Column Water Vapor Retrievals Based on Rotating Shadowband Spectroradiometer (RSS) Direct Solar Irradiance Measurements

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Abstract

Several investigators have retrieved column water vapor using sunphotometry through the 940-nm water vapor absorption band. In this paper, we retrieve water vapor using an approach that removes the requirement of an accurate understanding of the absolute response of the instrument, but, instead, relies on relative responses within the 940-nm absorption band and just outside the band in the continuum. We perform these retrievals for the Rotating Shadowband Spectroradiometer (RSS) on a wet, clear day, and a dry, clear day during the 1997 Water Vapor Intensive Operational Period (IOP). We compare the results to those retrieved from the Multifilter Rotating Shadowband Radiometer (MFRSR), from the Atmospheric Radiation Measurement (ARM) Program's Microwave Radiometer (MWR), and from the National Oceanic and Atmospheric Administration (NOAA) MWR.

This method of retrieving water vapor column from the RSS does not depend on a calibration performed against a standard method, and, consequently, it can be considered an independent, absolute determination. The limits to the accuracy of this retrieval are set by an accurate knowledge of band strength for this water vapor band, estimation of the extinction caused by aerosol in the water vapor band, and an accurate knowledge of the relative spectral output of the calibration lamp and the sun at the continuum and band centered wavelengths.

Introduction

In any attempt to validate radiation models by comparisons to actual measurements of radiation, it is critical to specify the inputs to the models as accurately as possible. In the ARM Program and elsewhere there has been a great deal of emphasis placed on the specification of total column water vapor and its distribution with height in the atmosphere. Clough et al. (1996) have shown that using the water vapor distribution obtained from balloon sonde's humidity measurements as a function of height yields differences in the infrared between Atmospheric Emitted Radiance Interferometer (AERI) measurements and the Line-by-Line Radiative Transfer Model (LBLRTM) results that are larger than when the height distribution of the water vapor measured by the balloon is scaled to give the same integrated water vapor column as that measured by the Cloud and Radiation Testbed (CART) MWR. Both methods should be valid ways to determine the column abundance.

In this paper, we present another method to determine total column water vapor that does not depend on a calibration based on another measurement of water vapor. Part of our goal is to make accurate measurements of water vapor that will be useful to direct shortwave radiation modeling since our measurements are in the solar direction. Moreover, this independent determination of column water vapor could help resolve the differences among other total column measurements.

The next section describes the procedure that we use with the RSS to derive water vapor. The third section contains results from two days during the 1997 Water Vapor IOP, and the final section summarizes the results.

RSS Water Vapor Derivation

In the past we have used the modified-Langley technique developed by Reagan et al. (1987), and applied in the form specified by Michalsky et al. (1995). Outside a strong molecular band, such as water vapor, transmission in a narrow wavelength band of radiation can be expressed as

$$V/V_o = \exp(-\tau_{scat} m),$$

where V is the output of the radiometer at a measurement point within the earth's atmosphere, V_o is the output at the top of the atmosphere, τ_{scat} is the optical depth resulting from molecular scattering and aerosol extinction, and m is the air mass relative to a value of one in the zenith direction.

For the water vapor band we multiply the right-hand side (RHS) of the last equation by the transmission due to water vapor, that is

$$V/V_o = \exp(-\tau_{scat} m) T(w).$$

At this point we need to model the transmission through the particular water vapor filter passband in our radiometer; in our case we chose to use MODTRAN3.7 (Berk et al. 1989). If we can solve for the transmission through the water vapor band by assigning all components on the RHS of the following equation, that is,

$$T(w) = V \exp(\tau_{scat} m)/V_o,$$

then this calculated value can be used to determine water vapor by comparing to the MODTRAN-calculated transmission. The main problem, as in aerosol optical depth measurements, is knowing V_o, the calibration constant.

Consider two narrow passbands with one centered on the 940-nm water band and one centered in the continuum at 870 nm. If we were to look at the sun with this radiometer at the top of the atmosphere, we would measure an output V in the two filters of

$$V_S^{870} = S_S^{870} \bullet R^{870} \text{ and } V_S^{940} = S_S^{940} \bullet R^{940},$$

where S_s is the extraterrestrial solar irradiance and R is the response of the radiometer. If we view the calibration lamp with the same radiometer, we would measure an output V in the two channels of

$$V_L^{870} = S_L^{870} \bullet R^{870} \text{ and } V_L^{940} = S_L^{940} \bullet R^{940},$$

where S_L is the lamp irradiance. Ratioing the last two sets of equations we get

$$V_S^{870}/V_S^{940} = S_S^{870}/S_S^{940} \bullet R^{870}/R^{940} \text{ and } V_L^{870}/V_L^{940} = S_L^{870}/S_L^{940} \bullet R^{870}/R^{940}.$$

Since the ratio of the responses is common to both, we can substitute with the result

$$V_S^{940}/V_S^{870} = S_S^{940}/S_S^{870} \bullet S_L^{870}/S_L^{940} \bullet V_L^{940}/V_L^{870}.$$

A radiometer measurement within the atmosphere, say at the surface, produces

$$V^{940}/V^{870} = V_S^{940}/V_S^{870} \bullet T(w) \bullet \exp[-(\tau_{scat}^{940} - \tau_{scat}^{870}) \bullet m].$$

Substituting for V_S^{940}/V_S^{870} in this equation using the previous equation we get

$$V^{940}/V^{870} = S_S^{940}/S_S^{870} \bullet S_L^{870}/S_L^{940} \bullet V_L^{940}/V_L^{870} \bullet T(w) \bullet \exp[-(\tau_{scat}^{940} - \tau_{scat}^{870}) \bullet m]$$

with the result that most measurements and calculated values appear as relative values, which are generally more accurately determined than are the absolute values. Solving for T(w) we can relate this calculated value to the MODTRAN calculation of transmission to derive water vapor.

Results

In Figure 1, we plot the water vapor measured by four instruments for September 18, 1997. The day was very hot and humid, but the skies were clear giving us a good opportunity to measure a large water vapor column throughout the day. Keep in mind that MWRs measure by pointing in the zenith direction, and the MFRSR and RSS calculate water vapor using direct solar irradiance measurements, so the direction of the measurement is constantly changing although the results are normalized to the zenith direction for comparison. The overlap is remarkable with MFRSR and RSS measurements falling in between the MWR results for the most part. This is most easily seen in the middle of the day (Figure 1 [bottom]) when the instruments are more nearly, but not quite, pointing in the same direction. Figure 2 contains results for a much dryer day later in the month. In Figure 2 (bottom), the RSS and CART MWR have switched their mid-day positions relative to Figure 1 (bottom), but are less than about 1 mm apart in both cases. Generally, there is some relative change in agreement at the beginning and end of each day compared to the middle of the days, perhaps, associated with the different lines of sight.

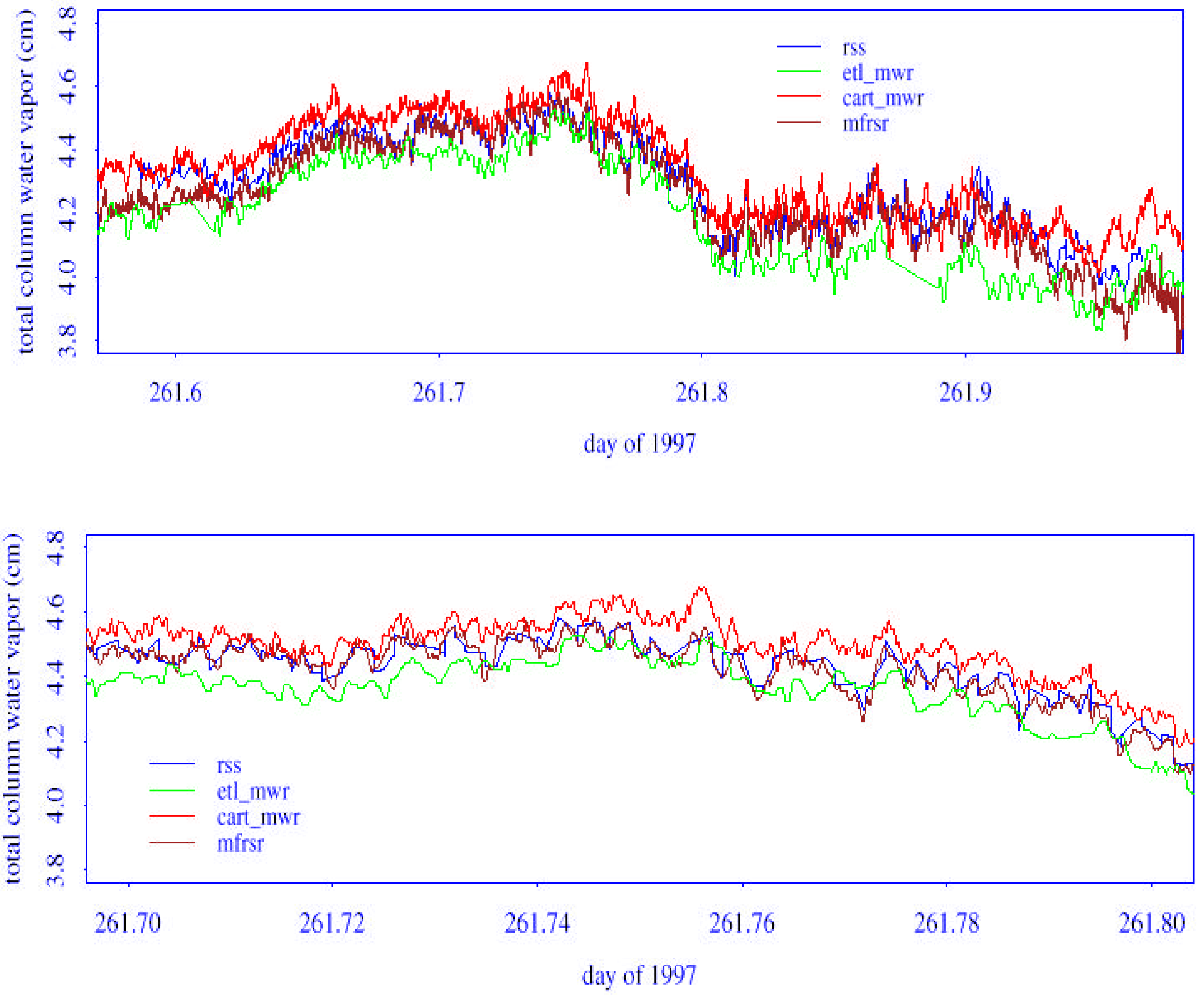

Figure 1. Water vapor versus time of day for September 18, 1997, for most of the day (top) and for the central portion of the day (bottom) to better show differences when observations are more nearly in the same direction.

Discussion

We have shown results from high and low water vapor content days to compare four different instruments. The observations generally agree within about 0.2 cm, or better. Zenith pointing and sun tracking instruments show a tendency to change their relative agreement, especially in the early morning and late afternoon.

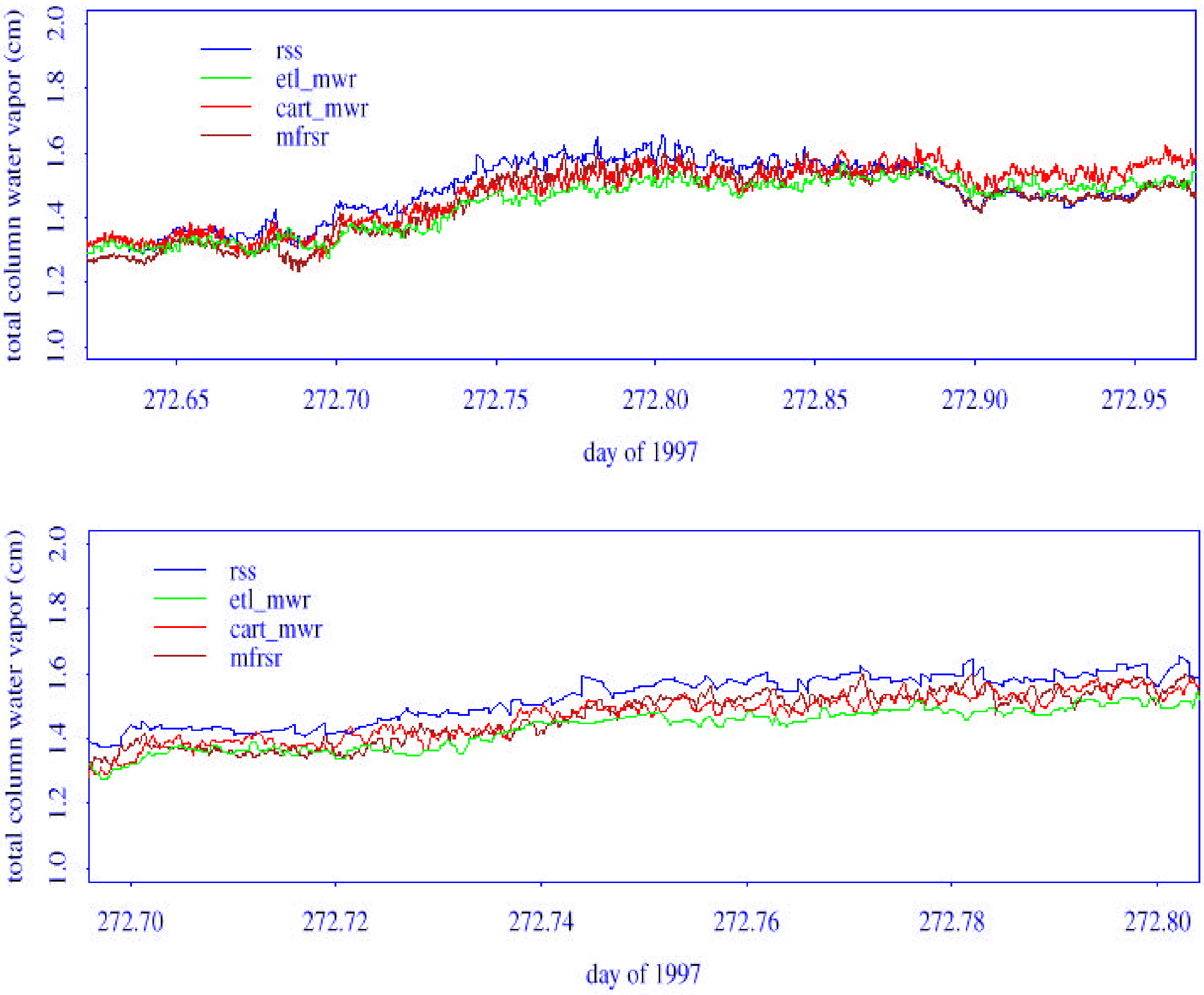

Figure 2. Water vapor column versus time of day for September 29, 1997, for most of the day (top) and for the central portion of the day (bottom).

The RSS, CART MWR, and the Environmental Technology Laboratory (ETL) MWR derive water vapor based on atmospheric models using fundamental physics. For this paper, the MFRSR uses a correlation between its measured water vapor transmission to the CART MWR to derive a calibration. In the future, the same basic technique used to derive water vapor for the RSS will be used for the MFRSR measurements.

In conclusion, we find the technique described for water vapor retrieval from the RSS to be robust compared to the results that we obtained using the modified-Langley approach, perhaps, because it relies on relative measurements in two nearby wavelength bands, which are easier than absolute measurements of RSS responses.

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