Ground-Based Microwave Radiometric Observations of Precipitable Water Vapor: A Comparison with Ground Truth from Two Radiosonde Observing Systems

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ABSTRACT

Dual-channel microwave radiometric measurements of precipitable water vapor are compared with values determined from two types of radiosondes. The first type is used in conventional soundings taken by the National Weather Service. The second is used by the CLASS system, as operated by the National Center for Atmospheric Research. The standard deviations of the two comparisons are nearly equal, being about 0.1 cm, but statistically significant biases occur between the radiometer and the radiosondes. A bias of 0.162 cm is present between radiometer and NWS values during the day and 0.075 cm during the night. The comparison shows that significant differences exist between the radiometer and the NWS moisture soundings when the relative humidity drops below 20 percent for pressures greater than 500 hPa. When this situation occurs, the NWS soundings contain a default dewpoint depression value of 30°C. After such data are removed from the comparisons, agreement between radiometer and NWS radiosonde data is excellent.

1. Introduction

For a number of years, radiosonde observations have represented the standard "ground truth" with which a variety of observations have been compared, methods have been evaluated, and instruments have been calibrated. National Weather Service (NWS) moisture soundings are routinely used to judge the quality of satellite thermal soundings (Hayden et al. 1981; Alishouse 1983; Hillger 1984), to determine regression relations for precipitable water vapor (PWV) from VAS observations (Chesters et al. 1988; Petersen and Keyser 1987), to provide corrections for various remote sounding techniques (Warner and Drake 1988), and, in general, to provide ground truth for a variety of remote sounders (Melfi et al. 1988).

We use NWS radiosonde observations in several ways. First, radiosondes have always served as our standard of truth in determining the accuracy of radiometric retrievals of meteorological parameters (Westwater et al. 1985a). Second, radiosondes have frequently been used when comparing measurements and calculations of atmospheric emission and absorption (Hogg et al. 1983a). Finally, some, but not all, radiometric calibration procedures require the use of radiosondes (Hogg et al. 1983b). Of particular interest and concern to us was that our dual-frequency radiometric retrievals of PWV have consistently been greater than those measured by colocated NWS radiosondes (Westwater et al. 1985b). Although it would be simple to adjust the radiometric measurements to be consistent with the radiosonde (by regression), the adjustment was not done, primarily to maintain the integrity of the measurements and to keep them independent of direct soundings.

Recently, as part of a regional experiment to study the initiation of convective storms, Convection Initiation and Downburst Experiment (CINDE), the National Center for Atmospheric Research (NCAR) provided soundings from a relatively new radiosonde package, the Cross-chain Loran-C Atmospheric Sounding System (CLASS). One of the launch sites was coincident with the NWS facility at Stapleton International Airport, Denver, Colorado. Since the humidity-sensing elements for CLASS soundings are different from those of conventional NWS radiosondes, it was of immediate interest to compare radiometric soundings with data from both balloon systems. Our comparisons brought to light certain features of NWS reporting procedures that adversely affect the computation of PWV. In addition, comparisons of the two balloon systems with the same independently calibrated radiometer may also be of general interest.

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2. Equipment

Over the past decade, the Wave Propagation Laboratory (WPL) has designed, constructed, and field-tested several ground-based microwave radiometers to observe the atmosphere (Hogg et al. 1983b,c; Westwater and Snider 1987). In particular, extensive experience has been gained by using zenith-viewing dual-frequency instruments operating at 20.6 and 31.65 GHz. The data that we are discussing in this paper come from an instrument colocated with the NWS radiosonde launch facility at Denver. The two channels share a common antenna and are constructed to have equal beamwidths of 2.5 deg. A complete description of the radiometers is given by Hogg et al. (1983b).

Our radiometers are calibrated using the "tipping curve" or elevation scan method (Hogg et al. 1983c). Here, the absolute absorption at each operating frequency is calculated from the slope of the absorption versus air mass. The air mass is varied as the antenna is scanned in elevation. Tipping curve calibrations are performed only during clear weather. The radiometer output at each operating frequency is related to the atmospheric brightness temperature T_b, which in turn is related to the absolute absorption τ (in nepers) by

$$T_b = 2.75e^{-\tau} + T_{mr}(1 - e^{-\tau}), \qquad (1)$$

where T_{mr} is the mean radiating temperature of the atmosphere and 2.75 is the cosmic background brightness temperature (both in kelvins). The value of T_{mr} is normally calculated from climatological radiosonde data representing Denver. Furthermore, the absorption at each frequency is derived from the measured T_b by

$$\tau = \ln\left\{\frac{T_{mr} - 2.75}{T_{mr} - T_b}\right\}. \qquad (2)$$

Finally, PWV is derived from the absorptions at the two frequencies by

$$\text{PWV} = C_0 + C_1\tau_1 + C_2\tau_2. \qquad (3)$$

The retrieval coefficients, C_0, C_1, and C_2, calculated from a priori climatological data, depend strongly on water vapor and cloud liquid absorption models. An error analysis, based on the correctness of the absorption and radiative transfer models, and based on a radiometric noise level of 0.5 K, predicts an rms error in the determination of PWV of 0.8 mm for summer conditions in Denver. The observed bias in vapor retrievals, however, could be due to the incorrectness of the absorption models, or calibration uncertainties of the radiometer, or both. For example, either a 5 percent error in the mass absorption coefficient of water vapor or a 1-K absolute error in T_b at T_b = 25 K leads to a 1-mm error in PWV for PWV = 20 mm. Thus, to measure PWV by the radiometric technique to an accuracy better than 1 mm is pushing the limits of both theory and calibration techniques.

Different humidity sensors are employed by the radiosondes of NWS and CLASS. The NWS units use standard VIZ ACCU-LOK humidity sensors. The CLASS soundings were made with Väisälä RS80 radiosondes with HUMICAP humidity sensors. To the authors' knowledge, the two units have not been rigorously compared. A comparison study is now being done, however, by NOAA and NCAR (Wolfe and Wade, 1989). Studies of the "functional precision" of NWS radiosondes by Hoehne (1980) lead to an uncertainty in PWV of about 1.1 mm rms. In addition, as we show in section 3, certain NWS reporting procedures and conventions lead to additional uncertainties.

3. Data analysis and comparisons

The CLASS radiosonde data from the CINDE experiment and the NWS radiosonde data were obtained from 22 June to 7 August 1987. At the same time, the NOAA radiometer was usually operated in the zenith-viewing mode. During the data-gathering period, seven tipping curve calibrations were made, but the calibration factors determined from these procedures did not change. This implies that the radiometer was stable over the 6-week period of the experiments.

A typical example of data (Fig. 1) includes a 24-h time series of radiometrically inferred vapor and cloud liquid. Also shown are the vapor amounts determined by integrating the NWS and the CLASS soundings. We note that the radiometer trace is consistently higher than either of the two radiosonde-determined values but that the last NWS determination on 2 August at 2300 UTC seems to be unusually low relative to previous determinations. After we examined the numerical values for the sounding, as well as the values for other seemingly out of line soundings, it became evident that most of the outliers in the NWS soundings were as-

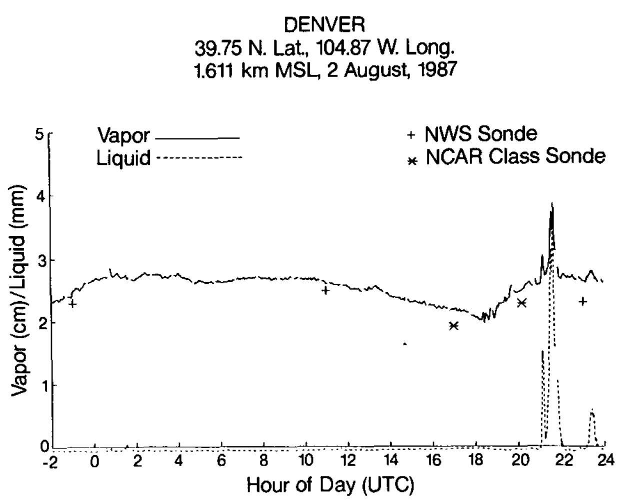

FIG. 1. Twenty-four-hour time series of radiometrically measured PWV and integrated cloud liquid, Denver, Colorado, 2 August 1987. Also shown are vapor amounts from NWS and CLASS soundings.

sociated with dewpoint depression (DPD) entries of 30°C. After consultation with a local NWS meterologist, we learned that, since relative humidity (RH) measurements lower than 20 percent were deemed unreliable, a DPD value of 30°C replaced the actual observations. Since we believed that such a DPD default value would have an appreciable effect on PWV only for pressures greater than about 500 hPa, we separated the NWS radiosonde data into two classes: B, those with one or more DPD values equal to 30°C for pressures greater than 500 hPa, and A, the complement of class B. A scatter plot resulting from this classification is shown in Fig. 2. Here, the difference in PWV between the radiometer and the NWS radiosonde is plotted vs. PWV determined from the radiometer. We note that all departures greater than 0.3 cm, and many of the departures greater than 0.2 cm, are associated with class B (shown as triangles). Of course, a DPD of 30°C could be reasonably accurate, and hence several of the members of class B are in statistical agreement with the distribution of class A.

A similar scatter plot for the CLASS soundings is shown in Fig. 3. Since the CLASS soundings do not use a humidity default condition, a classification scheme was not necessary here. In contrast to the unedited NWS data, all the radiometer–CLASS differences are less than 0.4 cm.

As seen in both Fig. 2 and Fig. 3, there is an apparent uniform distribution of radiometer–radiosonde differences with respect to radiometrically inferred PWV. Similar plots using radiosonde values on the abscissa also showed uniform distributions of differences. The nonzero average differences could come from incorrect modeling of oxygen attenuation or from a certain type

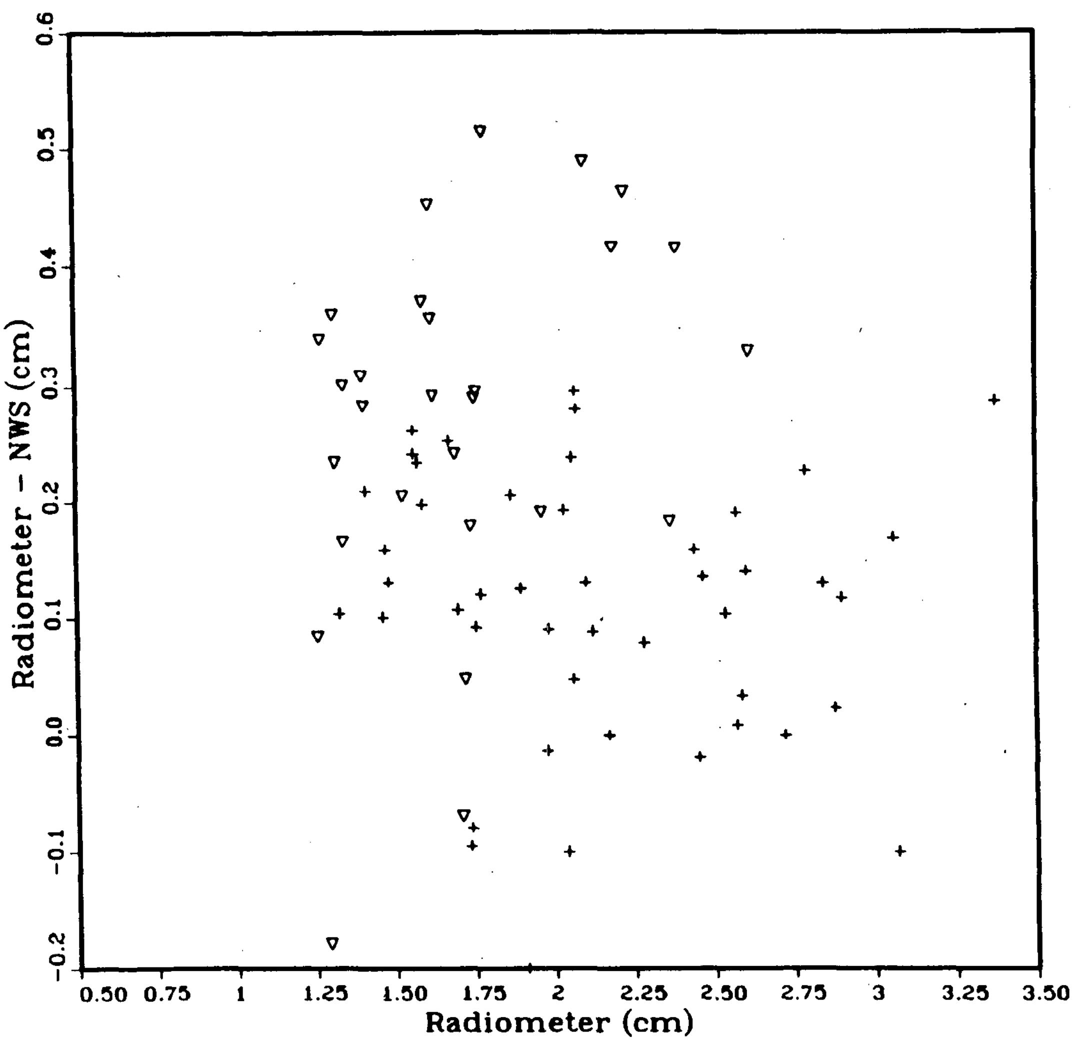

FIG. 2. Scatter plot of the difference between radiometrically determined PWV and that determined by integrating NWS radiosondes vs. PWV determined from the radiometer. The triangles designate soundings for which at least one level below 500 mb contained a dewpoint depression of 30°C. The pluses designate soundings that have no 30°C dewpoint depressions below 500 mb.

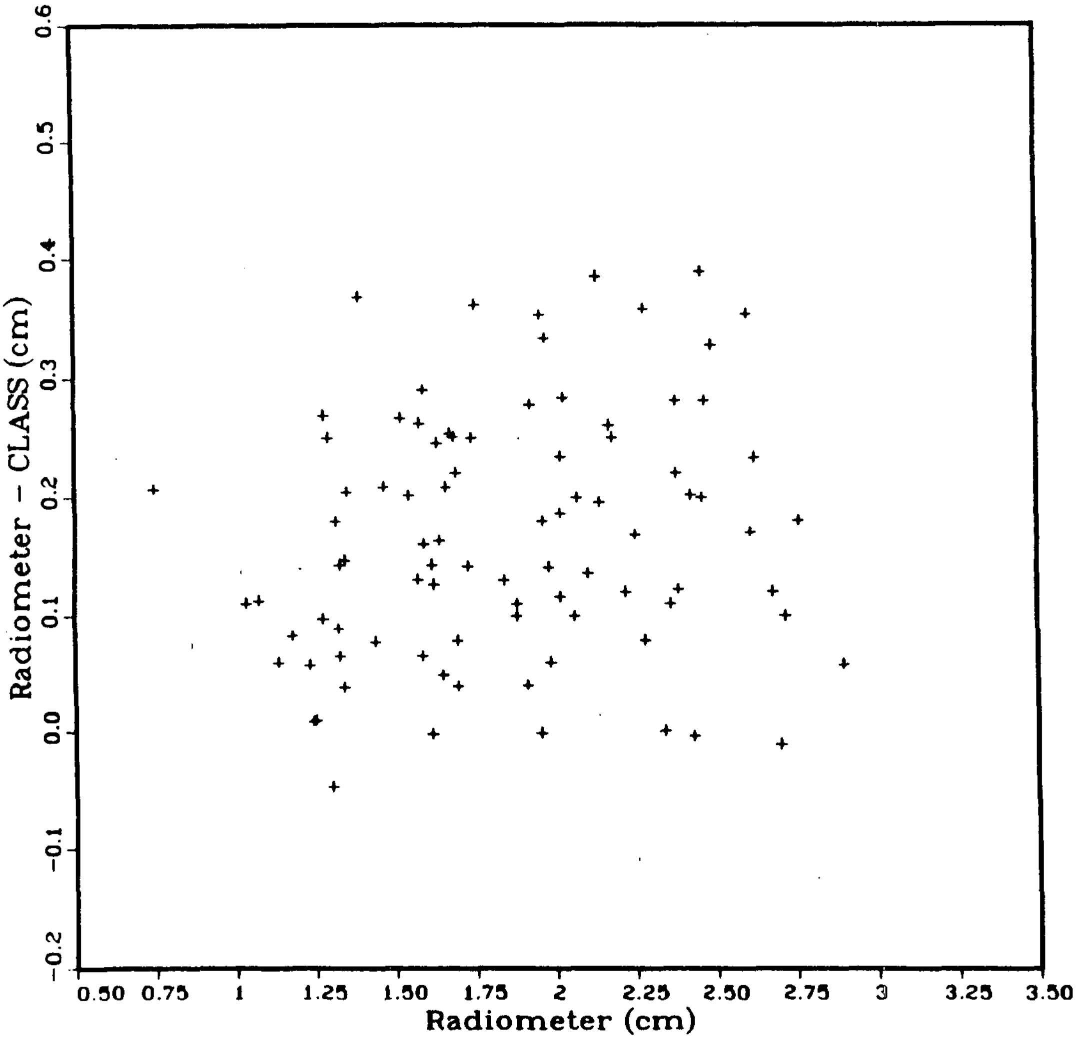

FIG. 3. Scatter plot of the difference between radiometrically determined PWV and that determined by integrating CLASS radiosondes vs. PWV determined from the radiometer.

of instrument bias. Since the differences are independent of PWV, however, modeling errors of water vapor absorption are less likely to be an important factor.

We also show in Fig. 4 the time series of the respective difference plots. For the radiometer–NWS plots, we show only the edited data, i.e., the data that do not contain DPD values equal to 30°C for pressures greater than 500 hPa. For these data, there is no apparent trend, which suggests that the calibrations of both the radiometer and the NWS radiosondes were stable over the 6-week period. Somewhat surprisingly, the radiometer–CLASS differences do show time-varying tendencies over this period. We checked with the person in charge of the CLASS balloon launches during CINDE, and, at his suggestion, we talked with the operator who launched the balloons at Stapleton. Neither could offer a reason for the observed behavior. Thus, it is not clear whether these variations are due to procedural problems or if they are instrumental. We also noticed several instances when the CLASS surface data were in error. As pointed out by an internal reviewer, these errors were associated with ventilation in the air-conditioned trailer from which the sounding were released; but numerical integrations showed that, with the high density of CLASS-reported observations, these surface contributions generally gave PWV contributions less than 0.01 cm. Hence, no attempt was made here to adjust the original CLASS data.

The statistics of the comparisons are shown in Table 1. We note that, for the radiometer–NWS comparisons of averages, a 0.159 cm difference exists between class A and class B. In addition, the standard deviation of the class B data is significantly higher than that associated with class A. This underscores the necessity of carefully editing the NWS data before computing PWV. We also note that there is an apparent 0.055-

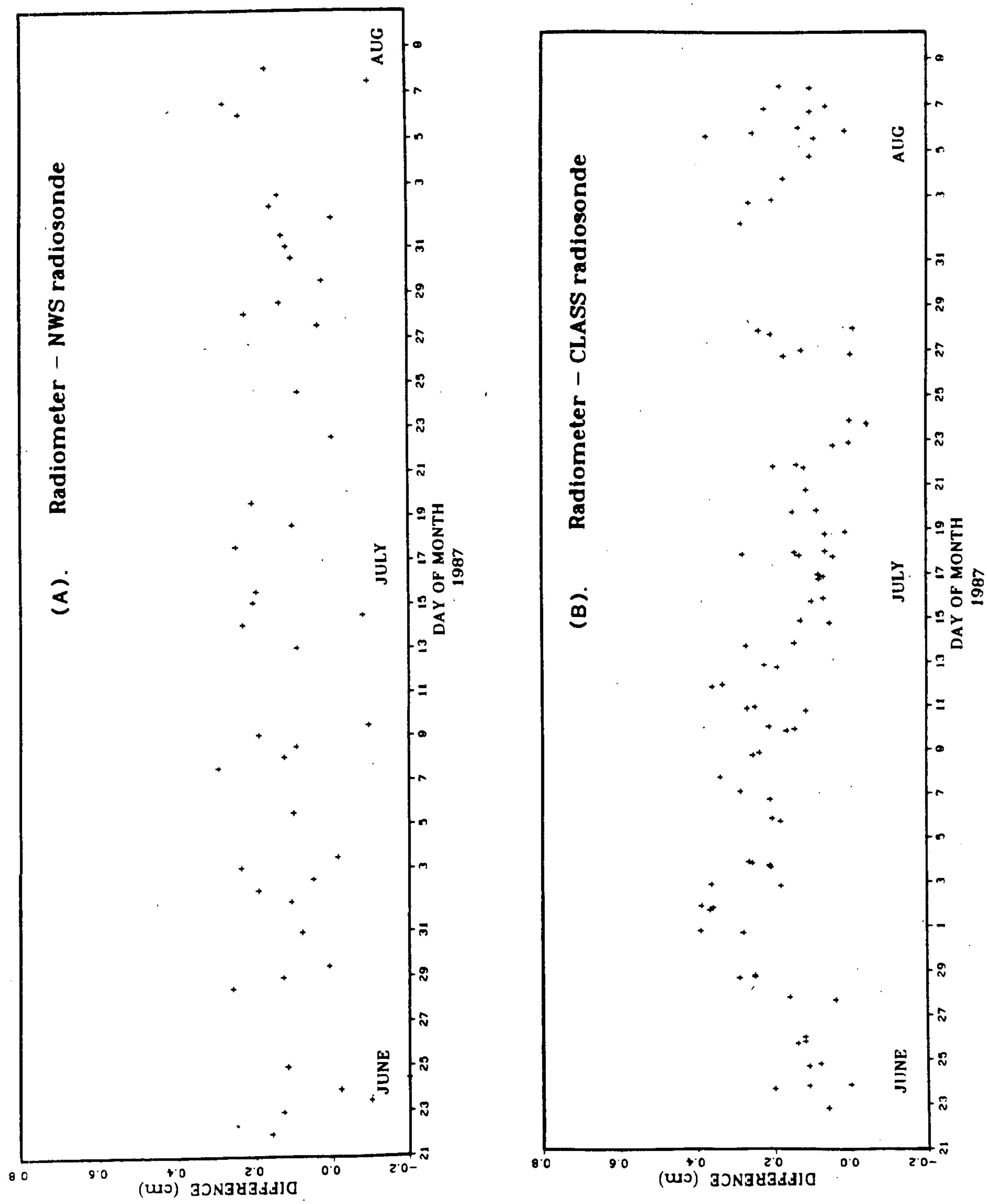

FIG. 4. Time series of the difference between the radiometrically determined PWV and that from (a): NWS radiosondes (category A), and (b): CLASS radiosondes.

TABLE 1. Statistical comparisons between radiometric and radiosonde determinations of precipitable water vapor, 22 June–7 August 1987, Denver, Colorado. For NWS radiosondes in category A, dewpoint depressions = 30°C were not present for pressures greater than 500 mb. For NWS radiosondes in category B, at least one dewpoint depression = 30°C occurred for pressures greater than 500 mb.

	Average difference (cm)	Standard deviation (cm)	rms difference (cm)	Sample size
CLASS	0.166	0.104	0.196	89
NWS (Category A)	0.111	0.114	0.159	46
NWS (Category B)	0.270	0.262	0.313	28
NWS (Total)	0.171	0.153	0.230	74

cm bias between the high quality NWS and the CLASS comparisons. To determine a possible cause for this bias, we further stratified the data into day–night classes to see if there were any diurnal effects. Since the CLASS observations were only taken during the day, it was not possible to compare NWS and CLASS nighttime soundings, but the results of the daytime comparisons (shown in Table 2) were revealing. We notice that the mean daytime difference between radiometer–CLASS and radiometer–NWS category A soundings is essentially the same, about 0.16 cm, and that the nighttime difference of radiometer–NWS Category A is less than half of this value. Two possibilities could explain the observed diurnal differences. The first is that the radiometer suffers from thermal effects that are not removed by the calibration procedure. The radiometer itself is enclosed in a temperature controlled trailer whose excursions are limited to ±5°C. A check of waveguide temperatures for the only part of the radiometer exposed to the trailer air showed only a standard deviation of 0.3°C for the month of July. The flat reflector of the radiometer is located outside the trailer and could be subject to thermal effects. Of course, for a perfect reflector, there are no thermal effects at all. Thus, although it appears unlikely that thermal effects on the radiometer are a source of error, a reliable ground truth measurement is needed to confirm or reject this possibility. The second possible cause for the diurnal difference is that both NWS and CLASS hygristors have common diurnal problems. As pointed out by Pratt (1985), VIZ humidity reports are usually biased downward, by several to as much as 20%, as a result of thermal (ventilation) lag and by warming by sunlight. Whether or not the HUMICAP sensor encounters a similar problem deserves careful investigation.

Finally, among other less likely sources of diurnal error are diurnal changes in the amount of PWV, as have been reported by Augustine (1985), and incorrect temperature dependence of the microwave absorption model.

4. Summary and conclusions

Dual-channel microwave radiometric determinations of PWV have been compared with values determined from NWS radiosondes and NCAR-operated CLASS radiosondes. The NWS and CLASS soundings were not made simultaneously. The standard deviations of the two comparisons are nearly equal, being about 0.1 cm, although statistically significant biases occur between the radiometer and the radiosondes. The bias between NWS and radiometer PWV was 0.162 during the day and 0.070 during the night. It would be desirable to conduct comparison experiments over a period of time during which all three instruments were making simultaneous soundings. In particular, it would be interesting to carry out experiments similar to those conducted by Hoehne (1980), in which both VIZ and HUMICAP hydristors are flown on the same balloon.

It was found that substantial differences, both in mean and standard deviation, exist between NWS radiosonde data and radiometer data when the NWS moisture soundings below 500 hPa contain one or more dewpoint depression default values of 30°C. This default value is used operationally whenever the measured relative humidity falls below 20 percent. After we removed such data from our comparisons, excellent agreement was found between radiometer and NWS data.

In several situations, quantities related to precipitable water vapor are calculated from NWS radiosonde data. We have shown that, without editing, such calculations may seriously underestimate PWV. For instance, both operational and research processing of satellite thermal soundings frequently employ "regression retrievals." The use of such spurious water vapor soundings in constructing retrieval coefficients could degrade the quality of subsequent retrievals.

Finally, the cause of the 0.1 to 0.15 cm bias observed between radiometric retrievals of PWV and those determined from NWS radiosondes has not been resolved, although the discovery of a diurnal variation

TABLE 2. Diurnal comparisons between radiometric and radiosonde determination of precipitable water vapor, 22 June–7 August 1987, Denver, Colorado. Categories A and B are defined in Table 1.

	Average difference (cm)	Standard deviation (cm)	rms difference (cm)	Sample size
CLASS	0.166	0.104	0.196	89
NWS (day)				
(Category A)	0.162	0.070	0.176	19
(Category B)	0.321	0.122	0.343	16
NWS (night)				
(Category A)	0.075	0.075	0.146	27
(Category B)	0.203	0.203	0.268	12

in this bias is an important clue. This bias can arise from (i) calibration uncertainties of the radiometer, (ii) incorrect parameters in absorption equations, or (iii) from an underestimate of PWV by radiosondes. Carefully designed experiments are required to eliminate either (i) or (iii) or both as a cause of this bias. For most meteorological purposes, however, the PWV accuracy of radiometer, CLASS, or high-quality NWS data would be adequate.

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