Upper Tropospheric Water Vapor: A Field Campaign of Two Raman Lidars, Airborne Hygrometers, and Radiosondes

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Introduction

Water vapor in the atmosphere plays an important role in radiative transfer and the process of radiative balance so critical for understanding global change. It is the principal ingredient in cloud formation, one of the most difficult atmospheric processes to model, and the most variable component of the earth-atmosphere albedo. And as a free molecule, it is the most active infrared absorber and emitter, thus, the most important greenhouse gas. The radiative impact of water vapor is important at all levels of the atmosphere. Even though moisture decreases by several orders-of-magnitude from the earth's surface to the tropopause, recent research has shown that, from a radiative standpoint, a small percentage change in water vapor at any level is nearly equivalent (Arking, private communication, 1998). Therefore accurate and precise measurements of this important atmospheric constituent are needed at all levels to evaluate the full radiative impact. The need for improved measurements in the upper troposphere is particularly important because of the generally hostile (very dry and cold) conditions encountered.

Because of the importance of water vapor to the understanding of radiative transfer, the U.S. Department of Energy's (DOE's) Atmospheric Radiation Measurement (ARM) Program initiated a series of measurement campaigns at the Cloud and Radiation Testbed (CART) site in Oklahoma, especially focused on atmospheric water vapor. Three Water Vapor Intensive Observation Periods (IOPs) were planned. Two of the Water Vapor IOPs have been completed: the first IOP was held during the fall of 1996 with a focus on boundary layer water vapor measurements, and the second was conducted during the fall of 1997 with a focus on both boundary layer moisture and moisture in the upper troposphere.

This paper presents a review of the intercomparisons of water vapor measurements in the upper troposphere acquired during the second Water Vapor IOP. Data to be presented include water vapor measurements from two Raman lidars, the NASA Goddard scanning Raman lidar (SRL) and the CART Raman lidar (CARL), a number of Vaisala radiosondes launched during the IOP campaign, and a dew point hygrometer flown on the University of North Dakota Cessna Citation Aircraft.

The Water Vapor IOP was conducted during September 15 to October 5, 1997, at the CART site near Lamont, Oklahoma. During the IOP there were ten nights where the meteorological conditions (thin or no cloud cover) allowed for lidar measurements up to and including the upper troposphere. Data acquired during these nights will be discussed after a brief description of the two lidar systems.

The SRL was developed in the early 1990s and was first deployed in the fall of 1991 in the Spectral Radiance Experiment (SPECTRE)/First International Satellite Cloud Climatology Program (ISCCP) Regional Experiment (FIRE) campaign in Coffeyville, Kansas (Whiteman et al. 1992). The SRL consists of an XeF excimer laser aligned with a 0.76-m diameter telescope. The average output of the laser is 24 W at a wavelength of 351 nm at a repetition rate of 400 Hz. The system has four spectral channels: the laser wavelength, and the Stokes-shifted Raman wavelengths associated with oxygen, nitrogen, and water vapor. Photon counting data is recorded simultaneously from the photomultiplier tubes (PMTs) in the four channels in sequential 0.5-microsecond bins, corresponding to a range resolution of 75 m. Data is typically accumulated from 23,200 laser shots (approximately 1 minute at 400 Hz) before being stored for real-time analysis. The SRL was optimized for nighttime operation.

The CARL system was developed during the mid 1990s and was delivered to the Oklahoma site during the summer of 1996 (Goldsmith et al. 1998). The CARL system uses a tripled Nd-YAG laser aligned with a 0.61 m telescope. The laser generates 12 W average power at the tripled wavelength of 355 nm, at a repetition rate of 30 Hz. It is a three spectral channel lidar (Raman scattering by oxygen is not observed), with the channel locations appropriate to the output frequency of the tripled Nd-YAG laser. The system acquires photon counting data in 0.25 microsecond bins (37.5 meter range resolution) typically accumulating data from 1740 laser shots before storing (corresponds to one minute of operation). The CARL system was optimized for daytime operation with narrow spectral channels and a narrow field-of-view, thus giving it outstanding characteristics for nighttime operations.

Both lidars routinely provide vertical profiles of water vapor mixing ratio, aerosol scattering ratio, and aerosol optical depth. Figures 1 and 2 show typical profile comparisons of water vapor mixing ratio data from the various measurement techniques during two different observation periods. The profiles shown in the two figures include integrated SRL data at full vertical resolution to an altitude of 8 km with smoothing to 300 m resolution above, average CARL data with vertical smoothing to 312 m above 9 km, data from two sondes launched during each observation period, and Citation data from the dewpoint hygrometer during both ascent and descent of the aircraft.

Data in Figure 1 were acquired on September 26, 1997 between 0230 UTC and 0430 UTC (between 2130 CDT and 2330 CDT on the evening of September 25, 1997) during the IOP. Independent synoptic meteorological information indicates that during the observation period there was moistening in the altitude range 9 km to 12 km, which is consistent with data from the two sondes given in the figure. Comparison of the data from all the measurements up to an altitude of 8.5 km shows good agreement. Above 8.5 km

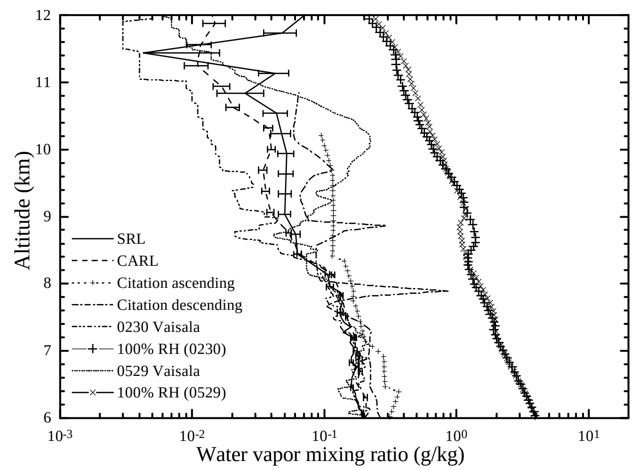

Figure 1. SRL and CARL on September 26, 1997, integrated from 0230 UTC to 0430 UTC compared to the Citation dewpointer, during ascent and descent, and to the Vaisala radiosondes. Also shown for comparison is the water vapor mixing ratio profile for 100% relative humidity derived from the sonde temperatures and pressures.

and up to 11 km, we see reasonable agreement between the two lidars and the aircraft measurements, with the SRL data slightly wetter than CARL, and the aircraft data wetter than SRL. These profiles lie between the measurements from the two sondes, which is consistent with the moistening of the atmosphere during the IOP.

Figure 2 shows data acquired during the IOP between 0100 UTC and 0400 UTC on October 4, 1997. Independent

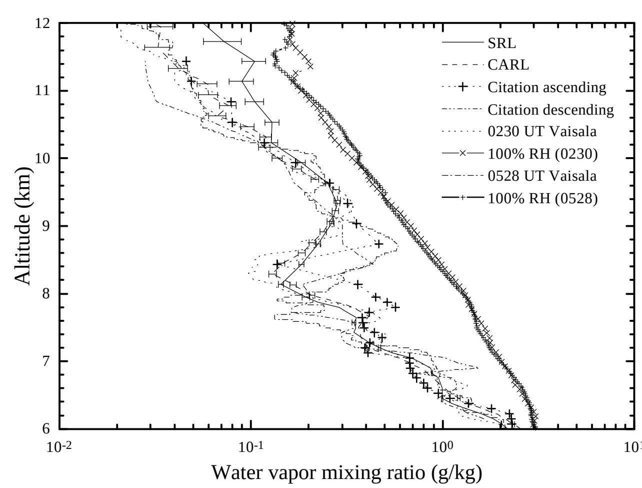

Figure 2. Same as Figure 1 except these data are from October 4, 1997, 0100 UTC to 0400 UTC. Note the scale on the abscissa.

observations indicate that the upper troposphere moisture was essentially unchanged during the IOP. Comparison of the profiles from all the measurement systems show good agreement from 6 km to 12 km with the exception that the SRL data indicates wetter conditions above 10 km.

The wet bias seen in the SRL data when compared to the CARL data, shown in both figures, could be due to a positive bias in the water vapor channel of the SRL, introduced by signal-induced-noise (SIN). The SRL has a larger field-of-view than the CARL and therefore, when the laser pulse first crosses into the field-of-view of the telescope, the PMTs in the water vapor channels of the SRL would be exposed to a relatively larger backscatter than the corresponding PMTs in the CARL. This relatively high exposure at short range (low altitude) would be more likely to produce SIN in the SRL water vapor data at high altitudes, where the backscatter from water molecules is low, leading to a wet bias in the upper troposphere.

Figure 3 is a summary of the comparison of the CARL data with the sonde data from the nine clear sky nights of observation between September 26 and October 4, 1997. Shown in the figure is the mean percentage difference between the CARL and the sondes, for 29 independent comparisons, calculated using the following relationship: (CARL-Sonde)/CARL. The bars in the figure represent the standard deviation of the mean difference. For the comparisons, CARL data was accumulated over a thirty minute period after the launch of each sonde. The timing difference allows for the balloon to rise to the upper troposphere so as to assure the best spatial and temporal overlap of the two measurements. In the comparison, only CARL data with a signal-to-noise greater than 4 was used. The figure shows a gradually increasing trend in the mean difference between the two measurements. The trend is seen as a wet bias in the CARL data compared with the sonde data. The wet bias could be due to a small amount of SIN in the CARL data and/or a dry bias of the sonde data. A dry bias in sonde data in the upper troposphere has been reported by other investigators (Soden et al. 1994).

We must continue our focus on upper tropospheric moisture observations until we are confident of the accuracy and precision of the measurements, and we come to understand the spatial and temporal variability of naturally occurring moisture. Until then, we cannot be certain of our predictions of the radiative effects of atmospheric water vapor.

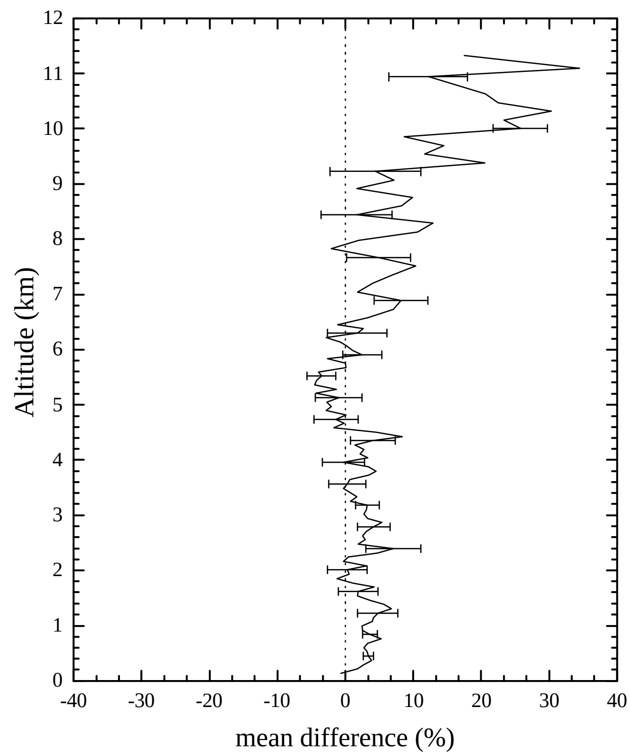

Figure 3. Mean difference profile comparing CARL to radiosondes for the 1997 Water Vapor IOP.

References

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