Liquid Water Distribution Obtained from Coplanar Scanning Radiometers

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ABSTRACT

Field trials have been carried out in the Boulder, Colorado area of a method of determination of cloud liquid-water distribution by inversion of brightness temperature data obtained from a pair of microwave radiometers spaced about 8 km apart and scanning in a coplanar mode through clouds located between them. In the absence of precipitation, the liquid water distribution in the cloud was retrieved with reasonable accuracy. In cases where precipitation was present, it had developed by the ice crystal process, and nearly all the liquid was in the form of rain below cloud base. For this condition the radiometer data was interpreted in terms of a distribution of rainfall rates.

1. Introduction

In a recent paper Warner et al. (1985) showed that it should be possible to determine the distribution of liquid water in a cloud by inversion of data obtained from a pair of radiometers scanning in a coplanar mode through a cloud located above the line between them. By a series of simulation studies they found that the accuracy with which the retrieval could be made depended upon the radiometer receiver noise level, the radiometer antenna beam width, the magnitude of the fluctuations in temperature and water vapor concentation about their mean values at any level, the number of separate angles from which each radiometer viewed the cloud and its surroundings, and the size of the cloud element it was desired to resolve. For radiometers having characteristics that should be readily obtainable, and for atmospheric conditions typical of those prevailing in the central United States, it was concluded that the distribution of liquid water could be determined to an accuracy of about 10% of its maximum value within the cloud (provided that value exceeded about 0.5 g m^{-3}) and with a spatial resolution of about 200 m.

As pointed out by Warner et al. (1985) ice particles emit only very weakly in comparison to water droplets of the same mass and are not detected provided they do not acquire a liquid water surface. The technique therefore detects only the liquid water. However, if a significant proportion of the liquid water in the cloud is in droplets larger than 1 mm, their emission depends upon the droplet size distribution as well as the liquid water content, and interpretation of the results can be ambiguous.

In the present note we examine the results from a limited field trial of the technique in which two radiometers about 8 km apart scanned through the zenith as convective clouds passed overhead.

2. Equipment

Both radiometers were of the type described by Hogg et al. (1983), one owned by the U.S. Bureau of Reclamation and the other by NOAA Wave Propagation Laboratory. By the use of two receivers operating at 20.6 and 31.6 GHz each radiometer can obtain simultaneous measurements of the integrated water vapor and liquid water in the direction of the antenna beam. The same antenna operates with a beam width of 2.5° at both frequencies and can be scanned in both elevation and azimuth. A frequency splitter separates the signals from the antenna for the 20.6 and 31.6 GHz receiver channels. The receivers are of the Dicke type, switching in turn at about 1 KHz from the antenna to each of two reference loads, which operate at different temperatures. The receiver sensitivity at either frequency is about 0.2 K when expressed in terms of brightness temperature. It should be mentioned that the clear sky brightness temperature at the zenith at the site of the experiment was 15–30 K at 31.6 GHz, while brightness temperatures of thin clouds were typically 100–150 K and of rain, up to 260 K. In the usual application of the radiometers, the brightness temper-

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atures at both frequencies are used to derive either integrated vapor or liquid. For example, Guiraud et al. (1979) give the following expressions where T_b is the brightness temperature at the given frequency

$$\text{Vapor} = -0.19 + 0.118T_{b(20.6)} - 0.0560T_{b(31.6)} \quad \text{(cm)}$$

$$\text{Liquid} = -0.018 - 0.00114T_{b(20.6)} + 0.0284T_{b(31.6)} \quad \text{(cm)}.$$

The coefficients in these relationships are based upon statistical meteorological conditions for the Denver, Colorado area.

In our case it was assumed that the temperature and water vapor content would be known to sufficient accuracy from a radiosonde released about 40 km away, and information from the 20.6 GHz vapor channel of the radiometers was not used.

3. The field trials

The radiometers were available for the month of August 1983, but operational rather than meteorological considerations dictated their location. One was located at the NOAA building on Marine Street in Boulder and the other at Marshall, which is roughly south of Boulder 8 km away.

The antennas were pointed toward each other and manually scanned from the zenith toward the horizon, stopping at an elevation angle of about 10° where trees near the NOAA building interfered with signals received by that radiometer. Radio communication between the radiometer sites ensured near simultaneity of scan. The scan rate was roughly 20° min^{-1} and brightness temperatures were read every 3–5 s, values which were governed by the 1 s integration time of the radiometer receiver and the need to complete a scan in a reasonably short time period. Hence, signals from only 40–50 beam positions at each radiometer were actually used in the analysis.

Clouds commonly built up over the foothills in the morning, but there were only three operational days during the month-long period of the trials on which reasonably discrete clouds moved over the line between the radiometers. On 16 August three successive scans between 1519 and 1533 MDT produced signals ranging up to 158 K in brightness temperature as a small cloud moved over the site. No precipitation was observed on this occasion. On 18 August successive scans of a cloud system between 1603 and 1612 MDT produced intense signals up to 257 K in brightness temperature. Moderate to heavy rain was observed to fall to the surface. A later run at 1715 MDT gave weaker signals from a different cloud. On 22 August only very weak signals were obtained from two successive scans at about 1415 MDT. The maximum brightness temperature observed was 107 K. Signals were obtained on other occasions but from much more complex cloud systems, and interpretation would be difficult. The possibility of retrieval of liquid water under these conditions might have been improved had the radiometer scans been made over the full 180° from horizon to horizon, but it was not realized at the time how infrequent suitable clouds would be and it was considered desirable to cut the scanning time down to the minimum.

An instrumented aircraft carrying a Johnson–Williams liquid water meter and PMS probes for measuring particle sizes was available. It was flying on 16 August at the time when clouds were observed by the radiometers, but was prevented by the local traffic control office at Stapleton Airport from penetrating the clouds. Indeed, it got no closer than 600 m below cloud base. The aircraft did not operate on 18 August, but was flying over the site on 22 August 20 min after the radiometers detected thin clouds. The aircraft made five cloud penetrations, but abandoned the operation when it failed to detect liquid water contents greater than 0.2 g m^{-3} anywhere within the cloud, with most values below 0.05 to 0.1 g m^{-3}. Low concentrations of ice particles were also observed and some light precipitation was seen below cloud base. At this time the radiometer signals were very low.

Hence, throughout the whole observing period there were no direct measurements of liquid water with which to compare the values derived from the radiometric data.

4. Results

Retrievals of liquid water distribution from the measured values of brightness temperature followed the procedure outlined by Warner et al. (1985). Since the total number of beam positions was only 80–100, as mentioned earlier, the number of elements in the hypothetical cloud field had to be restricted. (Obviously no retrieval is possible unless the number of elements is less than the total number of beams.) Hence, a total of 64 elements was used of size 800 or 1000 m. The results of retrievals from one scan on each of the three useful days are given below. In each case radiosonde data were used to define the mean temperature and vapor fields.

a. 16 August 1983

The retrieval, as shown in Fig. 1, suggests that there was a maximum liquid water content of about 2.0 g m^{-3} 1500 m above cloud base. A fully adiabatic cloud would have a liquid water content of 1.7 g m^{-3} at this level. From the simulation studies of Warner et al. the expected accuracy of the retrieval would be 0.3 g m^{-3}.

Some comment should probably be made on the values of liquid water shown in the bottom corners of the box representing the cloud in Fig. 1. It will be noticed that the measured brightness temperatures, represented by the length of the lines radiating from each

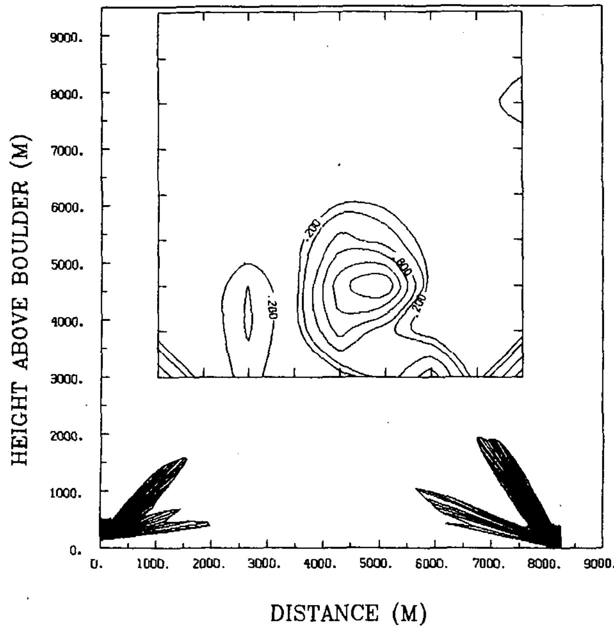

FIG. 1. Retrieval from field data for a small nonprecipitating cloud observed on 16 August 1983. Cloud base was 3300 m above the surface at a temperature close to 0°C. The contours are at 0.2, 0.4, 0.8, 1.2 g m^{-3}, etc. The measured brightness temperatures are indicated by the length of the lines radiating from the position of each ground station.

radiometer position, go through a weak minimum at some angle below the zenith. For the Marshall site a minimum brightness temperature of 21.08 K was observed at 76.2°. For equally clear sky conditions, this would suggest a brightness temperature of only 20.47 K at the zenith, where a temperature of 26.59 was observed by the radiometer. Clearly some cloud was present in this area, but full retrieval is not possible since inadequate information is available due to the limited scanning angles employed. Hence, the values and even locations of liquid water shown in the bottom corners of the box in Fig. 1 are not necessarily correct.

It is of interest to compare the measured brightness temperatures with those that can be calculated from the retrieved field of liquid water, since this gives a measure of how well the retrieval matches the given data. This is shown in Fig. 2. Apart from values outside the region of the retrieved "cloud," the mean difference between measured and calculated brightness temperatures was 6.0 K, and the mean percentage difference, i.e.,

$$\frac{\text{measured} - \text{calculated}}{\text{measured}} \times 100,$$

was 5.8%. The agreement does not, of course, prove the validity of the retrieved liquid water distribution, only that it is consistent with the observed brightness temperature data.

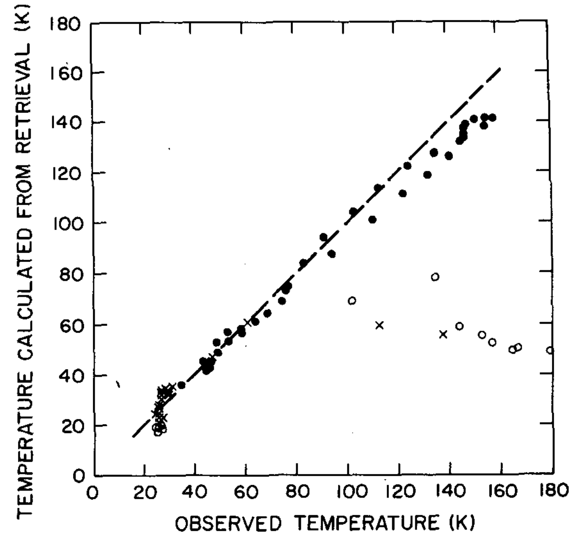

FIG. 2. Brightness temperature observed by the radiometer at Boulder on 16 August 1983 compared with that calculated from the retrieved liquid water distribution shown in Fig. 1 at each angle at which an observation was made and the known environmental temperature and humidity profiles. Full circles represent data wholly within the retrieved cloud, crosses represent data at the corners of the field and open circles represent data outside the field.

b. *18 August 1983*

A first attempt to retrieve a liquid water distribution in this case yielded the result shown in Fig. 3. This is

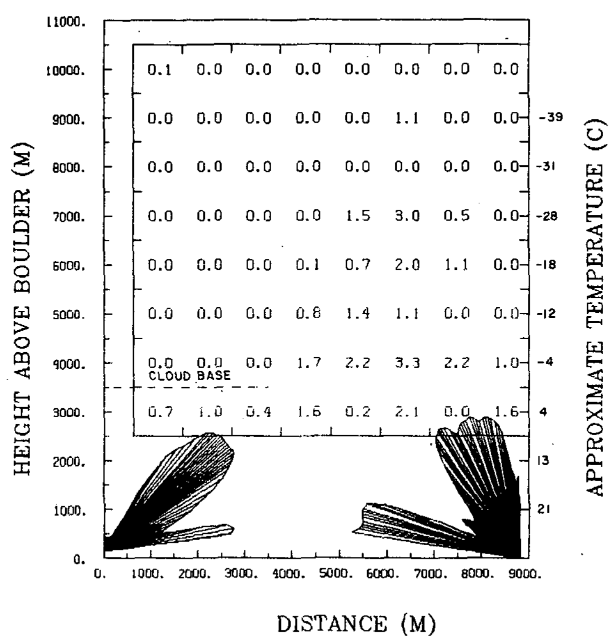

FIG. 3. Retrieval for a large precipitating cloud observed on 18 August 1985. Because of the high variability of the retrieved liquid water, taken to be uniform over each 1 km × 1 km box, no contours have been drawn.

a physically implausible result because of the high water content suggested high up in the cloud. At temperature levels well below −20°C, field observations suggest that most of the water would be in the ice phase and hence not visible to the radiometers. It is also improbable that any water accreted by the ice particles would remain frozen. The true liquid water content is unlikely to exceed 0.1 to 0.2 g m^{-3}. Hence, the reason for the high brightness temperatures measured on this occasion is probably the presence of rain below cloud base. If we constrain the inversion process in the retrieval to produce zero liquid water above some specific level, an alternative result can be obtained. If we put that level at a height of 500 m above cloud base and where the temperature is −4°C, a much more plausible result, shown in Fig. 4, is obtained. Here we have postulated zero liquid water throughout most of the cloud, and the inversion indicates high water contents below cloud base, but no indication of a melting band at the 0°C level. The values given in Fig. 4 are for rain rate, rather than liquid water content, using a relation between absorption and rain rate based on data given by Atlas and Ulbrich (1977).

Similar comparisons were made to that shown in Fig. 2 between measured brightness temperatures and those calculated from the retrieved values of water content. The average relative differences between measured and calculated brightness temperatures were 19% and 14% for the retrievals shown in Figs. 3 and 4, respectively.

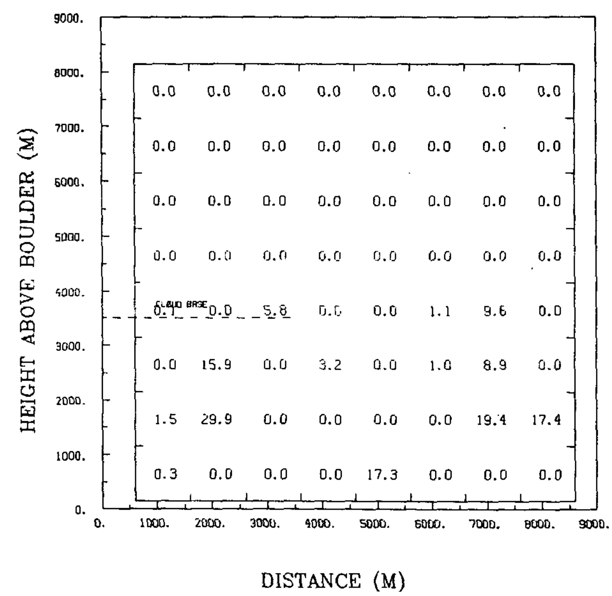

FIG. 4. Retrieval for the same cloud shown in Fig. 3 but where the solution has been constrained to give zero liquid water at all levels in excess of 500 m above cloud base. The values given here are of rain rate in mm h^{-1}.

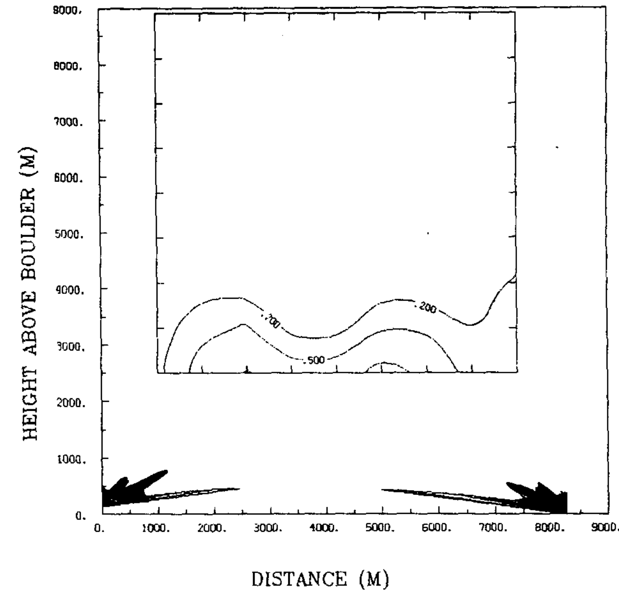

FIG. 5. Retrieval for a thin cloud observed on 22 August 1983. The contours are at 0.2, 0.5 and 1.0 g m^{-3}.

c. 22 August 1983

The retrieval, shown in Fig. 5, found essentially zero liquid-water content at all levels above cloud base, which was about 3500 m above the surface. The values indicated below cloud base are presumably due to light precipitation. This result is in agreement with the limited observational material available from the research aircraft.

5. Discussion

It is clearly unfortunate that no in situ observations are available with which to compare the values of liquid water retrieved from the radiometric data. The liquid water distribution derived for 16 August is certainly plausible from what we already know about convective clouds. It would be a mistake to push too far the results for 18 August. The magnitude, distribution and location of the rain cells are plausible, but this information could be obtained just as readily from radar. Further, if liquid, or liquid-coated, precipitation-sized particles had been present within the cloud as well as cloud droplets a retrieval would not have been possible from the radiometric information.

The spatial resolution of the liquid water distribution in the work reported here is poor, being governed by the 1 s integration time in the radiometer receivers and the need to complete a scan in a time that is short compared to cloud development or movement. However, it is questionable whether the time taken to scan the clouds was, in fact, short enough to avoid these problems. In a system designed for the purpose it would be desirable to reduce the integration time to 0.1–0.2 sec. This would result in improvements in spatial resolution and accuracy of retrieval even though it would simultaneously increase receiver noise levels.

Attempts to carry out further trials of the technique have been frustrated to date by difficulties in getting two otherwise highly committed radiometers located in the same area but appropriately separated. Further work will have to await the outcome of trials of an airborne version of the technique, expected to take place late in 1985.

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