Comparison of Columnar Water Vapor Measurements During the Fall 1997 ARM Intensive Operational Period: Optical Methods

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Introduction

Optical methods can provide water vapor data from ground-based, airborne, or space-borne measurements of direct or reflected sunlight in spectral channels in and adjacent to water vapor absorption bands. The water-vapor transmittance T_w derived from these measurements has to be translated into water vapor amounts. Although this relationship is well known qualitatively (Goody and Yung 1989), it has proven difficult to quantify. Attempts to do so for water-vapor absorption bands in the near-infrared date back to 1912 (Fowle 1912).

Recent findings that the H_2O line intensities in the visible and near infrared portion of the widely used HITRAN-96 (Rothman et al. 1998) database were in error (Giver et al. 2000) and that H_2O lines (especially weak ones) might be missing from the current databases (Carleer et al. 1999; Learner et al. 1999) have sparked renewed discussion of the accurate conversion of measured water vapor transmittance into amounts of water vapor.

Methodology

In the fall of 1997, the Atmospheric Radiation Measurement (ARM) Program conducted an intensive operational period (IOP) to study water vapor at its Southern Great Plains (SGP) site. Among a large number of systems such as radiosondes, microwave radiometers, raman lidars, Global Positioning System, and an infrared spectrometer, four optical instruments were present to measure water vapor (Revercomb et al. 1998).

In this paper, we focus on the four optical instruments: the National Aeronautics and Space Administration (NASA) Ames airborne tracking sunphotometer (AATS-6), a CIMEL CE-318 sun/sky photometer, a multi-filter rotating shadowband radiometer (MFRSR), and a rotating shadowband spectroradiometer (RSS). Instrument descriptions can be found in Schmid et al. (1999) and in references therein.

All four instruments retrieve columnar water vapor (CWV) by measuring solar transmittance in the 0.94-μm water vapor absorption band. The measurements were made between September 15 and October 5, 1997, at the SGP ARM central facility near Lamont, Oklahoma (36° 36’ N, 97° 22’ W, 316 m above sea level). Dry to very humid conditions, with CWV ranging from 1 cm to 5 cm, were experienced over the three-week period. As one of the steps in the CWV retrievals, the aerosol component must be subtracted from the total transmittance in the 0.94-μm band. The aerosol optical depths in atmospheric “windows” adjacent to the 0.94-μm band obtained from the four radiometers were found to agree within 0.015 [root mean square (rms)] (Schmid et al. 1999).

We have used three different methods to retrieve CWV. A publication containing a full description is in preparation. Here we present a brief summary:

Method A: Modified Langley Plot Technique

Calibration of the channels in the 0.94-μm band is achieved by means of modified Langley plots (Reagan et al. 1987). This requires the water vapor transmittance T_w to be modeled by an exponential with a negative argument proportional to some power of the slant path absorber amount such as

$$T_w = e^{-a(mu)^b} \qquad (1)$$

where u is the columnar water vapor, m the relative airmass, and a and b are constants. To determine a and b, we have used MODTRAN 3.5 for AATS-6 and LOWTRAN 7 for Cimel (Kneizys et al. 1996). For more details see Halthore et al. (1997), Michalsky et al. (1995), and Schmid et al. (1996).

Method B: Differential Lamp/Solar Spectrum Technique

In order to retrieve CWV, we consider the ratio of the instrument's output voltages measured in channels in (λ_{in}) and adjacent to (λ_{out}) the 0.94-μm band. Method B avoids the need to calibrate the channel at λ_{in} using the modified Langley method. Instead, it requires the ratios of the instrument output when viewing a calibration lamp, the lamp's irradiance and the extraterrestrial solar spectrum at λ_{in} and λ_{out}. Since this method does not depend on modified Langley plots, no parametrization of T_w is necessary and T_w can be converted into CWV using a look-up-table that was created using MODTRAN 3.7 (Kneizys et al. 1996). A complete description of method B can be found in Michalsky et al. (1999). We have applied this to the IOP data obtained from the MFRSR and RSS.

Method C: Empirical Technique

Method C calibrates the 0.94-μm MFRSR channel for the retrieval of water vapor by making measurements of the adjusted signal, $V_w(\lambda)$ (the signal that would be measured if water vapor were the only attenuator) with the MFRSR while simultaneously observing the water vapor path, mu, from another instrument nearby. In our case, the "other instrument" is a microwave radiometer (MWR) that operated continuously at the SGP (Liljegren 1999). An empirical curve can then be formed that shows the relationship between $V_w(\lambda)$ and mu. A four-parameter equation fit to this curve provides an algebraic expression relating $V_w(\lambda)$ and mu so that if $V_w(\lambda)$—the measurement—is known, then u can then be found.

Method C avoids both the need to calibrate using the modified Langley method and the use of a radiative transfer model. However, we have to keep in mind that because the four parameters (one is the calibration constant) are determined based on the MWR, method C cannot yield an independent measure of CWV.

Results

Following the philosophy of the aerosol optical depth intercomparison paper (Schmid et al. 1999), we first made no attempt to standardize on the same radiative transfer model and its underlying water vapor spectroscopy (i.e., for methods A and B, we have used the models indicated above). In a second round, we have used line-by-line radiative transfer model (LBLRTM) 5.10 (Clough and Iacono 1995) for all method-A and -B retrievals. We have compared all CWV retrievals to the AATS-6 results. Because of the different sampling strategies and days of operation, this resulted in as few as 465 to as many as 17,145 samples in the comparisons. We have produced time series and scatter plots. Statistical summaries are given in Figures 1 and 2.

In general, we observe a high correlation among the optical methods and a somewhat smaller correlation with the MWR. This is because the MWR and the optical instruments, despite their collocation did not observe the same volume of air (viewing direction is zenith for MWR and slant path to sun for the optical instruments; field-of-view of the MWR is considerably larger).

Water Vapor IOP, Sep 13 - Oct 5, 1997 Comparisons with respect to AATS-6 (Method A with MODTRAN 3.5)												
		Best Fit			Mean (cm)		Differences (cm)			Relative Differences		
	n	slope	inter	r2	AATS-6	y	mean	stdev	RMS	mean	stdev	RMS
Cimel (A)	465	1.05	-0.03	0.997	2.83	2.93	0.10	0.08	0.13	3.5%	2.7%	4.5%
RSS (B)	4015	0.98	-0.01	0.995	3.06	2.98	-0.09	0.07	0.11	-2.8%	2.4%	3.7%
MFRSR (B)	14649	1.01	0.03	0.996	2.73	2.77	0.04	0.06	0.07	1.6%	2.1%	2.6%
MFRSR (C)	16957	0.98	-0.01	0.997	2.86	2.78	-0.08	0.06	0.10	-2.8%	2.0%	3.4%
MWR CART	16990	1.00	-0.09	0.984	2.87	2.79	-0.09	0.12	0.15	-3.0%	4.3%	5.3%

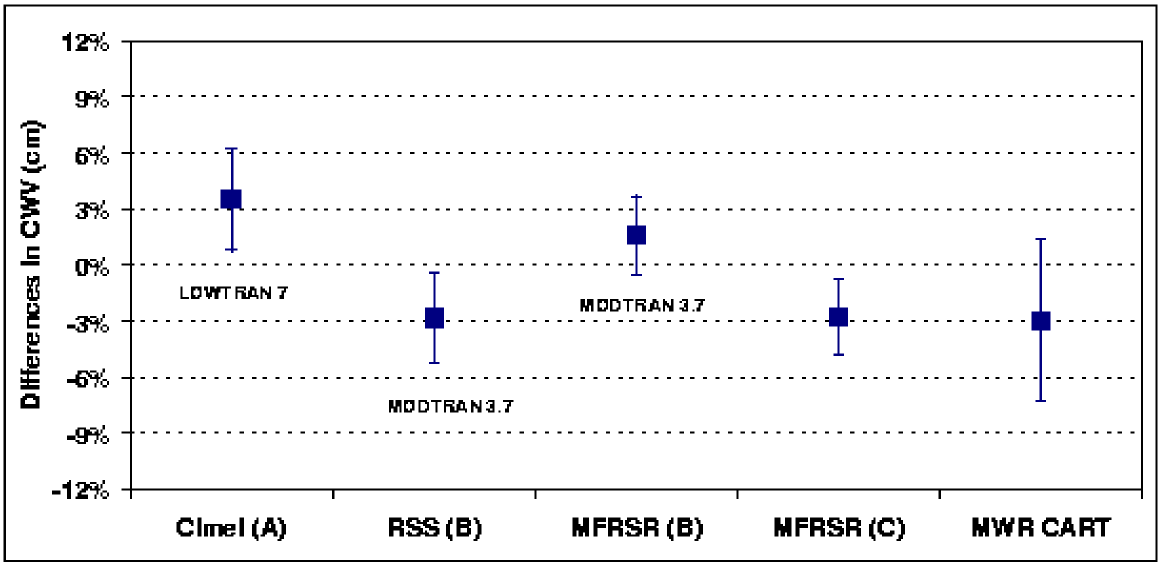

Figure 1. Comparison of CWV from different instruments and methods to AATS-6. This is the initial comparison where different radiative transfer models (as indicated) have been used.

In the first round of comparison (Figure 1), we find all methods including MWR agree within 5% (rms), all intercepts are within ±0.1 cm, and the slopes range from 0.98 to 1.05.

In the second round of comparison (Figure 2), we used LBLRTM 5.10 (the results obtained with the most recent version 5.21 were identical), which includes the updated spectroscopy of Giver et al. (2000). This decreased the mean CWV obtained from AATS-6, RSS, and MFRSR (method B) by 8%, 13%, and 13%, respectively (the reprocessed Cimel data are not available yet). At the same time, it further increased the correlation coefficients. However, the results of methods A and B are now 6% to 14% lower than the results of the MWR. Even the biases among the results of methods A and B have increased. This shows that the result of the first comparison round was somewhat misleading as differences in the models obviously compensated for other existing biases. The overall agreement (including the MWR but excluding Cimel) is now 8% (rms).

Water Vapor IOP, Sep 13 - Oct 5, 1997 Comparisons with respect to AATS-6 (Method A using LBLRTM 5.10)												
		Best Fit			Mean (cm)		Differences (cm)			Relative Differences		
	n	slope	inter	r2	AATS-6	y	mean	stdev	RMS	mean	stdev	RMS
Cimel (A)												
RSS (B)	4022	0.95	-0.08	0.998	2.80	2.59	-0.22	0.06	0.22	-7.7%	2.0%	8.0%
MFRSR (B)	14703	0.97	-0.02	0.998	2.50	2.41	-0.10	0.04	0.10	-3.8%	1.6%	4.1%
MFRSR (C)	18996	1.09	-0.07	0.999	2.63	2.78	0.16	0.09	0.18	6.0%	3.2%	6.9%
MWR CART	17145	1.12	-0.15	0.986	2.64	2.79	0.15	0.16	0.22	5.8%	5.9%	8.3%

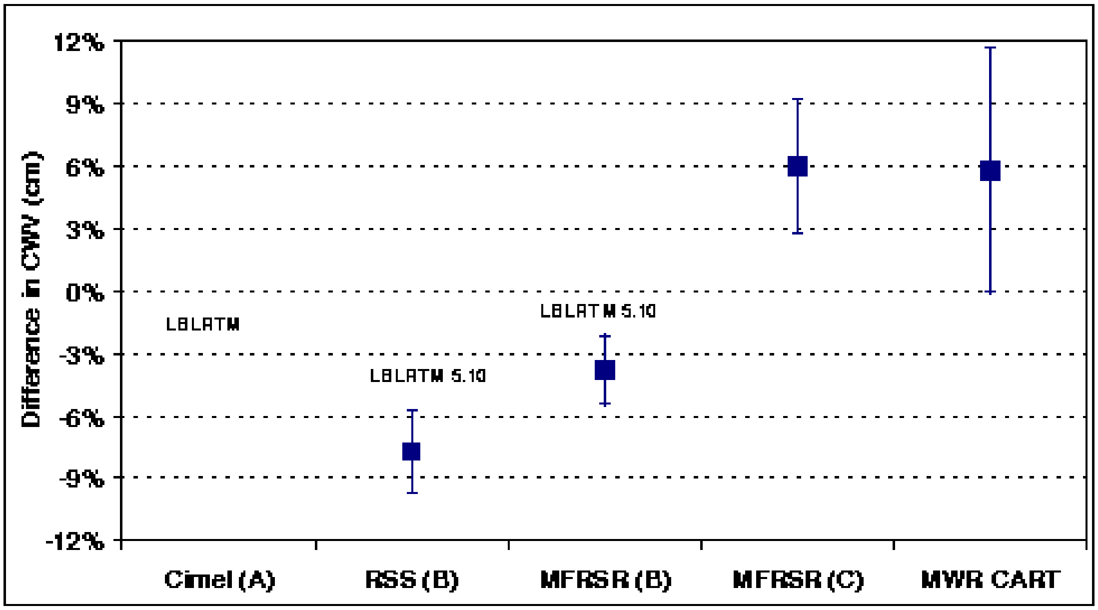

Figure 2. Same as Figure 1 but LBLRTM 5.10 has been used for methods A and B. The Cimel data are not available yet.

Conclusions

We have in hand a large data set of CWV retrievals from four optical instruments. We have used three different retrieval techniques and have also compared them to the MWR on which one of the techniques is based. The good agreement found in a first round of comparison turns out to be fortuitous because differences in the models obviously compensated for biases found once the same model was used for all the retrievals. The biases might be caused by uncertainties in calibration, and in the case of the RSS, by stray light. We hope to have more definite conclusions once we include the reprocessed Cimel data. The changes in spectroscopy suggested by Giver et al. (2000) decreased the mean CWV by 8% or 13% depending on which model was used initially. With the improved spectroscopy, the CWV retrievals from the optical methods are now 6% to 14% lower than the MWR results. However, this result needs to be considered in context with all CWV measurements performed during the IOP (Revercomb et al. 1998). A publication showing all water vapor results remains in preparation.

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