three panel small differences in the spatial structure of moisture looking in the three directions.

5. Summary

The Raman lidar has proven to be a valuable tool for studying small scale structure and variability of atmospheric water vapor. The opportunity to measure water vapor profiles up to 8-9 km has opened up the atmosphere above tower heights for detailed temporal studies. Prior to these lidar measurements we did not have the ability to investigate true temporal changes. Aircraft measurements while a valuable means to study fluctuations provide primarily a spatial look at atmospheric variability. Our attempts over the years to calibrate our lidar system has helped identify short-comings in the standard methods of measuring atmospheric water vapor.

References

- 1) V. Ramanathan: Science 240 (1988) 298.
- 2) J. F. B. Mitchell, C. A. Senior and W. J. Ingram: Nature 341 (1989) 132.
- 3) W. P. Elliot and D. J. Gaffen: Bull. Amer. Meteor. Soc. 72 (1991) 1507.
- 4) S. H. Melfi: Appl. Opt. 11 (1972) 1605.
- 5) R. A. Ferrare, S. H. Melfi, D. N. Whiteman, K. D. Evans, F. J. Schmidlin, D. O'C. Starr: submitted to J. Atmos. Oceanic. Tech. (1994).
- 6) C. G. Wade: J. Atmos. Oceanic. Tech. 11 (1994) 687.