A differential technique to retrieve column water vapor using sun radiometry

Joseph J. Michalsky, Qilong Min, and Piotr W. Kiedron
State University of New York, Albany

Donald W. Slater and James C. Barnard
Pacific Northwest National Laboratory, Richland, Washington

Abstract. Techniques for retrieving column water vapor from Sun radiometer measurements involving the 940-nm water vapor absorption band have been around for the better part of a century. Arguably, the best method to use for this retrieval is the modified Langley technique. However, to apply this method one must obtain the instrument response at the top of the atmosphere using modified Langley plots on clear days with a very stable water vapor column. Using subsequent measurements in this filter, ratioed to the top-of-the-atmosphere response allows one to determine the transmission in the 940-nm water band. In this paper, we present an approach that does not require an absolute knowledge of the extraterrestrial instrument response. The method discussed here relies, instead, on relative measurements of a calibration lamp and the extraterrestrial spectral irradiance within and just outside the 940-nm absorption band. We execute these retrievals for the rotating shadowband spectroradiometer (RSS) on 3 days during the Department of Energy's Atmospheric Radiation Measurement program's 1997 Water Vapor Intensive Observation Period. We compare the results to those retrieved from a colocated multifilter rotating shadowband radiometer (MFRSR) that uses an empirical calibration and from a colocated microwave radiometer. Since our optical method of retrieving column water vapor from RSS measurements does not depend on a calibration performed against another water vapor measurement, it contributes an independent estimate in the search for absolute accuracy. The major contributors to the uncertainty of this retrieval are the water vapor band strength calculations, the difference in aerosol extinction in and near the water vapor band, the relative spectral irradiance output of the calibration lamp and the Sun at the nonabsorbing and band-centered wavelengths, and the stability of the spectral response of the instrument, which will be discussed in detail.

1. Introduction

Accurate inputs are essential to radiation model validation when comparing with radiation measurements. In the Atmospheric Radiation Measurement (ARM) program [*Stokes and Schwartz*, 1994], there has been an emphasis on the specification of total column water vapor and its distribution with height in the atmosphere. *Clough et al.* [1996] have shown that water vapor profiles obtained from balloon sonde humidity measurements yield differences between measured and modeled infrared radiation that are larger than if these same profiles are forced through scaling to give the same column water vapor as a colocated microwave radiome-

ter. Typically, radiosonde water vapor is dry relative to the microwave and has to be scaled upward at every level.

In this paper we present a method of determining total column water vapor that does not depend on a calibration against a reference measurement of water vapor, such as the balloon sonde or the microwave radiometer. This should provide an accurate measurement of water vapor along the solar path that can be used in direct shortwave radiation modeling. Microwave radiometers do not measure in the solar direction, but, typically, make zenith measurements, and balloon sondes, which sample along a path governed by the winds, do not represent the true water path directly to the Sun. Moreover, this independent determination of column water vapor may help resolve the differences among other column measurements.

Water vapor retrievals using the near-infrared water bands were made as early as the turn of the 20th cen-

tury by *Fowle* [1912, 1915]. *Thome et al.* [1992] reviewed this literature up to the time of their publication. Since then several papers have been published based on the modified Langley technique introduced by *Reagan et al.* [1987]. *Bruegge et al.* [1992], *Michalsky et al.* [1995], *Shiobara et al.* [1996], *Schmid et al.* [1996], and *Halthore et al.* [1997] used the method to derive a calibration for their radiometers, which is the instrument response for the 940-nm water vapor band filter at the top of the atmosphere. In the case of the standard Langley method, which is used to calibrate the aerosol channels of a Sun radiometer, a successful calibration depends on a stable aerosol load during a significant change in atmospheric pathlength, or air mass. However, the atmosphere for a modified Langley calibration of a water channel must be stable in water. The latter is rare at most sites, which leads to a greater uncertainty in the calibration of the water vapor channel.

Section 2 describes our procedure that avoids the need to calibrate using the modified Langley method. The procedure is applied to measurements using the rotating shadowband spectroradiometer (RSS) [*Harrison et al.*, 1999]. Section 3 contains comparisons among three instruments for 3 days during the 1997 Water Vapor Intensive Observation Period (IOP), followed by section 4 which discusses the uncertainties of this technique and section 5 to state our conclusions.

2. Water Vapor Derivation for the RSS

In the past we have used the modified Langley technique developed by *Reagan et al.* [1987] and applied in the form outlined by *Michalsky et al.* [1995]. Outside of the strong molecular absorption bands in the near-infrared, atmospheric transmission in a narrow wavelength band of radiation can be expressed as

$$V/V_0 = \exp(-\tau_{scat}m), \tag{1}$$

where V is the output of the radiometer at a measurement point within the Earth's atmosphere, V_0 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 through which the direct solar beam travels relative to the zenith direction. For the water vapor band we must modify the right-hand side of (1) by multiplying by the transmission resulting from a water vapor path w, that is,

$$V/V_0 = \exp(-\tau_{scat}m)T(w). \tag{2}$$

At this point we model the transmission through the particular water vapor 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 right-hand side of the following equation, that is,

$$T(w) = V \exp(\tau_{scat}m)/V_0, \tag{3}$$

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 determinations, is knowing V_0, the calibration constant.

Alternatively, consider two narrow passbands, one centered on the 940-nm water band and one centered in the nonabsorbing spectrum at 870 nm. If we were to measure the direct solar beam flux with this radiometer at the top of the atmosphere, we would measure an output V in the two channels of

$$V_S^{940} = S_S^{940} \cdot R^{940}$$
$$V_S^{870} = S_S^{870} \cdot R^{870}, \tag{4}$$

where S_S is the extraterrestrial solar irradiance convolved with the effective filter function of the RSS in $W/(m^2 \text{ nm})$ and R is the response of the radiometer, for example, in volts per $W/(m^2 \text{ nm})$. In the results to follow in section 3 we used the extraterrestrial spectrum tabulated by *Gueymard* [1995].

If we view the calibration lamp with the same radiometer, we would measure an output V in the two channels of

$$V_L^{940} = S_L^{940} \cdot R^{940}$$
$$V_L^{870} = S_L^{870} \cdot R^{870}, \tag{5}$$

where S_L is the lamp irradiance convolved with the effective filter function of the RSS. In the results to follow in section 3 we used a lamp whose calibration was based on three NIST lamps [*Kiedron et al.*, 1999]. Note, however, that it is the relative calibration at the two wavelengths that is needed here not the absolute calibration. Ratioing the last two sets of equations we get

$$V_S^{940}/V_S^{870} = S_S^{940}/S_S^{870} \cdot R^{940}/R^{870}$$
$$V_L^{940}/V_L^{870} = S_L^{940}/S_L^{870} \cdot R^{940}/R^{870}. \tag{6}$$

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

$$V_S^{940}/V_S^{870} = S_S^{940}/S_S^{870} \cdot S_L^{870}/S_L^{940} \cdot V_L^{940}/V_L^{870}. \tag{7}$$

Radiometer measurements at the surface can be expressed as follows from eqns. (1) and (2)

$$V^{940} = V_S^{940} \exp(-\tau_{scat}^{940}m)T(w)$$
$$V^{870} = V_S^{870} \exp(-\tau_{scat}^{870}m). \tag{8}$$

Ratioing the two results we get

$$V^{940}/V^{870} = V_S^{940}/V_S^{870} \cdot T(w)$$
$$\cdot \exp[-(\tau_{scat}^{940} - \tau_{scat}^{870}) \cdot m]. \tag{9}$$

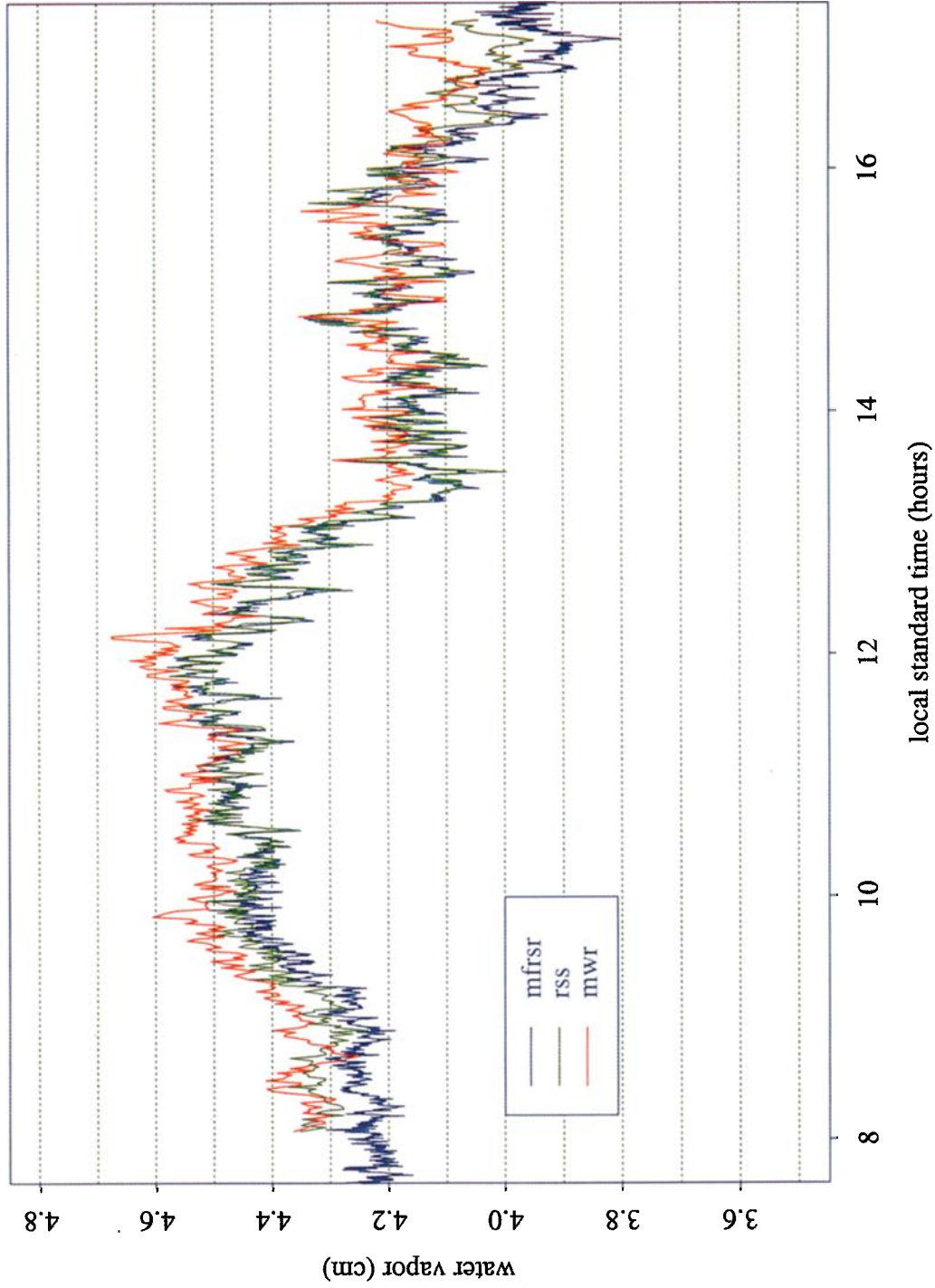Substituting for V_S^{940}/V_S^{870} in this equation from (7), we get

Plate 1. Time series column water vapor measured by three instruments normalized to the zenith direction on a humid day.

$$V^{940}/V^{870} = S_S^{940}/S_S^{870} \cdot S_L^{870}/S_L^{940} \cdot V_L^{940}/V_L^{870}$$
$$\cdot T(w) \cdot \exp[-(\tau_{scat}^{940} - \tau_{scat}^{870}) \cdot m] \quad (10)$$

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

3. Results

In Plate 1 we plot the water vapor determined by three instruments on September 18, 1997, at the Southern Great Plains (SGP) ARM site in northern Oklahoma. The day was hot and humid, but the skies were clear giving us an opportunity to measure a large water vapor column throughout the day. Recall that the microwave radiometer (MWR) determined water vapor by pointing in the zenith. The RSS and MFRSR calculate water vapor using direct solar irradiance measurements so the direction of the measurement is slowly changing and most nearly aligned with the MWR at solar noon. The MFRSR and RSS retrievals are normalized to the zenith direction by dividing by the air mass in the solar direction for these comparisons. The overlap is remarkable between MFRSR and RSS retrievals, especially in the middle of the day (see Plate 2). Note that the RSS and MWR samples are once per minute and the MFRSR samples are every 20 s. The MWR is biased high by 0.05 cm relative to the RSS with a root-mean-square difference of only 0.08 cm.

At air masses greater than 2 or where the equivalent water column is greater than 8 (before 0900 and after 1600 LST) we see slightly poorer agreement among all of the measurements but notably between the MFRSR and RSS that agreed extremely well at other times during the day. One possibility is differences in the accuracy of the angular response corrections. The MFRSR angular response is measured by an automated procedure at every degree of zenith angle, but the RSS requires a tedious manual calibration with fewer angles characterized. Another possibility is differences in the retrieval procedure where the RSS retrieval is based on interpolations between calculated transmission versus water column and the MFRSR retrieval uses a fit to an empirical function. At high water vapor the transmission changes slightly with increasing water vapor, and small errors in transmission are amplified in the retrievals. The air mass calculated to normalize the RSS and MFRSR retrievals underestimates the water vapor air mass by about 1% at the largest air masses in Plate 1; therefore the discrepancy between direct solar measurements and the MWR are slightly larger (about 0.04 cm) at the beginning and end of the period shown in Plate 1. The worst case difference for this day is still less than 10% even at the highest air masses shown.

Plate 3 contains results for a somewhat less humid day 2 weeks later. In Plate 3 the RSS and MFRSR again agree well through the 5 middle hours of the day. The MWR now has a negative bias relative to the RSS of about -0.06 cm as compared with a bias of +0.05 cm in Plate 1. Although the RSS and MFRSR have the best agreement on the short time step scale, the MWR captures the overall trends and much of the small-scale structure in the time variation as well. The differences and slight apparent phase shifts could be explained by occasional spatial heterogeneity in the water vapor since the lines-of-sight are different for the MFRSR and RSS versus the MWR.

Plate 4 is a plot for a relatively dry day during the IOP. In this case there is a noticeable bias between the MFRSR and RSS with the MFRSR and MWR agreeing most closely among the three methods. However, the bias between the RSS and MWR is only -0.04 cm with a root-mean-square difference of 0.05. The disagreement between the MFRSR and RSS appears more severe than normal because the scale is expanded relative to the previous plots. The worst agreement is still about 0.1 cm. A possible explanation is a bias caused by the differences in the treatment of the aerosol correction. For the MFRSR the aerosol optical depth at 940 nm is estimated by extrapolation from shorter wavelength filters assuming an Angstrom type relationship. For the RSS we perform the same interpolation, but the relative difference between the estimate for the 870-nm and 940-nm aerosol optical depths is required rather than the absolute value of the aerosol optical depth as in the MFRSR case. As we shall see in section 4, differences in aerosol optical depth of about 0.01-0.02 (the accuracy for good aerosol optical depth measurements [*Schmid et al.*, 1995]) can lead to errors of the magnitude seen in Plate 4 between the MFRSR and RSS.

4. Uncertainty and Sensitivity

The sources of column water vapor retrieval uncertainty using the current method will be discussed term by term in reference to (10) repeated here

$$V^{940}/V^{870} = S_S^{940}/S_S^{870} \cdot S_L^{870}/S_L^{940} \cdot V_L^{940}/V_L^{870}$$
$$\cdot T(w) \cdot \exp[-(\tau_{scat}^{940} - \tau_{scat}^{870}) \cdot m]. \quad (10)$$

The instantaneous measurements of the MFRSR and RSS represented on the left-hand side of this equation are uncertain to about one-half count because of the digitization of the measured voltages. This is very small because we, typically, measure several hundred counts within the water vapor band and a larger signal outside the water vapor band; therefore no appreciable error will arise from this source. This assumes that we have checked to ensure that the signal is linear with the strength of the source and that there is no significant "dark" signal or that it is stable and removed. We expect much less than 1% uncertainty from this first term in (10).
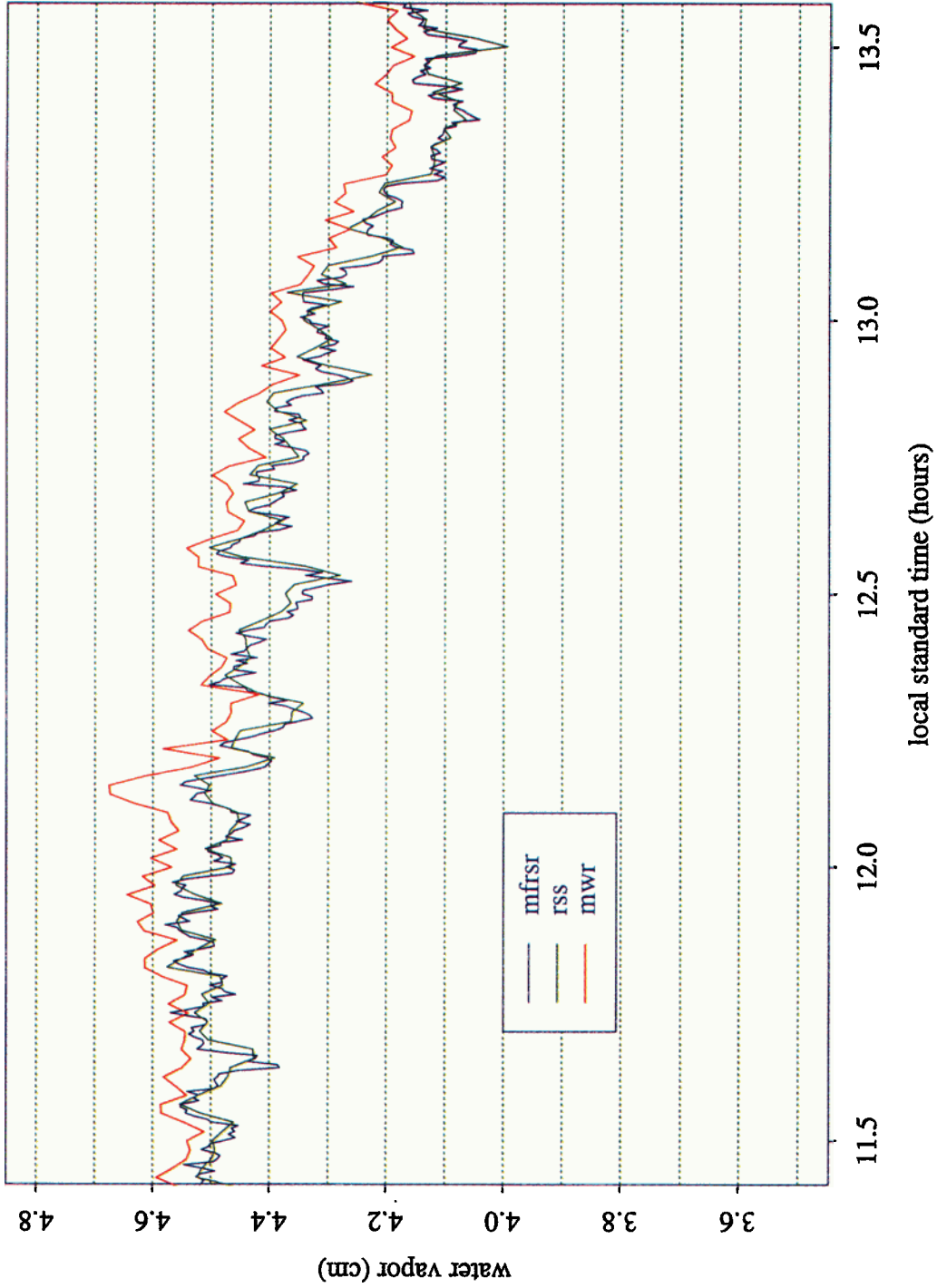
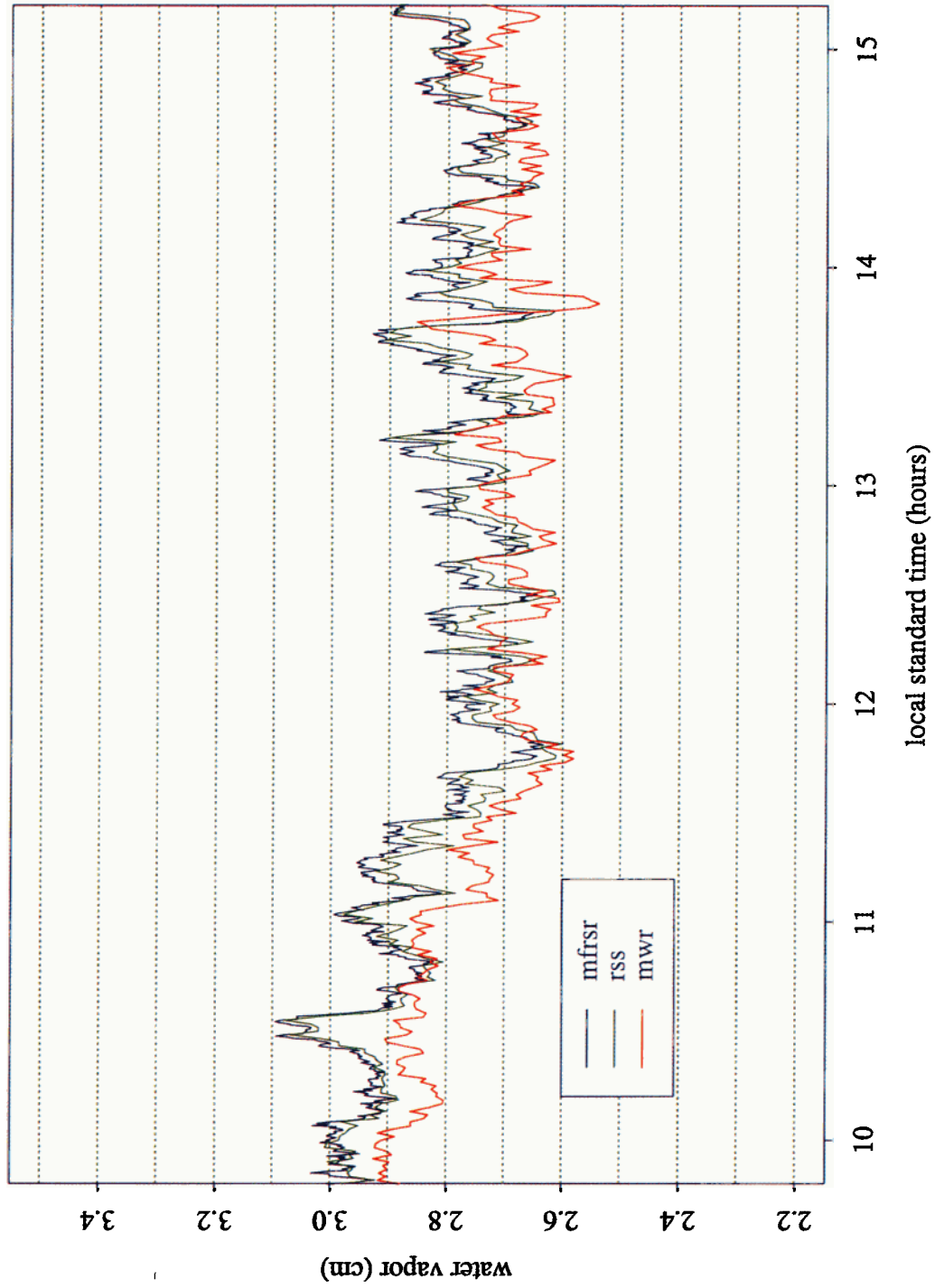**Plate 2.** Time series for same day as in Plate 1, but only the 2 hours centered on solar noon to better see small scale.

Plate 3. Time series column water vapor on moderately humid day. The MWR is now lower that the RSS and MFRSR (see Plate 1).
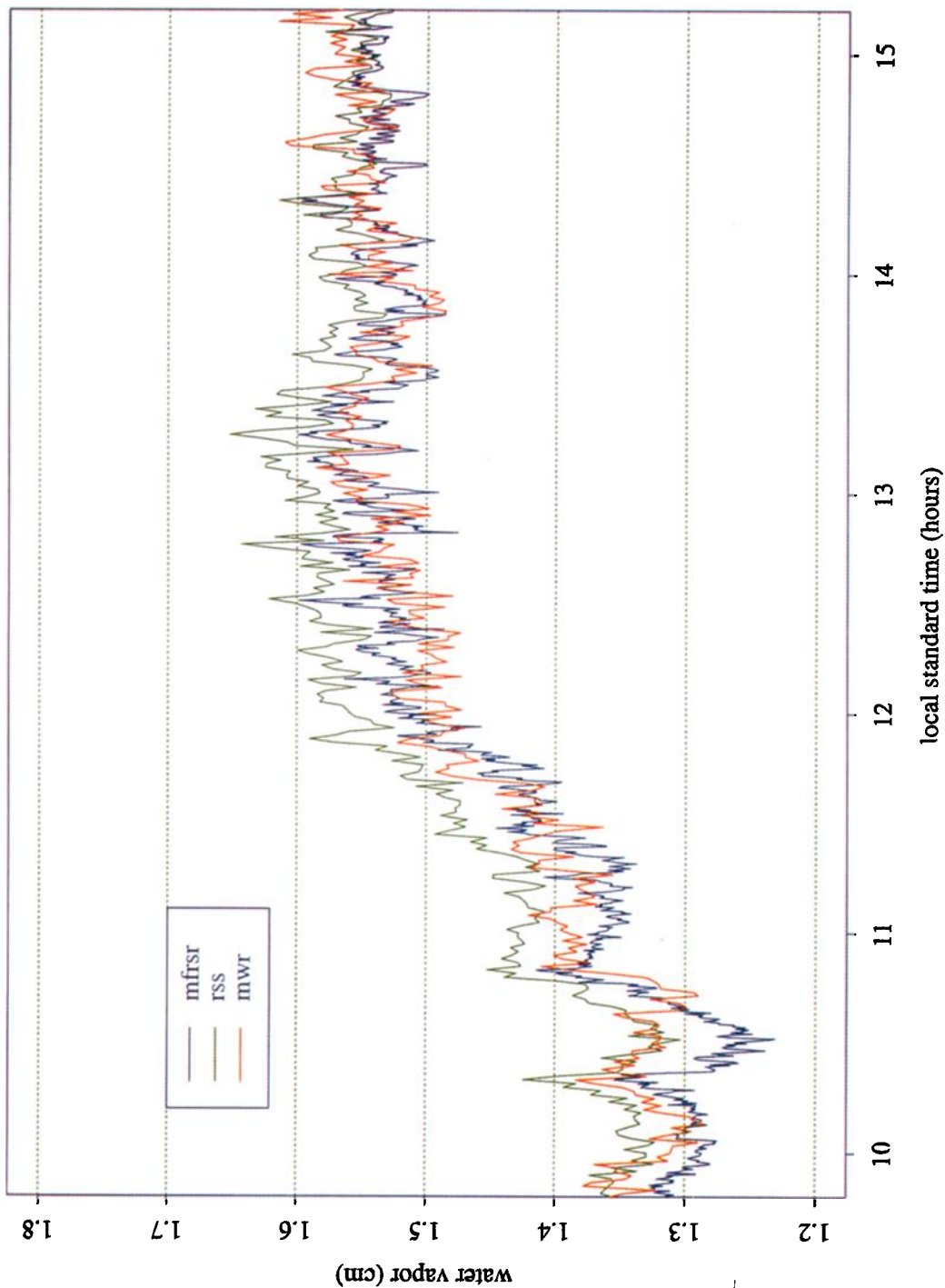
Plate 4. Times series column water vapor on relative dry day. Note that the RSS now agrees less well with other two measurements.

The extraterrestrial irradiance in two filters appears as a ratio. Various tabulations of extraterrestrial irradiance indicate differences of several percent in the region under investigation. We used the tabulation of *Gueymard* [1995] in this paper. Using the tabulation of *Wehrli* [1985], instead, we get a ratio for the two filters that is 3.2% different. Other independent tabulations give us smaller differences, but we have limited ability to distinguish among the choices.

The spectral irradiance measurements made with the calibration lamp appear as a ratio. While the absolute value may be up to 3% in error, the error in the ratio at the two wavelengths in question, 870 and 940 nm, is near one since both are near the broad peak of the approximate blackbody curve for the 3100°K lamps. We expect an error much less than 1% for this ratio.

The instrument responses to the calibration lamp at the two wavelengths appear as a ratio. Instantaneously, this ratio will be very accurate. The greatest uncertainty is related to the stability of this ratio since MFRSR interference filters can drift and the RSS in this version had some wavelength dependence on temperature. The stability of this ratio and the ratio of measurements on the left-hand side of (10) are especially sensitive to wavelength stability, but, in fact, there is some sensitivity to wavelength stability for all of the terms of this equation. For example, with regard to the ratio of instrument responses to the calibration lamps, we found MFRSR calibrations using the same standard lamp before field deployment and after field deployment revealed that the 870-nm filter was stable, but the 940-nm filter had decreased in sensitivity by nearly 10% sometime during the 18-month deployment. The actual difference in response at the time of the water vapor measurements is related to the timing of this decrease. For example, do we assume that it decreased linearly with time or that it changed suddenly?

The next term of (10), the transmission in the 940-nm band, depends on the filter or slit function profile. For the MFRSR we noted a 0.8-nm shift in the 940-nm filter from its initial central wavelength after a nearly 18-month deployment. This shift would affect all components of (10) with the measurement ratios and transmission most affected. Plate 5 indicates the change in retrieved water vapor column caused by this wavelength shift on transmission calculations when all other terms are held fixed. In this figure we have added MFRSR retrievals that are based on the method described in this paper, and the difference in the middle red and the blue curve illustrates the effect of our 940-nm filter shifting in wavelength. In the RSS, which is a more stable instrument, there is a different problem related to the infiltration of scattered light from other portions of the spectrum. Since the slit function does not go to zero outside the near-triangular passband, scattered light can add to the measured radiation at 940 nm yielding a larger transmission than would otherwise be detected biasing the result toward less water vapor in the

column, which may be what is illustrated by the green curve in Plate 5. These instrumental errors are in addition to the transmission errors that are discussed by *Ingold et al.* [2000].

We, also, indicate in Plate 5 the column water vapor sensitivity that can arise from a small uncertainty in the aerosol estimate for the 940-nm band based on the last component of (10) (compare differences in red curves). If the absolute value of aerosol at 940 nm is required, as in the MFRSR retrievals that are based on a calibration using the microwave radiometer (gold curves), then an error of 0.01-0.02 in aerosol optical depth may translate into the size of the differences seen in Plate 5 (compare blue and gold curves).

The largest uncertainty in determining water vapor using this technique is in the systematic errors that can affect virtually every component of the retrieval equation. To minimize these errors requires frequent characterization and calibration of the instruments or a very stable radiometer. It is unlikely that the systematic errors all have the same sign and therefore there will be some cancellation of effects. Our estimate of the combined errors is about 10% for the MFRSR and between 5 and 10% for the RSS, if we neglect the modeling errors discussed by *Ingold et al.* [2000].

5. Discussion

We have shown results from high, moderate, and low water vapor days to compare three different methods of determining total column water vapor. The observations generally agree within about 0.1 cm or better. There are slight changes in the submillimeter biases from one day to the next and the biases are not consistently of the same sign. Root-mean-square errors have about the same magnitude as the bias errors, that is, under a millimeter. There is better agreement in the small-scale structure between the MFRSR and RSS, probably because they both view the solar beam in the same direction; however, most of the small-scale structure is reflected in the MWR results as well, and the low frequency changes track very well. Zenith pointing and sun tracking instruments show a tendency to disagree more in the early morning and late afternoon than at midday because of path differences.

The RSS and MWR derive water vapor based on atmospheric models using fundamental physics. For Plates 1-4 of this paper the MFRSR uses a calibration where a best fit to MFRSR-measured water vapor transmission versus the ARM MWR water vapor over a several month period before the IOP is the basis for the water vapor retrieval. This is similar to the method used by *Schmid et al.*, [1996].

In conclusion, we find this technique for water vapor retrieval from the RSS to be more robust than our previous modified Langley approach. The primary reason is that it relies on relative measurements in two nearby wavelength bands that are relatively easy to perform,
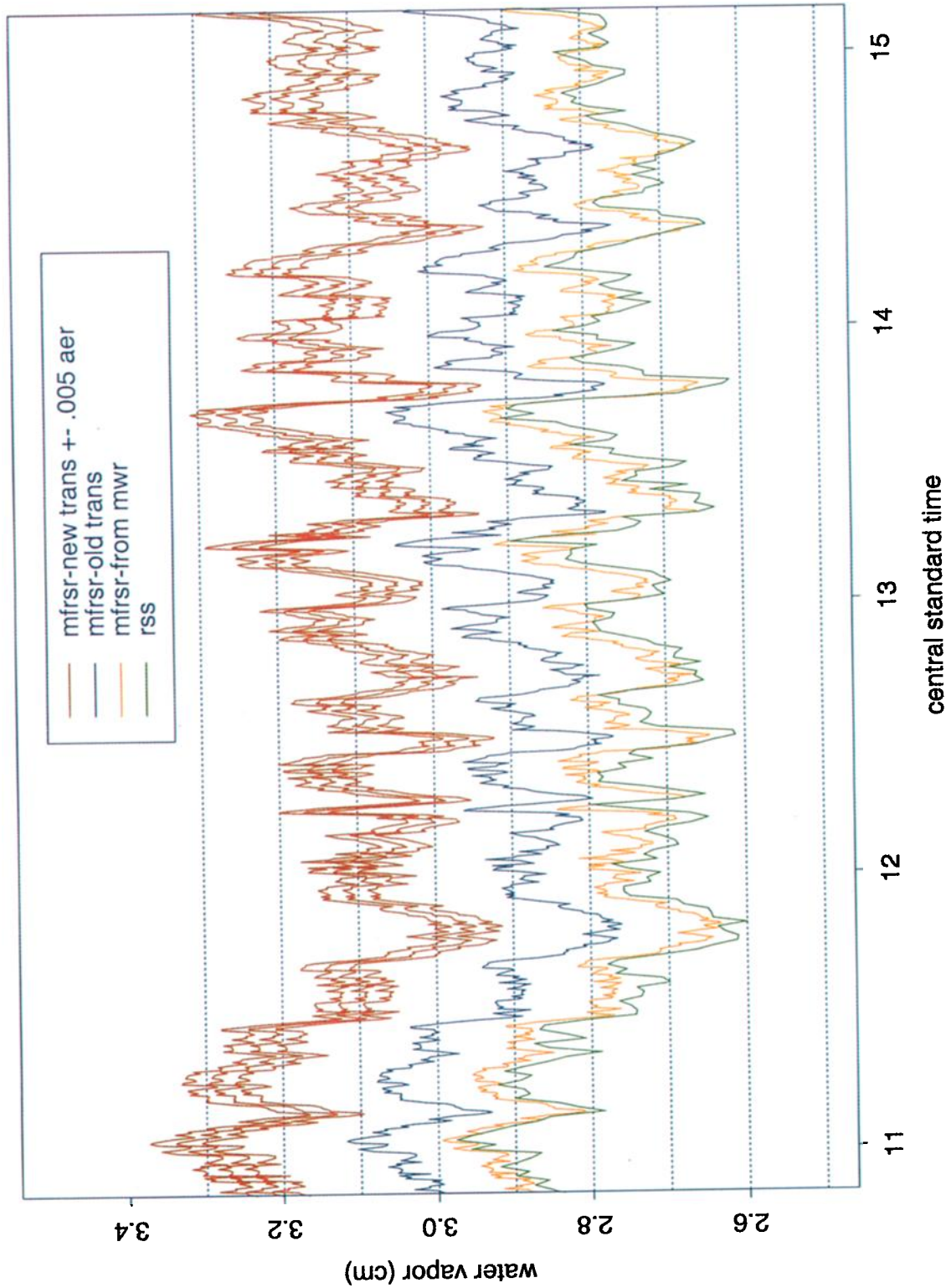
Plate 5. Times series of column water vapor for October 2, 1997, showing sensitivity to aerosol differences (red curves), sensitivity to changes in a 0.8-nm filter shift (compare middle red and blue curves), differences in MFRSR retrievals using an MFRSR calibrated with the present technique and one calibrated using a calibration versus an microwave radiometer (blue and gold curves), and MFRSR retrievals versus an RSS retrieval (blue curve and green curve).

while the modified Langley procedure did not work well at the ARM site in northern Oklahoma because of the unstable water column above the site. Finally, the technique described in this paper could have been applied to any Sun radiometer.

References

Berk, A., L.S. Bernstein, and D.C. Robertson, MODTRAN: A moderate resolution model for LOWTRAN7, *GL-TR-89-0122*, Geophys. Dir., Phillips Lab., Hanscom AFB, Mass., 1989.

Bruegge, C.J., J.E. Conel, R.O. Green, J.S. Margolis, R.G. Holm, and G. Toon, Water vapor column abundance retrievals during FIFE, *J. Geophys. Res., 97*, 18,759-18,768, 1992.

Clough, S.A., P.D. Brown, J.C. Liljegren, T.R. Shippert, D.D. Turner, R.O. Knuteson, H.E. Revercomb, and W.L. Smith, Implications for atmospheric state specification from the AERI/LBLRTM quality measurement experiment and the MWR/LBLRTM quality measurement experiment, paper presented at 6th ARM Science Team Meeting, U.S. Dept. of Energy, March 4-7, 1996.

Fowle, F.E., The spectroscopic determination of aqueous vapor, *Astrophys. J., 35*, 149-162, 1912.

Fowle, F.E., The transparency of aqueous vapor, *Astrophys. J., 42*, 394-411, 1915.

Gueymard, C., SMARTS2, a simple model of the atmospheric radiative transfer of sunshine: Algorithms and performance assessment, *FSEC-PF-270-95*, Fl. Sol. Energy Cent., Cocoa, 1995.

Halthore, R.N., T.F. Eck, B.N. Holben, and B.L. Markham, Sun photometric measurements of atmospheric water vapor column abundance in the 940-nm band, *J. Geophys. Res., 102*, 4343-4352, 1997.

Harrison, L., M. Beauharnois, J. Berndt, P. Kiedron, J. Michalsky, and Q. Min, The rotating shadowband spectroradiometer (RSS) at SGP, *Geophys. Res. Lett., 26*, 1715-1718, 1999.

Ingold, T., B. Schmid, C. Matzler, P. Demoulin, and N. Kampfer, Modeled and empirical approaches for retrieving columnar water vapor from solar transmittance measurements in the 0.72, 0.82, and 0.94-μm absorption bands, *J. Geophys. Res., 105*, 24,327-24,343, 2000.

Kiedron, P.W., J.J. Michalsky, J.L. Berndt, and L.C. Harrison, Comparison of spectral irradiance standards used to calibrate shortwave radiometers and spectroradiometers, *Appl. Optics, 38*, 2,432-2,439, 1999.

Michalsky, J.J., J.C. Liljegren, and L.C. Harrison, A comparison of Sun photometer derivations of total column water vapor and ozone to standard measures of the same at the Southern Great Plains Atmospheric Radiation Measurement site, *J. Geophys. Res., 100*, 25,992-26,003, 1995.

Reagan, J.A., K. Thome, B. Herman, and R. Gali, Water vapor measurements in the 0.94 μm absorption band: Calibration, measurements, and data applications, paper presented at *International Geoscience Remote Sensing Symposium*, IEEE, Ann Arbor, Michigan, 1987.

Schmid, B., J. Michalsky, R. Halthore, M. Beauharnois, L. Harrison, J. Livingston, P. Russell, B. Holben, T. Eck, and A. Smirnov, Comparison of aerosol optical depth from four solar radiometers during the fall 1997 ARM intensive observation period, *Geophys. Res. Lett., 26*, 2725-2728, 1999.

Schmid, B., K.J. Thome, P. Demoulin, R. Peter, C. Matzler, and J. Sekler, Comparison of modeled and empirical approaches for retrieving columnar water vapor from solar transmittance measurements in the 0.94-μm region, *J. Geophys. Res., 101*, 9345-9358, 1996.

Shiobara, M., J.D. Spinhirne, A. Uchiyama, and S. Asano, Optical depth measurements of aerosol, cloud, and water vapor using sun photometers during the FIRE Cirrus IFO II, *J. Appl. Meteorol., 35*, 36-46, 1996.

Stokes, G.M., and S.E. Schwartz, The Atmospheric Radiation Measurement (ARM) program: Programmatic background and design of the cloud and radiation test bed, *Bull. Am. Meteorol. Soc., 75*, 1201-1221, 1994.

Thome, K.J., B.M. Herman, and J.A. Reagan, Determination of precipitable water from solar transmission, *J. Appl. Meteorol., 31*, 157-165, 1992.

Wehrli, C., Extraterrestrial solar spectrum, *Publ. 615*, World Radiat. Cent., Davos, Switzerland, 1985.

J. C. Barnard and D. W. Slater, Pacific Northwest National Laboratory, PO Box 999, Richland, WA 99352. (james.barnard@pnl.gov; donald.slater@pnl.gov)

P. W. Kiedron, J. J. Michalsky, and Q. Min, Atmospheric Sciences Research Center, State University of New York, Albany, 251 Fuller Road, Albany, NY 12203. (kiedron@asrc.cestm.albany.edu; joe@asrc.cestm.albany.edu; min@asrc.cestm.albany.edu)