Accomplishments of the Water Vapor IOPs: An Overview

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Introduction

The second Water Vapor Intensive Observation Period (WVIOP) was held at the Southern Great Plains (SGP) Central Facility (CF) from September 15 to October 5, 1997, almost exactly 1 year after the first. As with the first WVIOP, this year's activities have resulted in an improved ability to measure atmospheric water vapor. This paper presents an introduction to the goals and participants, and a sampling of significant findings of the 1997 WVIOP from the perspective of the WVIOP chief scientist. For more detailed accounts of specific instrumentation and analyses, refer to the papers presented in this proceedings by the many investigators who participated in these IOPs.

The overall goal of the WVIOPs has been to improve the way climate models handle radiation by way of reducing the uncertainties in atmospheric water vapor measured at the Cloud and Radiation Testbed (CART) sites. The accuracy of Atmospheric Radiation Measurement (ARM) radiosonde water vapor observations was first called into question by the longwave Quality Measurements Experiment (QME) (Brown et al. 1998; Whitney et al. 1997), which compares infrared spectra from the Atmospheric Emitted Radiance Interferometer (AERI) with spectra computed with the line-by-line radiative transfer model (LBLRTM) using radiosonde input. The QME results showed that the limiting factor in comparing measured and computed longwave radiances was the uncertainty in the measured atmospheric water vapor. The radiance residuals were shown to be highly correlated with the difference between microwave and radiosonde precipitable water vapor (PWV), suggesting rather large variations (25% to 30% peak to peak in mixing ratio) in the radiosondes (Lesht and Liljegren 1997). A major objective of the first WVIOP was therefore to understand and reduce this radiosonde-to-radiosonde variation, and that goal was achieved. The radiosonde variations were found to be largely a calibration batch dependent problem (Lesht 1998), and the prescribed solution has been to adopt a radiosonde scaling exercise, whereby the radiosonde profiles are multiplied by a scalar factor to make them have the same PWV as that derived from the microwave radiometer for the same time period. QME residuals with and without this PWV scaling clearly demonstrate the need for this type of radiosonde scaling using a stable reference (Turner et al. 1998).

The objectives of the second WVIOP are many. All of them are aimed at characterizing the current observing accuracy and developing improvements to reduce the uncertainties and approach by 2% absolute accuracy. To that end, perhaps the main focus of the second WVIOP is to understand and resolve the differences between the various absolute standards for measuring atmospheric water vapor: the salt bath calibration (radiosonde and similar in situ sensors), microwave radiometer-derived PWV (based on its calibration and well-known forward model), and the chilled mirror (direct measure of dew point temperature). Also, the Global Positioning System (GPS) and a variety of solar sensor-derived PWV measurements were included in the comparisons for the first time. Profiling capabilities of the CART and Goddard Space Flight Center (GSFC) Raman lidars were investigated and tethered balloon and kites were used to obtain profiles in the lowest few kilometers using in situ sensors. Facilitated by the many aircraft present for the other five simultaneous IOPs, the WVIOP also had a strong focus on water vapor measurements and comparisons at higher altitudes.

Observations from the 1997 WVIOP

September in Oklahoma again provided a wide range of clear-sky atmospheric water vapor conditions, with the PWV ranging from ~1 cm to over 5 cm. Figure 1 shows a time series of PWV for the IOP, derived from the GPS receiver stationed at the CF.

Instrumentation and typical operating procedures during the IOP included 1) continuous measurements of PWV by the microwave radiometers [including the ARM CF, Environmental Technology Laboratory (ETL), and National Aeronautics and Space Administration (NASA) GSFC DOER instruments], numerous solar radiometers [including the CIMEL, multifilter rotating shadowband radiometer (MFRSR), and NASA Ames AATS instruments], and GPS (sensors at the CF and Lamont); 2) Raman lidar profiling

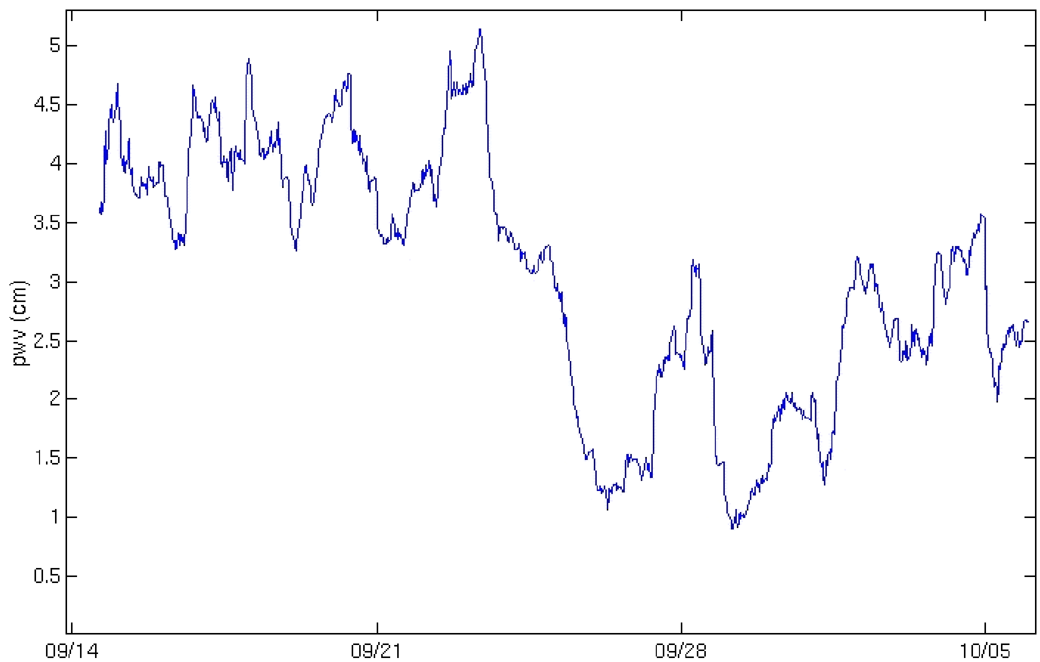

Figure 1. GPS PWV time series. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/revercomb-98.pdf*.)

with the CF instrument (day and night), and the GSFC scanning Raman lidar (with new daytime mode); 3) Vaisala RS-80 radiosonde launches every 3 hours, combined with dual radiosonde launches using several calibration batches every 6 hours; 4) continuous in situ measurements with the surface meteorological observation system (SMOS), ground- and tower-based (25-m and 60-m) chilled mirrors, and ground- and tower-based relative humidity sensors (Qualimetrics and high quality Vaisala); 5) AERI radiance observations and water vapor retrievals with the CF instrument and the mobile prototype unit; 6) AERI-ER (extended range AERI) and Absolute Solar Transmittance Interferometer (ASTI) radiance observations; and 7) nightly profiling with Meteolabor chilled mirrors and/or AIR tethersondes using tethered balloons and kites. Many observations focused on clear nighttime conditions, and on the many aircraft (Altus UAV, Twin Otter, Citation, King Air) over-passes, offering higher altitude comparisons with their on-board in situ sensors (chilled mirrors or frost point hygrometers). Daily meetings were held at 2 p.m. to review instrument status, compare observations, and prepare for upcoming operations. Table 1 summarizes the focus groups and organizers of the IOP.

Absolute Standards

As mentioned earlier, the main focus of this WVIOP was to understand and resolve differences between various instruments considered to be candidates for absolute measurements of water vapor. In all cases, this requires a well calibrated and stable instrument, and a sound, proven way of deriving water vapor from the measurements. Initial quandaries regarding this absolute issue going into the 1997 IOP were as follows:

- 5% differences in total PWV common, range of 15%
- microwave instruments (CART, ETL) differ by 5% to 10%
- GPS much dryer than CART microwave, slightly dryer than ETL
- Solar instruments differ by 5% to 10% also.

Figure 2 shows a time series of various PWV measurements for September 18. The overall agreement between the different sensors on this scale is a great achievement. The differences shown in this plot, however, are large compared to our goal of 2% absolute accuracy. A comparison of PWV measurements from the 1997 WVIOP is summarized in Figure 3 (compliments of B. Schmid). The bottom panel shows the differences in the various PWV measurements interpreted as pure offsets (independent of water vapor amount) from the values obtained from the CF GPS. Interpreted as percent errors, these differences correspond to

Table 1. Focus groups.

Topic	Organizers
Raman Lidar (water vapor mixing ratio profiles)	Dave Turner, Keith Evans, Harvey Melfi
Microwave/GPS/Solar (microwave brightness temperatures and total precipitable water)	Ed Westwater, Vic Morris, Paul Racette, Dave Jones, Seth Gutman, Beat Schmid, Joe Michalsky, Jim Barnard
Balloon-Borne Sounding System (BBSS) (water vapor and temperature for single and dual launches)	Barry Lesht, Dave Tobin
In Situ Chilled Mirror Intercomparisons (before and after IOP)	Scott Richardson, Mike Splitt
Tower/SMOS/BSS Launch Site In Situ Sensors	Scott Richardson, Dave Cook, Dave Tobin
Chilled Mirror/Tethersonde from Balloon and Kite (water vapor and temperature profiles)	Bill Porch, Ben Balsley, Mike Jensen
AERI (water vapor and temperature retrievals and longwave radiances)	Wayne Feltz, Bob Knuteson
AERI/LBLRTM QME (radiance residuals)	Bob Knuteson, Dave Turner, Pat Brown

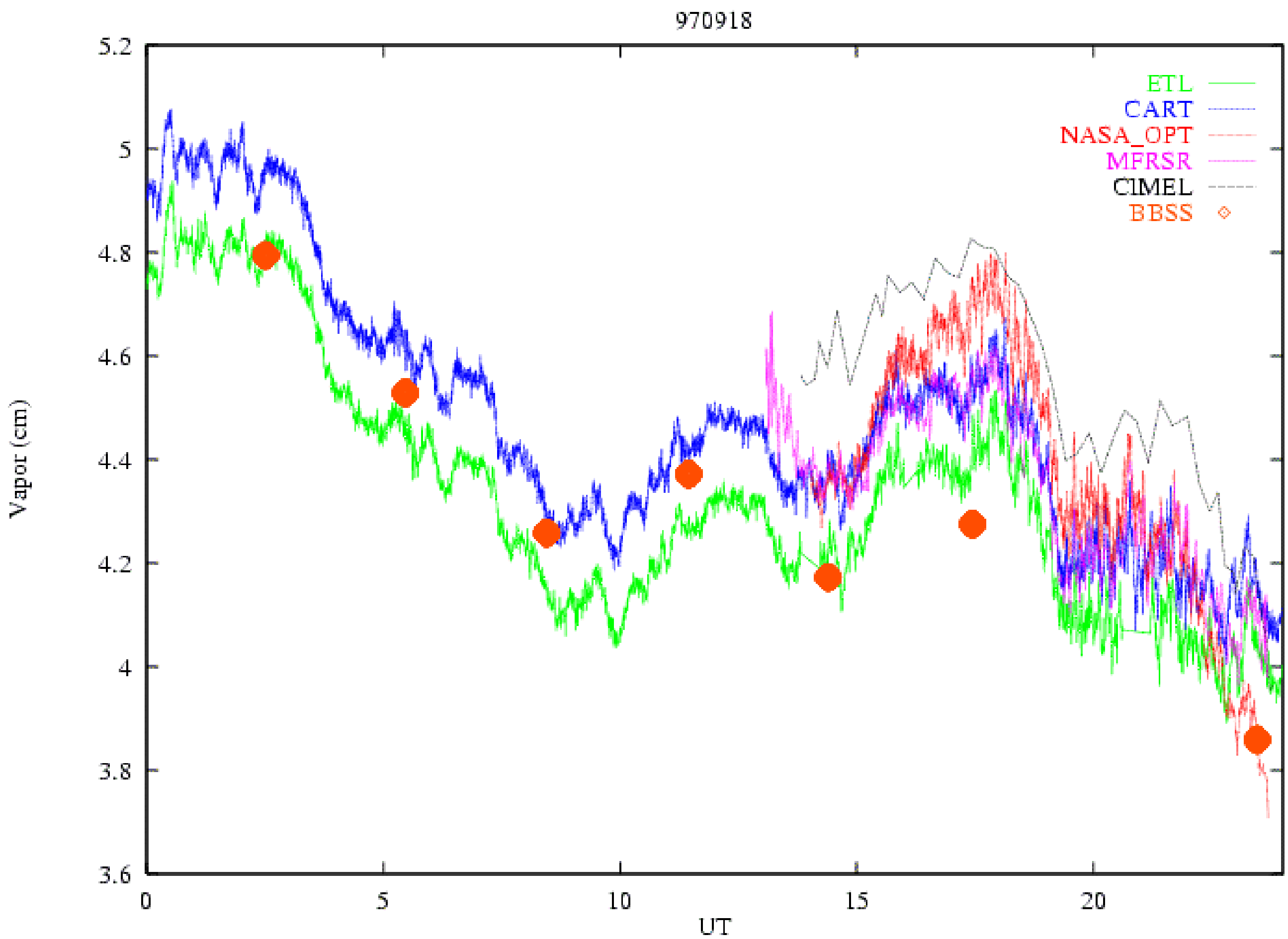

Figure 2. PWV observations for September 18, 1998. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/revercomb-98.pdf*.)

Water Vapor IOP, Sep 13 - Oct 5, 1997
Comparisons with respect to GPS at CF
Half hour averages, Interpolation to nearest neighbor for BBSS
Additional constraint max. ILW 0.2 cm for MWR

	Best Fit					Absolute Differences			Relative Differences	
	n	slope	intercept (cm)	r^2	RMSE (cm)	mean (cm)	stdev (cm)	RMSE (cm)	mean (%)	stdev (%)
GPS Lamont	1025	1	0.029	0.992	0.093	0.029	0.093	0.097	1.1	3.1
MWR ETL1	967	1.007	0.051	0.983	0.14	0.072	0.14	0.157	3.4	5.7
MWR ETL2	373	0.999	0.104	0.907	0.151	0.101	0.151	0.182	2.6	3.7
BBSS	145	0.996	0.133	0.976	0.162	0.12	0.162	0.203	5.1	6.7
AATS-6	242	1.005	0.127	0.984	0.126	0.14	0.126	0.189	6.2	5.4
GSFC Lidar	103	1.041	0.132	0.982	0.148	0.232	0.154	0.281	10.1	7
CART Lidar	388	1.081	0.067	0.974	0.124	0.237	0.136	0.274	11.7	6.5
MFRSR	309	0.991	0.266	0.978	0.161	0.241	0.161	0.291	10	7
MWR CART	852	1.031	0.202	0.989	0.116	0.293	0.12	0.317	11.4	5.8
Cimel	279	1.058	0.236	0.979	0.151	0.395	0.161	0.428	15.7	6.7

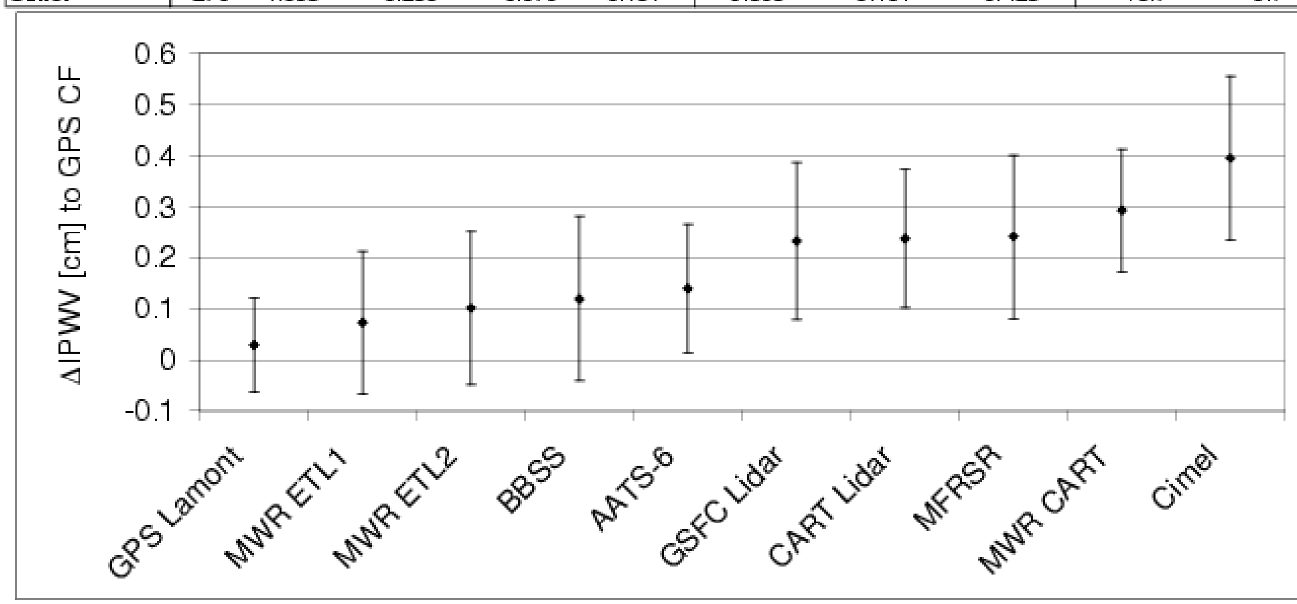

Figure 3. PWV comparison summary for the 1997 WVIOP. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/revercomb-98.pdf*.)

roughly a 16% spread in PWV, from the Lamont GPS to Cimel. The average difference between the radiosondes [Balloon Borne Sounding System (BBSS)] and the CART microwave is ~2 mm, or 8%, and the average difference between the Lamont GPS (with ERL processing) and the CART microwave is ~3 mm, or 12%. These figures represent the differences between the salt bath, microwave, and GPS standards.

Other candidates for absolute water vapor include the in situ ground- and tower-based sensors. Analysis of the radiosonde comparison to tower measurements in the 1996 WVIOP pointed out significant problems with the existing ARM tower sensors and peculiar artifacts related to the processed Vaisala radiosonde data near the surface (Knuteson et al. 1998). During the 1997 IOP, comparisons of 25-m and 60-m tower observations showed that the Qualimetrics relative humidity sensors were not performing correctly, and they have since been replaced with redundant sensors packaged by Vaisala. Figure 4 shows a comparison of the 60-m Vaisala and chilled mirror sensors for the 1997 IOP. For nearly the entire IOP, the two sensors agreed to better than 2% in mixing ratio. In one particular analysis (Richardson and Tobin 1998), the scanning Raman lidar profiles were used as a transfer standard and scaled to match the 60-m tower mixing ratios. These profiles were then integrated to yield total column values in order to relate the in situ tower measurements to the other PWV observations.

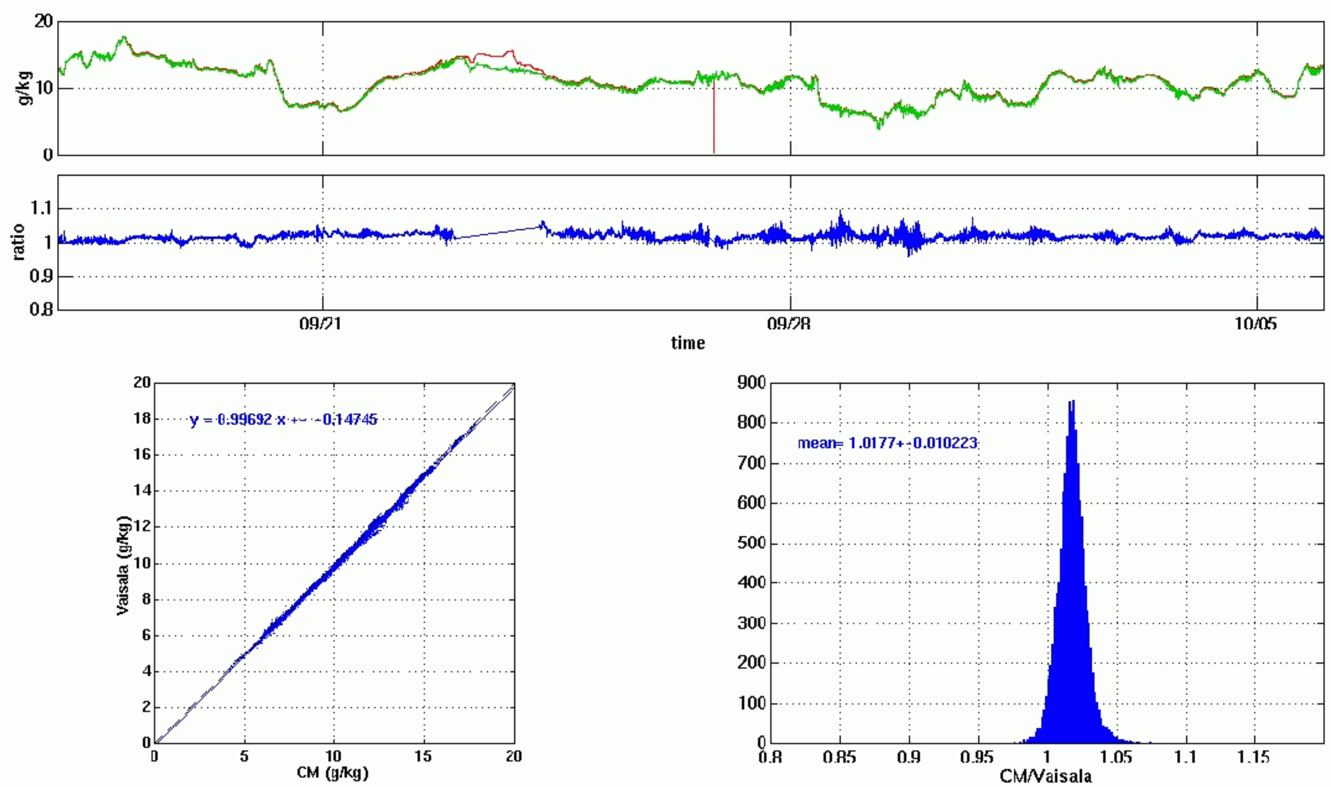

Figure 4. 60-m chilled mirror (red) and Vaisala (green) observations and comparison for the IOP project. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/revercomb-98.pdf*.)

Results from this analysis, which rely on the altitude invariance of the Raman lidar calibration, are shown in Figure 5. The comparison with the CART microwave PWV values shows very good stability (slope = 1.01 +- 0.01) but an offset of ~1.8 mm. The comparison with the CF GPS values shows no significant offset, but a ~5% dry fractional error with respect to the tower/Raman values. A similar comparison of the tower/Raman PWV values to the BBSS shows no significant offset or bias, suggesting overall consistency between the in situ chilled mirror and Vaisala sensors and the radiosondes. Several hypotheses for the differences between the MWR, tower/Raman, and GPS values are under ongoing investigation.

Upper Altitude Results

The 1997 IOP also had a focus on upper level water vapor measurements and comparisons. While PWV and tower-based radiosonde scaling exercises can remove much of the radiosondes' calibration-dependent uncertainty, this type of scaling weights the lowest portion of the profile and does not remove relatively small errors (in terms of their contribution to PWV) in upper level water vapor. Such errors at high altitude and low water vapor concentrations have a very large effect on computed outgoing longwave radiation and are an important issue when producing best estimate profiles for the CART sites, especially with respect to using CART as a satellite validation site. Numerous aircraft observations with dew and frost point hygrometers and chilled mirrors, and long time average analysis of the Raman Lidar data has led to some very exciting findings regarding high altitude radiosonde water vapor measurements at the SGP (Melfi et al. 1998). Initial comparisons, such as the one shown in Figure 6, suggest a dry bias of the radiosondes at high altitude/cold temperature.

Summary

The 1997 WVIOP is highlighted by the collection of perhaps the most comprehensive set of state-of-the-art atmospheric water vapor measurements: a month-long data set of multiple microwave, GPS, solar, in situ, tethered and kite-based, Raman lidar, infrared, and aircraft observations. Mean PWV values for the IOP are summarized in Figure 3, and differ by significant amounts for the various absolute standards (for example, roughly 3 mm or 12% between the

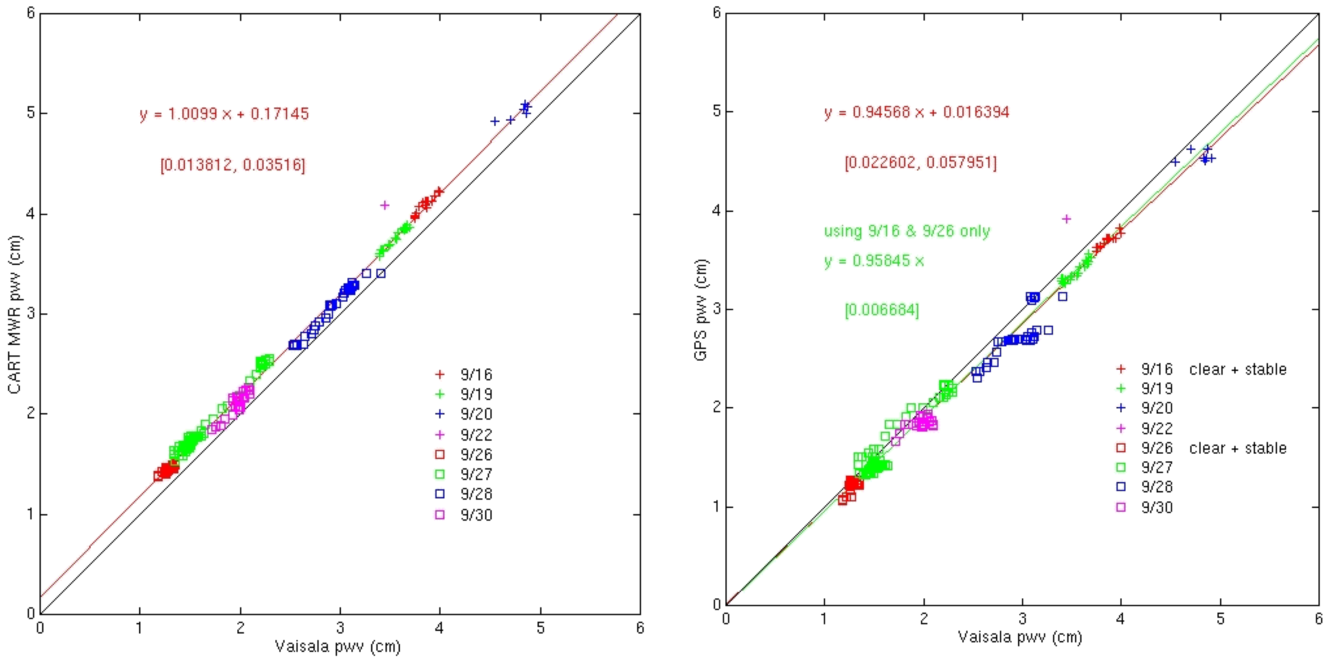

Figure 5. CART MWR and CF GPS PWV versus 60-m tower/Raman lidar PWV. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/revercomb-98.pdf*.)

BBSS and CART MWR). Continuing analysis of this data set will resolve these questions regarding the absolute measurement issue. Initial upper-level measurements and comparisons from several case studies involving CART and GSFC Raman lidar and aircraft-based observations suggest a dry bias in the radiosondes.

The next WVIOP is scheduled for fall 1999. It will continue with a focus on the absolute issue, and more emphasis will be put on upper-level measurements with the participation of an aircraft-based Lidar [Lidar Atmospheric Sensing Experiment (LASE)] and a high spectral resolution spectrometer. Participation with several CO2 Differential Infrared Absorption Lidar (DIAL) systems is also expected.

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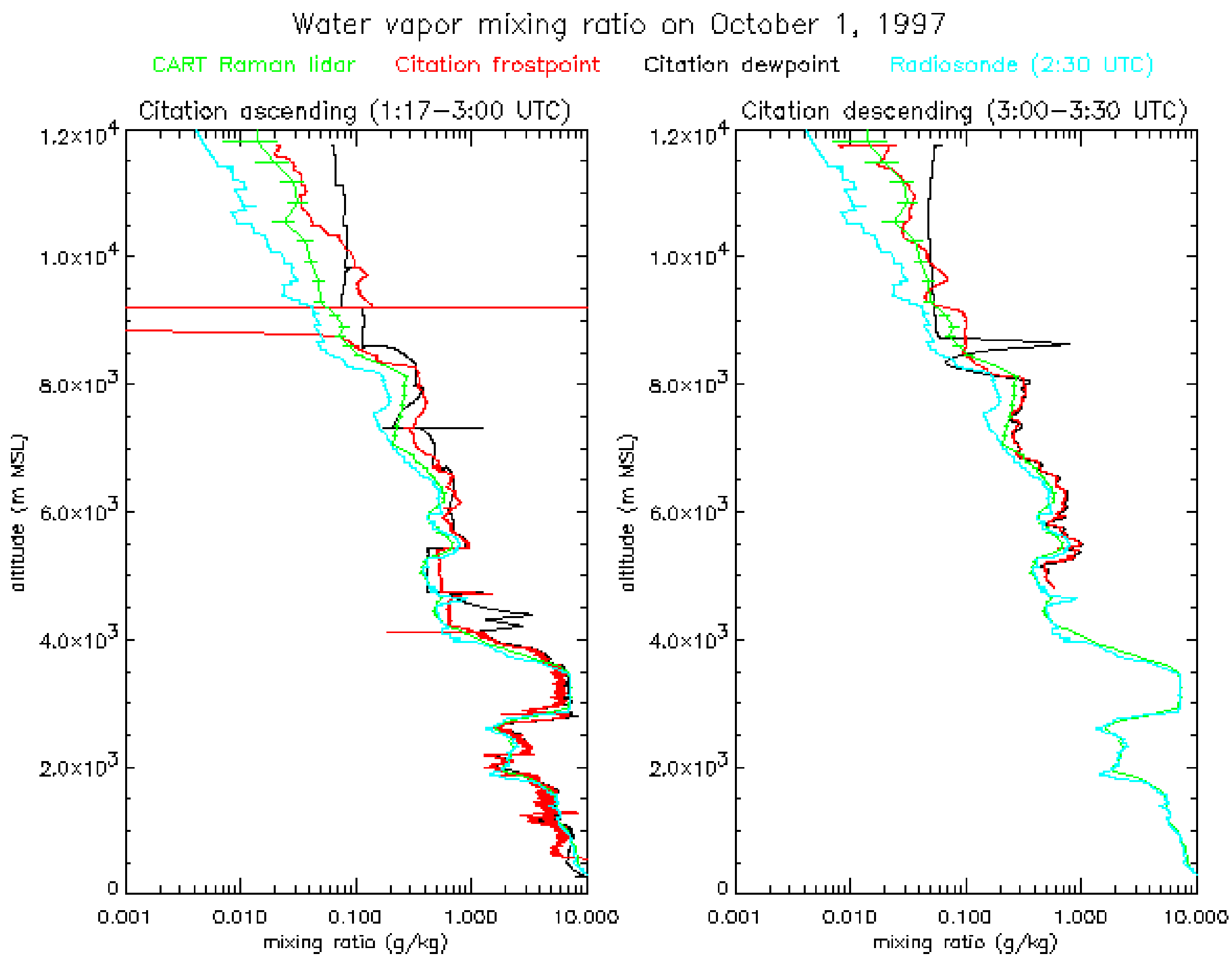

Figure 6. Comparison of radiosonde, Citation frost and dew point hygrometers, and CART Raman lidar at altitude. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/revercomb-98.pdf*.)

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