Field Performance of a Spinning-Reflector Microwave Radiometer

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ABSTRACT

In the winter of 1986, two microwave radiometers were operated side by side at a high-altitude weather observation site in the central Sierra Nevada for the purpose of comparing measurements in a variety of ambient weather conditions. The instruments continuously recorded measurements of vertically integrated water vapor and liquid water during storms affecting the area. One radiometer was designed with a spinning reflector to shed precipitation particles, while the other radiometer's reflector was fixed. Temporal records of the data show periods of wet weather contamination for the fixed reflector radiometer. The absence (presence) of these contaminated periods is mainly explained by the difference in the design of the radiometers. These contaminated periods led to larger standard deviation in the data from the fixed-reflector radiometer and lower correlation coefficients between the two instruments. Correlation coefficients of 0.83 for the liquid and 0.68 for the vapor values were found for the radiometer–radiometer comparisons. When some of the points suspected of contamination were removed, the correlation coefficients improved to 0.87 and 0.71 for the liquid and vapor values, respectively. The standard deviations were 0.1 mm and 0.12 cm for the liquid and vapor channels, respectively, of the spinning reflector radiometer. For the fixed-reflector design radiometer, a standard deviation of 0.1 mm for the liquid and 0.26 cm for the vapor was found. Comparison of radiometer vapor and rawinsonde precipitable water resulted in a correlation coefficient of 0.97 for the spinning-reflector radiometer and 0.8 for the fixed-reflector radiometer.

1. Introduction

The use of dual-channel microwave radiometers for measurements of atmospheric water vapor and liquid water have become increasingly important. Several winter storm cloud investigation projects have used dual-channel microwave radiometers. The Winter Icing Storm Project (WISP) in Colorado (Stankov et al. 1990), the Sierra Cooperative Pilot Project (SCPP) in the central Sierra Nevada (Reynolds and Dennis 1986), and the Snowy Mountains Atmospheric Research Program in Australia (Warburton and Wetzel 1992) are examples of such projects. The SCPP, designed to study precipitation enhancement potential of wintertime storms in the central Sierra Nevada, made use of two radiometers in the winter of 1986/87. One was operated by the United States Bureau of Reclamation (USBR) and another by the Desert Research Institute (DRI). The USBR radiometer had previously been compared to the National Oceanic and Atmospheric Administration (NOAA) Wave Propagation Laboratory (WPL) steerable radiometer during the winter of 1985/86. The results, reported by Heggli et al. (1987), showed generally very good agreement between the USBR and WPL instruments.

In the winter of 1986/87, two radiometers were operated at research sites west and east of the central Sierra Nevada main crest. The USBR radiometer was located at Kingvale (KV), California, while the DRI radiometer was at Truckee, California. Kingvale is located approximately 10 km west (upwind) of the Sierra Nevada crest at an altitude of 1857 m MSL, and Truckee is about 10 km east (downwind) of the crest at an altitude of 1799 m. Prior to moving the DRI radiometer to the downwind site (Truckee) on 13 December 1986, both radiometers were located side by side at KV.

The knowledge of the evolution of integrated liquid water and vapor across a mountain barrier is important to understanding how storms that pass over such a barrier are modified. Since measured liquid and vapor values at the upwind and downwind sides of the barrier were to be used simultaneously for water budget, storm evolution, and modification studies, comparison and performance analysis of the collocated radiometers was necessary in order to validate measurements made when the instruments were separated. In this work, we present such a comparison between the USBR and the DRI radiometers. The data for this study were selected from SCPP measurements made at KV on 5–6 December 1986.

The storm period selected for comparison was not originally set aside for an intercomparison experiment. One radiometer (DRI's) was, in fact, being field tested after its recent construction. The data systems of the

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two instruments were not synchronized for consistent averaging periods. In addition, the radiometers were operator attended for only a part of the sampling time, so continuous monitoring of weather conditions was not conducted. In contrast to more carefully designed intercomparisons, the study reported here probably offers a more realistic assessment of radiometer operation in weather conditions that often contaminate the brightness-temperature measurements when data are collected with unattended instruments. In fact, the situation described, where ambient temperatures at the site were often greater than 0°C during precipitation periods, provided an opportunity to compare the effectiveness of the two radiometers in obtaining reliable measurements under much less than optimum circumstances.

Operation of the dual-channel microwave radiometers during wet snow conditions is very difficult, for it introduces contamination to the actual data. Absorption, reflection, and refraction of the electromagnetic wave as it passes through multisheet mylar windows that isolate the azimuth flat from outside weather (as in the USBR radiometer) and reflection from water-wetted reflectors are among the main weather-induced problems. During the day of the comparison discussed below, both USBR and DRI radiometers were exposed to wet snow conditions. A comparison of the performance of the radiometers during the varying weather conditions is presented.

2. Instrument description

Both the DRI and USBR radiometers operate at the same frequencies, 20.6 and 31.65 GHz. The first frequency is near a water vapor absorption line, while the second, 31.65 GHz, is located in an atmospheric window between the vapor line at 22.235 GHz and the O_2 band at 60 GHz, and is more sensitive to emission by liquid water than water vapor. The methods of reducing the observed brightness temperatures at these two frequencies into water vapor- and liquid water-integrated depths have been explained by Westwater (1978), Westwater and Guiraud (1980), and others.

The radiometers used have similar operating characteristics that are also described by Hogg et al. (1983). The equations relating the vapor or liquid to the brightness temperatures are assumed linear, with coefficients calculated statistically based on climatological meteorological conditions for a given area. Westwater (1978), Hogg et al. (1983), Jacobson et al. (1986, 1988), Heggli et al. (1987), Wei et al. (1989), and others have discussed the principles and methods of dual-channel radiometry and some of the problems that arise in the measurements. Jacobson et al. (1986) reported that wet snow leads to values of liquid and vapor that are cyclic (periodicity of π and both channels out of phase by $\pi/2$) when a radiometer was operated in scan mode.

The radiometers were calibrated (front-end calibration) in the field by the "tipping curve" (Hogg et al. 1983) method. In this method, absorption is computed at several antenna elevation angles, each of which represents an incremental number of atmospheres (secant of the zenith angle). The total absorption values are plotted against the number of atmospheres, and the fitted curve (a straight line) is then forced to pass through zero (i.e., no atmosphere corresponds to no absorption). The true zenith brightness temperature is then found from the true zenith absorption by the following equation:

$$\tau = \ln(T_m - 2.9)(T_m - T_b).$$

In the equation, T_m is the mean radiating temperature of the atmosphere, T_b is the brightness temperature, τ is the absorption in nepers, and 2.9 (K) is a constant accounting for the cosmic background brightness temperature.

Condensation and melting of snow on the outer mylar sheet of the window and melting snow or rain on the reflector are the main problems that can arise during periods of wet snow precipitation. Currently, the NOAA WPL group (Stankov et al. 1990) controls the quality of the radiometer data statistically. First, data are removed when water vapor estimates are negative and/or their time derivative exceeds a threshold value, and then the remaining data are filtered using a running median technique to remove outlier points. Hill (1991) used compressed air to rid the antenna viewing window of snow or water. The effect of scattering and emission by wet hydrometers can also be minimized by using nonlinear retrieval techniques as shown by Sheppard et al. (1991).

a. USBR radiometer

The arrangement of the USBR radiometer components is shown in Fig. 1a. The receiver, feed horn, offset paraboloid, and a minicomputer (LSI-11/02) were housed in a temperature-stabilized trailer. The offset paraboloid and feedhorn design are discussed by Hogg et al. (1979). There were two flat reflectors on top of the trailer (azimuth and elevation flats) fixed on two different bearings. The elevation flat, mounted 45°C from the horizontal, is rotatable in elevation for calibration. Full-sky coverage by the antenna is achieved by rotation of both bearings. Multilayer mylar sheets (thickness 0.05 mm separated by a 50-mm air gap), protected by the cowling, formed a low-loss window (Jacobson et al. 1988) for the reflected energy from the exposed elevation flat.

The USBR radiometer had a bandwidth of 1 GHz, sensitivity of 0.26 K at both frequencies, and receiver noise temperatures of 680 and 725 K at 20.6 and 31.65 GHz, respectively. The antenna beamwidth for both channels was 2.5°. Data acquisition was possible at fixed azimuth and elevation angles and during contin-

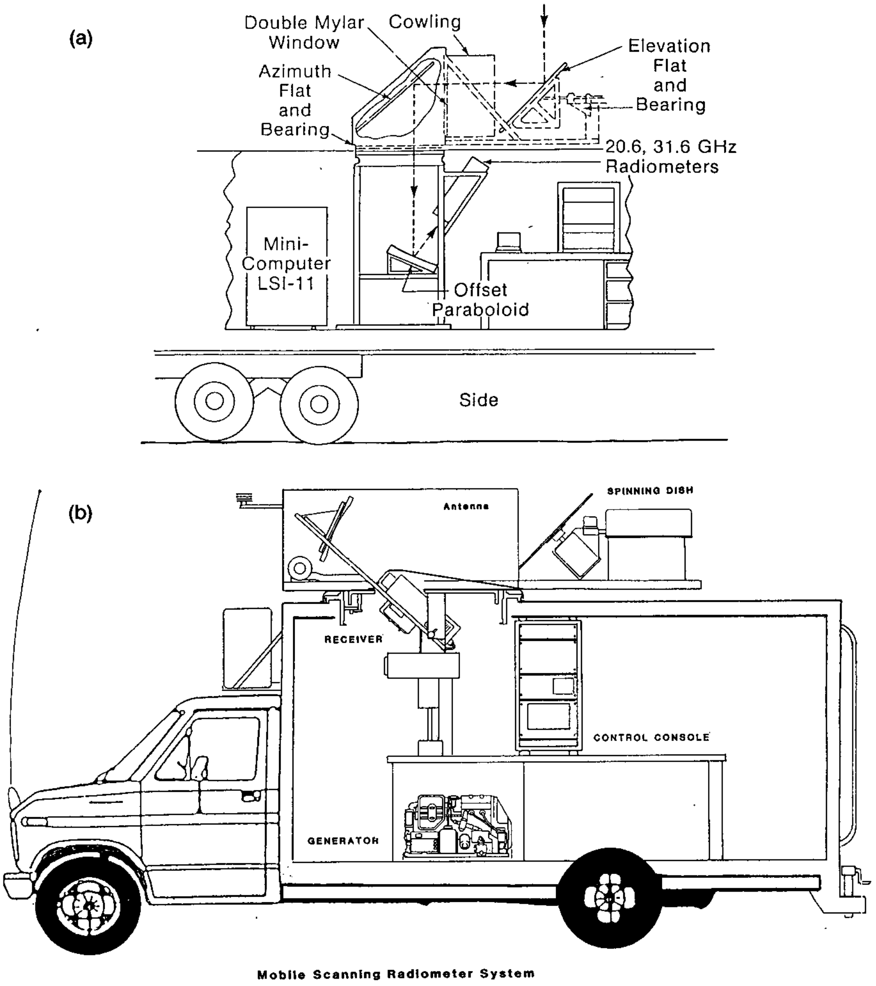

FIG. 1. (a) USBR and (b) DRI radiometers [panel (a) is taken from Hogg et al. 1983].

uous azimuth scanning at a fixed elevation angle. A full 360° azimuth scan took about 12 min.

b. The DRI radiometer

The DRI radiometer has an intermediate frequency bandpass of 50–550 MHz, a noise temperature of 445 K, and a sensitivity of 0.1 K in both channels. The feed horn and offset paraboloid have a design similar to the NOAA WPL system with antenna beamwidths of 2.5° at both frequencies. The DRI design is shown in Fig. 1b. The receiver, offset paraboloid, and elevation flat (or reflector) are mounted on a common frame and turret assembly and can be rotated 360° in azimuth. The flat spinning reflector can be tipped to provide viewing between the zenith and ±90° from the zenith. The elevation angle is measured by an inclinometer mounted on the frame that holds the spinning reflector. The entire system is built into a van (see Fig. 1), with the offset paraboloid and flat reflector on the roof of the van. The paraboloid is protected by an enclosure that is open on only one end, while the reflector, which is exposed to the weather, is capable of spinning (0 to more than 500 rpm) in order to shed precipitation particles. The reflected electromagnetic wave from the offset paraboloid passes through a small mylar window located just above the feed horn.

The body of the van is insulated and houses the receiver and computer, which serves both antenna control and data collection functions. The van is mobile and can be transported and set up by one person with little effort. Software enables collection of tipping curve calibration data, fixed zenith-pointing-mode data, and scanning data. The data collection rate during scans was about one record per degree with a full scan taking about 12 min (approximate rate of 0.5° s^{-1}). All the raw data are recorded so that they may be reprocessed later, if necessary, with different calibration coefficients.

The main difference in the two systems is in the way they are designed to prevent melting or liquid precipitation from interfering with the measurements of cloud liquid and vapor. The USBR radiometer used multilayer sheets of mylar and a fixed elevation flat, while the DRI radiometer design used an enclosure and a spinning reflector.

3. Radiometer comparison case study

The period selected for the comparison was 5–6 December 1986. The storm that passed through the Sierra Nevada during this period was classified by Heggli and Rauber (1988) as a moderate amplitude short wave associated with an occluded storm. The storm began at 2230 (all times are UTC) 4 December and ended at 1630 6 December 1986. The cold-frontal clouds moved into the experiment area after 0530 5 December. Radar echo (not shown here) showed that the back edge of the frontal band crossed KV at 1600 5 December. Radiometer measurements (Fig. 2) were made

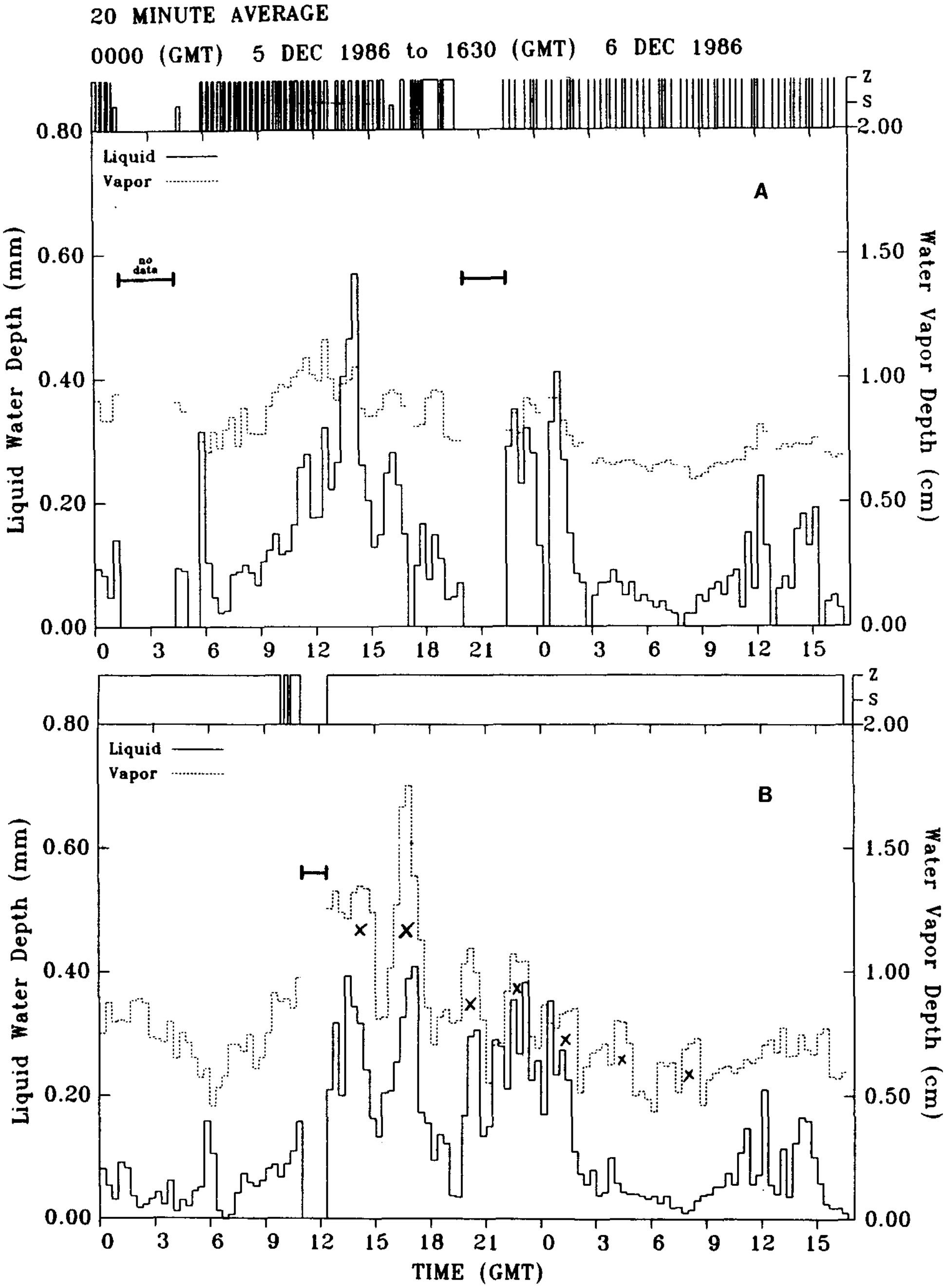

FIG. 2. Integrated liquid water and vapor depths as measured by (a) DRI and (b) USBR microwave radiometers on 5–6 December 1986. The letters Z and S at the top of the figures indicate the zenith and scan modes of operation, respectively. The letter X indicates regions of suspected contamination.

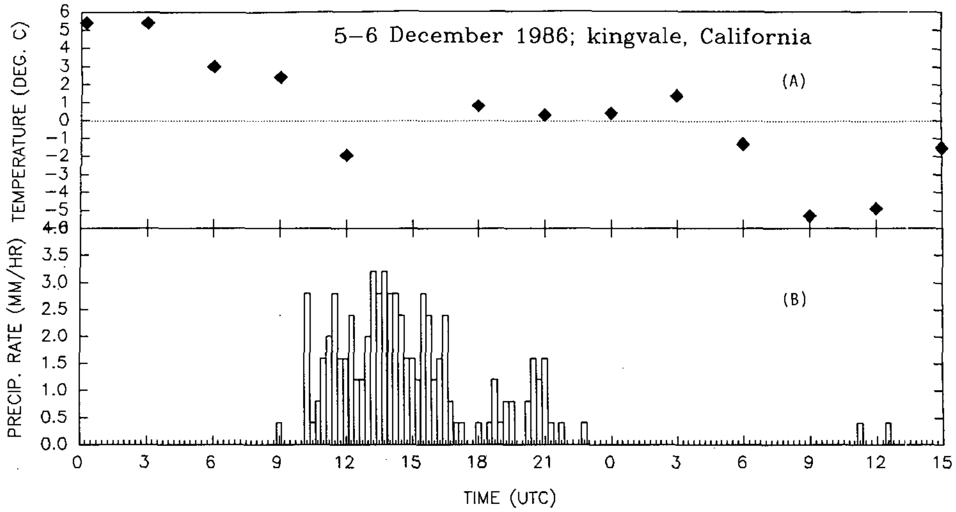

FIG. 3. Precipitation and 3-h temperature record at Kingvale, California, on 5–6 December 1986.

throughout the storm while precipitation (see Fig. 3) was recorded at KV from 0900 5 December to 1300 6 December. The precipitation rate peaked at 3.5 mm h^{-1} at 1345 on 5 December, then gradually decreased with time to near zero by 2300. The period from 2300 5 December to 1100 6 December was nearly precipitation free.

The atmospheric retrieval coefficients used to calculate liquid and vapor depths were the same for both the radiometers, while the tipping calibration coefficients were determined separately for each instrument on 2 December. The USBR radiometer operated only in zenith-pointing mode. The DRI radiometer was used in zenith as well as scan mode. Even though both instruments had user-adjusted sampling rates and averaging intervals (via menu-driven software), the sampling rates used during this storm were not the same. The USBR radiometer recorded averaged data every 2 min, while the DRI radiometer zenith records were 10-min averages. Each 10-min DRI average was computed from about 350 point samples.

A few scans were made with the DRI radiometer at an antenna elevation angle of 25°. These scan data were then averaged in postprocessing and normalized to the zenith to give a value for each 12-min scan interval. For comparison purposes the data from both radiometers were averaged over a longer time interval (20 min). Figure 2 shows 20-min averages of the liquid water and water vapor depths from both radiometers for the storm period sampled between 0000 5 December and 1630 6 December. At the top of the plot the mode of operation of the instrument is shown. Short bars indicate the scan mode of operation at fixed elevation (indicated by "S" on the upper-right corner of the graph) while longer bars are for the zenith mode of operation (indicated by "Z"). The spacing of lines in the mode of operation shows that data were not uniformly collected by the DRI radiometer throughout the comparison period.

Figure 2 shows that, generally, the two radiometers recorded very similar trends in liquid and vapor depth. The DRI radiometer values were slightly greater than USBR values. There were, however, several periods of major disagreement, most notably in the vapor depth. These periods where prominent vapor (and liquid) peaks occurred are marked with an "X" on Fig. 2b. These relative vapor maxima are absent in Fig. 2a. Aside from these obvious differences, the two time-sequential plots from both the instruments followed each other closely. The slight consistent offset in both channels could have been caused by a slightly inappropriate tipping curve calibration in one or the other of the radiometers.

The isolated radiometer disagreements might have been related to ambient weather conditions at the radiometer site. Figure 3 indicates that surface temperature was greater than 2°C before 0900 5 December, warmer than 0°C between 1700 5 December and 0200 6 December, and below 0°C after 0300 6 December. Continuous temperature records were unavailable between 0600 and 2200 5 December but 3-h radiosonde profiles indicated that the temperature near the surface remained warmer than 0.3°C. Subfreezing temperatures occurred in the post-cold-frontal environment after 0600 6 December. Precipitation (see Fig. 3) started at 0900 5 December and ended at about 0000 6 December. Additional small amounts of precipitation were observed near 1200 6 December. The temperature was warmer than 0°C for almost all of the time that precipitation occurred (except between 1200 and 1500 where there is uncertainty in the data), suggesting that melting snow or rain on the reflector may have caused the relative maxima in vapor and liquid seen in the USBR data (Fig. 2b). In addition, the radiometer operator's log also indicated that wet snow was blowing against the lower part of the mylar window from 1200 to 2400 5 December. The accumulated snow was cleaned at 1800 5 December when a decrease in both

TABLE 1. Statistical summary of USBR and DRI radiometer measured integrated water vapor and liquid depth at Kingvale, California, from 0000 UTC 5 December to 1630 UTC 6 December 1986.

Quantity	Radiometer	Mean	Standard deviation	Correlation coefficient
Liquid	USBR	0.119 mm	0.100 mm	0.83
	DRI	0.134 mm	0.111 mm	
Vapor	USBR	0.798 cm	0.256 cm	0.68
	DRI	0.792 cm	0.122 cm	

vapor and liquid values is evident in Fig. 2b. As shown by Jacobson et al. (1986), wet reflectors cause increases in measured brightness temperatures in both channels with the resulting values of vapor and water increasing simultaneously. The increase in the vapor is much larger than the increase in liquid. The same authors found that even a layer as small as 0.15 mm on the reflector can cause large errors in the measurement of the brightness temperature. This problem of contamination of the data by melting snow on the reflector was not apparent in the DRI data (Fig. 2a). This is an indication that the rotating reflector on DRI's radiometer successfully shed the melting particles and prevented the reflector from getting wet.

Table 1 presents a statistical summary of the USBR and DRI radiometer 20-min-averaged data, and Fig. 4 shows scatterplots of the same data. It shows that the correlation coefficient between liquid values, 0.83, was better than for the vapor values, 0.68. The mean liquid values for both radiometers were almost the same, with DRI's mean liquid value being slightly greater. This is also apparent on the scatterplot (Fig. 4a) where the majority of points reside above the 1:1 ratio line. When the more fundamental quantity—the brightness temperature—was used, correlations of 0.75 and 0.73 were found between 20 and the 30 GHz of each radiometer. For the data after 0900 6 December, when temperatures were below 0.0°C and no precipitation fell, the correlation in the liquid was 0.92 while for the vapor channel it was 0.87.

The lower correlation coefficient for vapor values was likely due to the greater variability in the USBR vapor. Although the mean values were almost the same for both instruments, the standard deviation for the USBR vapor was almost twice as great as that of DRI vapor. The larger spread in USBR vapor values was caused by the relative peaks (marked in Fig. 2), which are assumed to be due to contamination from melting snow on the reflector or accumulations of snow on the mylar window. These contaminated values are also evident in Fig. 4b as outliers (USBR values at 1.2 cm). For values at 1 cm, the DRI vapor values tended to be consistently larger, as was the case with liquid.

The USBR radiometer was not operated in a scan mode during this storm, but Jacobson et al. (1986) have shown that for a radiometer similar to the USBR design a thin film of water due to melting snow on the reflector causes the recorded brightness temperatures to vary sinusoidally. They calculated theoretically and measured a periodicity of π associated with the water layer. The errors introduced into the vapor values were much larger than errors in liquid values. In Fig. 5 values of vapor and liquid are shown for two periods when the DRI radiometer conducted a 360° azimuth scan at a 25° elevation angle. At the time of the scan, the precipitation rate was more than 2.5 mm h^{-1} and the temperature was +1°C. The time of the scans matches the time of the first suspected melting snow contribution to the USBR data in Fig. 2b. The vapor traces do not show any sinusoidal periodicity resembling that reported by Jacobson et al. (1986); hence, contamination by melting snow on the DRI reflector did not appear to be a problem.

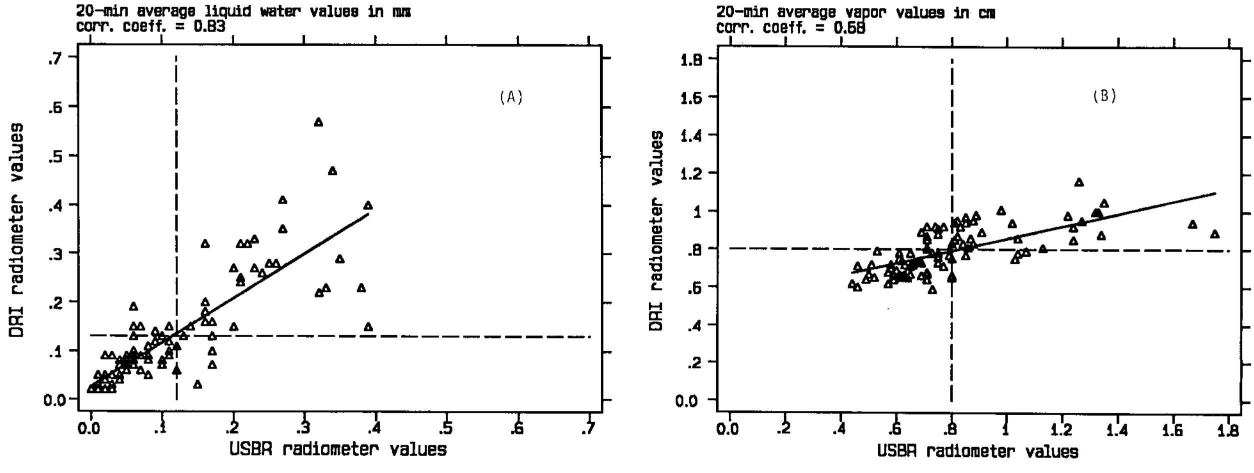

FIG. 4. Scatter plot of USBR- versus DRI-measured values of integrated (a) liquid water and (b) vapor depths. The vertical and horizontal lines represent mean values of the measurements.

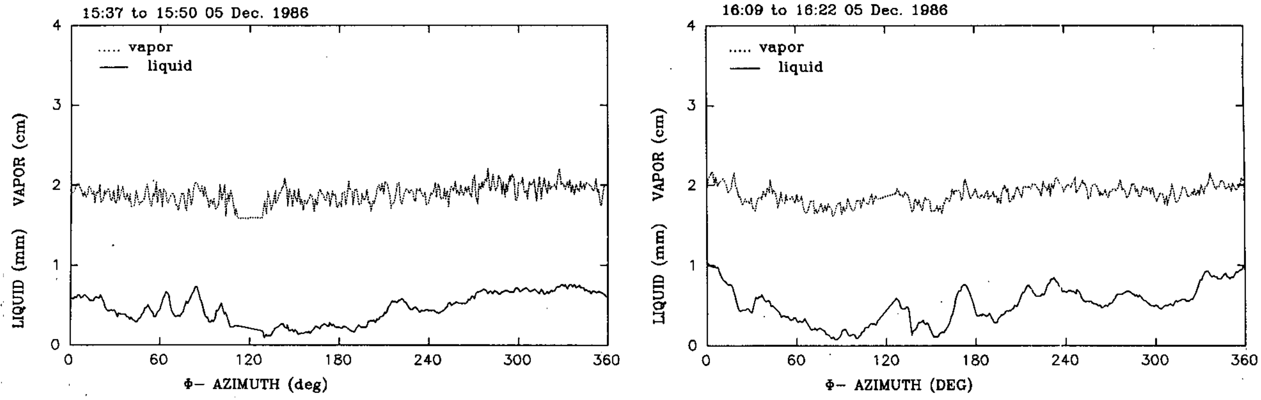

FIG. 5. Integrated liquid water and vapor (dotted line) measurements made by DRI radiometer in scan mode from (a) 1537 to 1550 UTC and (b) 1609 to 1622 UTC 5 December 1986.

4. Discussion of results and conclusions

In an earlier study, Heggli et al. (1987) compared the performance of two microwave radiometers, the USBR radiometer and one from NOAA WPL. They reported a 0.99 correlation coefficient, an average absolute difference of 0.02 mm, and a root-mean-square difference of 0.02 mm for the liquid water values measured by the radiometers. Measurements less than 0.05 mm of liquid were not included in their comparison, and periods when melting occurred or the reflector was wet were removed from their dataset prior to analysis. The correlation coefficient that they found was much higher than the 0.83 reported here. The lower correlation (0.83) found in the current study is thought to be the result of contamination by liquid or melting particles and by differences in averaging intervals of the raw data. If some points, suspected to be contaminated, are removed from the USBR liquid data (points at 1640–1720, 0020–0040, 2240–2300, and 2320–2340), the correlation coefficient between DRI and USBR radiometers increases to 0.87. This better correlation might have been achieved if both radiometers had been equipped with a spinning reflector. The correlation after 0900 6 December when there was no precipitation falling and temperatures were less than 0.0°C was 0.92.

Heggli et al. (1987) reported a correlation of 0.79 for the vapor when liquid was being detected by the radiometer. This compares to 0.68 in the present case. This lower correlation in vapor values for the current study is obviously due to the outlying points in Fig. 4b, again thought to be caused by a wet reflector or mylar window. The correlation without the outliers improves to 0.71, a better comparison to the Heggli et al. (1987) results. In fact, the correlation when there was no precipitation falling and temperatures were less than 0.0°C was 0.87. The current study may be a more realistic comparison for radiometers operating in problematic weather conditions.

Heggli et al. (1987) compared the USBR radiometer vapor measurements with precipitable water vapor

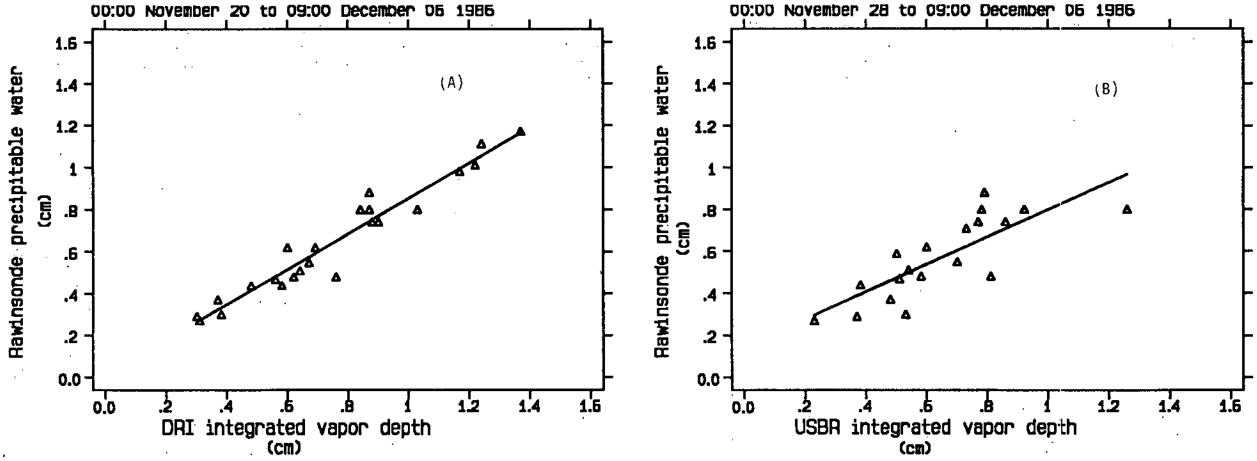

FIG. 6. Scatterplot of rawinsonde precipitable water versus radiometer measured integrated water vapor depth for (a) DRI and (b) USBR radiometers.

measured by rawinsonde at Kingvale, California. A correlation coefficient of 0.94 was reported. Data from rawinsonde launches at Kingvale from 0000 20 November to 0900 6 December are compared to the DRI and USBR radiometer vapor values (30-min averages after the rawinsonde launch) in Fig. 6. It shows a 0.97 correlation coefficient with the DRI vapor data and a 0.80 correlation with USBR radiometer vapor. The data show that the DRI radiometer overestimated integrated vapor by about 0.1 cm on average when compared to the rawinsonde values. It is important to note that rawinsonde precipitable water values are by no means absolute. There are errors associated with the relative humidity measurement. Also, for comparison with radiometers, the drift of the instrument as it rises results in a somewhat different sampling volume of the atmosphere. Nevertheless, the two types of instruments generally show a good agreement, probably because water vapor exhibited minor horizontal variations over the relatively small areas where comparisons were made.

5. Summary

We have compared data from two radiometers with similar receivers but different reflector designs. One (DRI's) used a spinning reflector to remove any snow or water drops that fell on it while the other (USBR's) was fixed. The USBR–DRI radiometer temporal plot showed a similar trend between vapor and liquid throughout the comparison period data except at points of suspected contamination. The correlation between the liquid water depths of the two radiometers was 0.83, which increased to 0.87 after removing some of the suspected values. The vapor correlation coefficient was 0.68 and increased slightly to 0.71 after removing some of the contaminated points. The standard deviation in the vapor values was almost twice as much as that of the liquid.

The radiometers were also compared to rawinsonde launches made at the same location. Correlation coefficients of 0.80 and 0.97 were found for the USBR and DRI instruments, respectively. This correlation coefficient of 0.80 is less than reported by Heggli et al. for the same instrument (0.94) and could be due to the wet reflector problem.

It is important to point out once more that this study was not set up as a careful intercomparison of instruments as was done by Heggli et al. (1987). However, the data collected show that improvements can be achieved by modest changes in the overall design of the radiometers.

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