# Field Tests of an Airborne Remote Sensing Technique for Measuring the Distribution of Liquid Water in Convective Cloud

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ABSTRACT

A comparison has been made between the distribution of liquid water in maritime cumulus clouds deduced from radiometric measurements below cloud base and that measured directly by penetrating the clouds at various altitudes. Because the clouds available during the field program were changing quite rapidly, the comparison could only be made on a statistical basis and at coarse spatial resolution. However, on this basis excellent agreement was observed between liquid water values given by the direct and the remote sensing techniques.

## 1. Introduction

Microwave radiometry has been used increasingly in recent years to detect the presence and approximate quantity of liquid in clouds by remotely measuring their emissions. Warner et al. (1985) describe a technique whereby a complete vertical cross section of the distribution of cloud water can be obtained by measuring the microwave radiation from the cloud and its surroundings in many different directions and mathematically inverting these data. The method is similar in principle to various imaging techniques, such as computer-aided tomography as used in the medical field. Warner et al. describe three equipment configurations which could be used for the collection of the radiometric data necessary to calculate the distribution of liquid water in a cloud; they concentrate upon a particular ground-based version of the technique. Drake and Warner (1988) describe the results of computer simulation studies of an airborne version in which data are collected from two fixed antennas alternately switched to a radiometer receiver as the aircraft carrying the system flies below cloud base. The configuration is shown schematically in Fig. 1.

The present paper describes the results of field trials of the airborne system. In these trials an aircraft fitted with a dual-beam 31.65 GHz radiometer flew below the bases of convective clouds obtaining information from which the distribution of cloud water could be obtained. Simultaneously, a second aircraft fitted with liquid water and droplet sizing probes flew through the cloud at some greater altitude making direct measurements of cloud properties at that level. The purpose of the trials was to obtain verification of the remote-sensing technique.

## 2. Location of trials and meteorological conditions

The observations were carried out over the Gulf of Mexico with both aircraft operating out of the same airport at New Iberia in Louisiana. Although the program lasted from 22 October–9 November 1985, by the time preliminary testing had been completed Hurricane Juan developed in the Gulf and prevented operations until 1 November. Unfortunately, its dissipation left clear skies or thin cloud until the passage of a cold front on 6 November. The following three days produced good cloud conditions about 150 km offshore, and the results from these three days are reported here.

The altitude below which the atmosphere was conditionally unstable, as determined by soundings made by the King Air in the operating area, dropped from about 3200 m on 7 November to about 1500 m on 9 November, and the freezing level dropped from 4000 m to 3600 m. Ice was not observed in any of the clouds studied and when precipitation occurred, which it did infrequently, it was by the condensation–coalescence process.

## 3. Equipment and flight patterns

The radiometer was installed in NCAR's Electra aircraft with two antennas mounted on top of the fuselage and the radiometer receiver and associated data recording equipment mounted inside the cabin. The liquid water and droplet sizing equipment were mounted in their standard mode on NCAR's King Air. Both aircraft were fitted with inertial navigation systems

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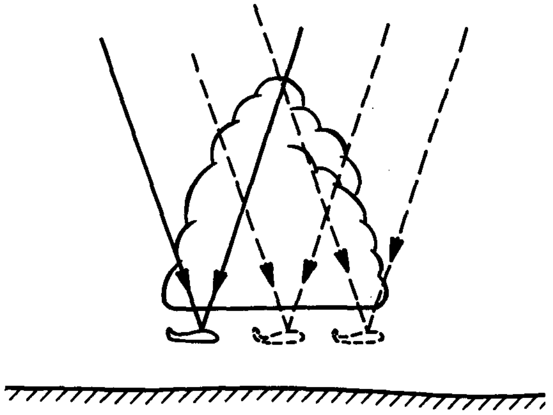

FIG. 1. Schematic of airborne radiometer system. A receiver is switched alternately between two antennas and measures the emission from cloud and atmosphere at many positions as the aircraft flies below cloud base.

(INS) and Loran-C equipment which could be used to update the INS.

### *a. Radiometer*

The radiometer was very similar to that described by Hogg et al. (1983). It was, however, only a single channel instrument operating at 31.65 GHz with the input switched at about 1000 Hz between antenna 1, antenna 2, and a temperature reference load. In order to obtain frequent measurements of emission from the cloud above the aircraft, the integration time of the radiometer receiver was reduced to 0.1 s from its normal value of 1 s, resulting in some increase in noise level. However, for the particular instrument used, the minimum change in brightness temperature was found to be only 0.2 K with the 0.1 s integration time.

The radiometer receiver output was sampled at 50 Hz and filtered to 10 Hz before recording. Temperatures at various critical points in the system were sampled at 10 Hz and recorded at 1 Hz after filtering. The monitoring points included the antenna lens, waveguide runs in the faired housing supporting the antennas on the roof of the aircraft, and two points in the radiometer receiver box. The temperature of the blackbody reference in the radiometer was similarly recorded.

Two circular horn-lens antennas were used, one pointing forward at an angle of 45° above the longitudinal axis of the aircraft and the other pointing backward at a similar angle above the axis. The antenna beamwidth was 2.5° to half-power points with side lobes 27 db below the main beam. Since radiation from the sun provided a strong (but not saturation) signal, antenna pointing was checked in flight during turns against known sun position and found to be within 1° of its geometrical position.

The radiometer was calibrated in the field using two known or calculable temperatures and assuming linearity between them; such an assumption was justified by prior laboratory calibrations. A sheet of microwave-absorbing material with losses >50 db was placed directly in front of each antenna in turn, and the signals corresponding to its measured temperature (about 300 K) formed one calibration point. The other point was determined by placing a metal mirror in front of each antenna in turn so that the antenna beams pointed to the zenith, then again observing the radiometer output. This observation was only made with clear sky conditions when the sky brightness temperature could be calculated from radiosonde data taken simultaneously, the sonde being released from the airport where the aircraft was stationed. The calculated sky brightness temperatures varied from day to day and ranged from about 16–36 K. Calibrations were performed on seven days during the program and showed no marked changes throughout. The rms difference between all calibration points and the line of best fit was 1.6 K.

Since changes in the temperature of the antenna, waveguide components, and the radiometer receiver itself all affect the calibration, varying measures of temperature control were imposed. In spite of this some temperature changes occurred during flight and some differences appeared between flight and calibration conditions. Changes in component temperatures during flight should not have resulted in changes in sky brightness temperature of more than about 0.5 K, while the maximum departure between flight and ground-based calibration conditions could have resulted in similar errors.

### *b. Liquid water probe*

Liquid water content was measured by a Particle Measuring Systems (PMS) version of the probe described by King et al. (1978). It is an electrically heated hot-wire device operating at a constant temperature near 100°C in which the power required to evaporate the liquid drops impacted is measured and interpreted in terms of water concentration. It is reported to have a sensitivity of 0.02 g $m^{-3}$, a response time of better than 0.05 s and an accuracy of 5% at 1 g $m^{-3}$ (at 0.2 g $m^{-3}$ the accuracy is about 16%). According to Biter et al. (1987) the response of the probe at an airspeed of 60 m $s^{-1}$ decreases from 100% for a cloud of droplets with a median volume diameter of 20 $\mu$m to about 50% for a cloud where the median volume diameter is 150–200 $\mu$m. With droplets of 300 $\mu$m or greater diameter, the response probably drops to 25% or less. Data from the probe were sampled at 10 Hz and filtered to 1 Hz before recording.

### *c. Droplet measuring probes*

A forward-scattering spectrometer probe (FSSP) and a one-dimensional optical array probe (OAP), both manufactured by PMS, were employed for measuring droplet sizes. These probes are described by Knollenberg (1981). The FSSP sizes particles in the 2–47 μm diameter range in steps of 3 μm, and the OAP used in this program sizes particles in the 300–4500 μm diameter range in steps of 300 μm. In the present application exact sizing was not a critical requirement: what was necessary was some idea of the partitioning of liquid water above about 300 μm diameter where the Raleigh approximation to absorption/emission at 31.65 GHz begins to depart from full Mie theory. This question is discussed in Drake and Warner (1988). Sampling and recording procedures were similar to those for the liquid water probe.

### *d. Navigation equipment*

For a direct comparison between the radiometrically determined distribution of liquid water and that measured by the penetrating aircraft, the following conditions have to be met:

(i) Changes in the liquid water distribution in the time taken to make the necessary measurements (typically 3 min for the Electra) would have to be small.

(ii) The Electra platform for the radiometer should be stable, particularly in roll, which should not vary by more than about ±0.5° during the run under cloud. Pitch changes can be taken into account in the retrieval process.

(iii) The King Air would need to be vertically above the Electra, at least to within the radiometer antenna beamwidth, which at a separation of 2000 m means to within ±50 m.

The last condition required precise navigation and was probably not possible to achieve, except rarely and then probably by chance. Nevertheless, it was considered that relative aircraft positions might be available to about that accuracy after the event and records were taken of the INS position data with this in mind. Unfortunately, the best accuracy that could be achieved, even after applying corrections from Loran-C, appeared to have rms fluctuations of the order of 300 m.

An examination of the flight records showed that the second condition was also generally not met. Roll changes of ±1.5° were common during the flight of the Electra below cloud base and ±2.5° excursions occurred on occasion.

The implications of these two factors together with a consideration of the observed spatial variability of liquid water will be discussed later.

### *e. Flight patterns*

Clouds for study were selected by the observer in the King Air while that aircraft was at a level approaching cloud top. The Electra was directed to the chosen area and lined up on the selected cloud, usually operating at an altitude of 300 m, about halfway between the surface and cloud base. The King Air took up a position trailing 0.5–1 min flying time behind the Electra so that visual contact was maintained. It is estimated that on the first sampling run on the selected cloud the two aircraft were generally within ±100 m laterally from each other. For the second and successive sampling runs the Electra came back on reverse headings after procedure turns which were intended to bring it back to the same air position each time. The length of each Electra run was governed by the need for the 45° forward pointing antenna to see clear air and no cloud for about 0.5 min before it saw the selected cloud top and for the aft pointing antenna to see clear air for a similar period after it last saw cloud top. This made for straight runs of 3–4 min in duration with turns at each end occupying a further 2–3 min. After its first penetration was completed, the King Air made an orthogonal pass at the same level using its navigation equipment to bring it back through the region of maximum water observed on the first pass. It then continued to make penetrations at other levels approximately parallel or perpendicular to the Electra track until the cloud commenced to break up. At that time the King Air selected another cloud for study and the process was repeated. The time interval for successive cloud penetrations by the King Air was typically 2–3 min, less than half that required for successive samplings by the Electra.

After the cloud observations were completed the King Air made a sounding in the vicinity between cloud base and cloud tops measuring temperature and dewpoint.

## 4. Results from direct measurements

### *a. General characteristics of clouds*

On 7 November the clouds sampled formed along the front mentioned in section 2. Cloud base was approximately 600 m above the surface and cloud tops ranged from 2500–4000 m. Weak radar echoes were observed on several occasions on the King Air weather radar (corresponding to a precipitation rate of between 0.3 and 1 mm $h^{-1}$) and traces of precipitation were encountered fairly frequently by both aircraft. Late in the operation (from about 1400 h) the signals observed by the radiometer on the Electra increased markedly and the King Air observed moderate radar echoes and heavier precipitation—probably amounting to about 10 mm $h^{-1}$. Results from measurements under these conditions were excluded from all analyses. Clouds on 8 and 9 November were somewhat smaller on the average although their bases were at essentially the same altitude. No evidence of the front observed on 7 November remained in the working area. Weak radar echoes were observed occasionally on 9 November though not on the previous day. Neither aircraft reported precipitation on either of these two days. Wind shear was present throughout the cloud layer on all three days with changes in direction as well as speed. The least change in speed occurred on 8 November but there was a big change in direction near cloud top on this day.

### *b. Sampling levels*

Clouds were penetrated by the King Air at various altitudes up to about 2100 m which was close to the tops of many clouds. Most penetrations were made below this level down to 1500 m on 7 November and to 1000 m on 8 and 9 November. As mentioned before, the Electra operated at an altitude of about 300 m, roughly halfway between the surface and cloud base. A total of 116 cloud penetrations were made by the King Air in 20 clouds in the three-day period while the Electra completed 66 runs below cloud bases.

### *c. Cloud liquid water content*

The most obvious feature of the liquid water records is their fluctuating character during the cloud traverse. The liquid water decreased markedly from its maximum value many times on almost every traverse regardless of where the traverse was made relative to cloud base or cloud top. On many traverses the liquid water fell to, or close to, zero well inside the cloud boundaries. Successive traverses at the same altitude but on roughly reciprocal or orthogonal tracks, which as far as could be determined passed through the same part of the cloud, often gave very different values for the maximum water content than were observed on the first traverse. This occurred even on the few occasions when the first traverse showed a more or less steady maximum water content. These features are illustrated in Fig. 2.

The maximum liquid water content of 2.2 g $m^{-3}$ was observed on 7 November though a number of observations of 2 g $m^{-3}$ were made. Only 25% of the maximum water content values observed were greater than 90% of the adiabatic water content at the observation level. However, 70% of the values exceeded 50% of the adiabatic value. In view of the great variability of the water content and the apparent presence of "holes" in the clouds, no attempt has been made to obtain average values.

### *d. Cloud droplet size distribution*

The mean volume diameter measured by the FSSP on all three days was always close to 14 $\mu$m, the total range being 12–17 $\mu$m. The dispersion of the distribution was typically 0.3. Concentrations ranged from

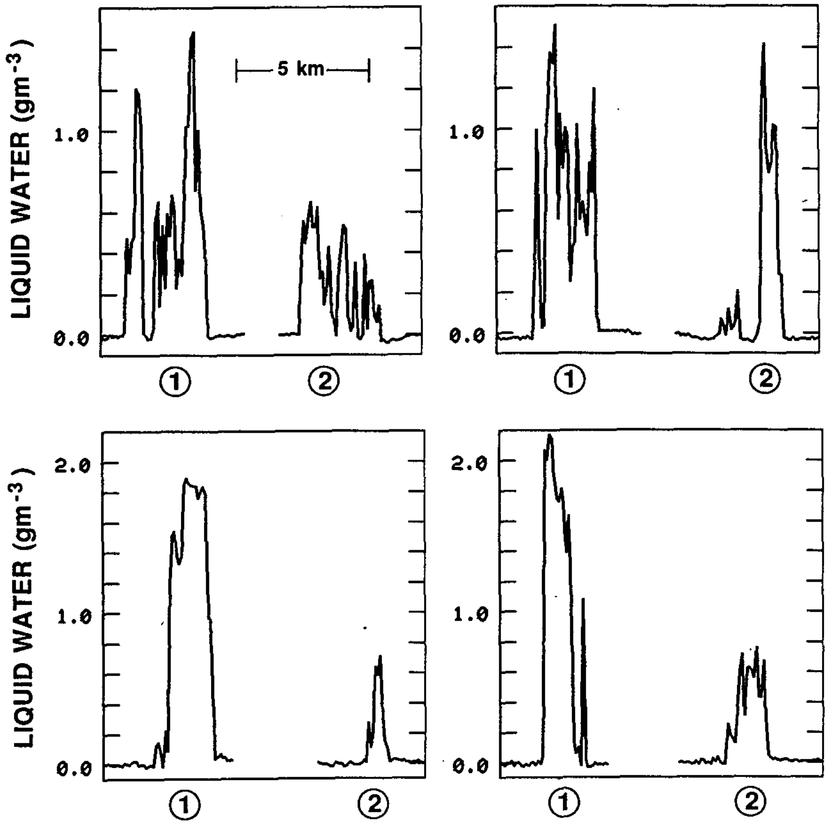

FIG. 2. Direct measurements of liquid water content on successive passes, 1 and 2, at the same altitude and air position for four clouds. Passes 1 and 2 were separated in time by about 2.5 min.

200–800 $cm^{-3}$ with a mean of about 450 $cm^{-3}$. Considering the location of the observations—150 km or more offshore—the continental character of the droplet spectrum is somewhat surprising.

### *e. Large drops*

The results from the OAP showed that drops of about 450 $\mu m$ diameter were present on many occasions, but usually in concentrations of less than 1 $L^{-1}$. Less than 8% of the cloud traverses showed liquid water contents in the 300–4500 m diameter range of greater than 0.02 g $m^{-3}$ at any point in the traverse, and only 2.5% showed such liquid water in excess of 0.05 g $m^{-3}$. There was only one observation of a water content greater than 0.1 g $m^{-3}$. These results are in agreement with the reported observations of radar echoes. Note that for a Laws and Parsons or similar drop size distribution 0.3 mm $h^{-1}$ corresponds to about 0.025 g $m^{-3}$, 1 mm $h^{-1}$ corresponds to about 0.07 g $m^{-3}$ of rainwater, and 10 mm $h^{-1}$ corresponds to about 0.5 g $m^{-3}$.

### *f. Statistical analysis of liquid water data*

Because of the high variability of the liquid water throughout the regions of cloud explored by the King Air and because of uncertainties in the relative positions of the two aircraft, it appears that the only basis for intercomparison of their results must be statistical. Further, it is clear that no attempt should be made to go to a high spatial resolution in such an analysis. Hence, the liquid water data were first smoothed by averaging over 5-s periods, which correspond to about 450 m of flight path, before a statistical analysis was commenced.

In order to obtain a reasonable number of measurements in each height interval the following ranges were chosen: 700–1200 m, 1200–1700 m, and 1700–2200 m. In the lowest range there were 0, 9 and 13 cloud penetrations by the King Air giving useful data on 7, 8 and 9 November respectively; in the middle range there were 31, 14 and 14 penetrations and in the upper height range there were 8, 2 and 30 penetrations on these respective days.

The fraction of the cloud width for which the 5-s smoothed liquid water exceeded a given value was determined for each penetration in each of the three height ranges. Presence or absence of cloud was based on measurements by the FSSP of droplet concentration. If this fell to zero for more than 2–3 s the point at which it fell was regarded as the edge of the cloud; if the zero reading lasted a lesser time it was regarded as a "hole" in a continuing cloud body. Averages of all the data in each height range were then obtained, giving the results shown in Fig. 3. The standard error of the mean fractions ranged from about 0.03 to 0.06 of the cloud width. Since analyses on a daily basis gave similar results only the overall average is shown here.

The figure shows that on 500 m scales only 10% of the cloud liquid water exceeds 0.8, 0.95 and 1.2 g $m^{-3}$ in the 700–1200, 1200–1700, and 1700–2200 m height ranges respectively, while only 1% of the cloud water exceeds 1.1, 1.5 and 2 g $m^{-3}$ in the same height ranges. The liquid water condensed in an adiabatic ascent from cloud base at 600 m would be approximately 0.2, 1.4, 2.4 and 3.2 g $m^{-3}$ at 700, 1200, 1700 and 2200 m respectively. Thus Fig. 3 shows that on the average the liquid water content was closer to its adiabatic value near cloud base than at high levels, a result that might have been anticipated from many prior studies. The figure also shows that large fractions of the clouds observed during this program must have suffered mixing with their environment resulting in low or near zero values of liquid water content.

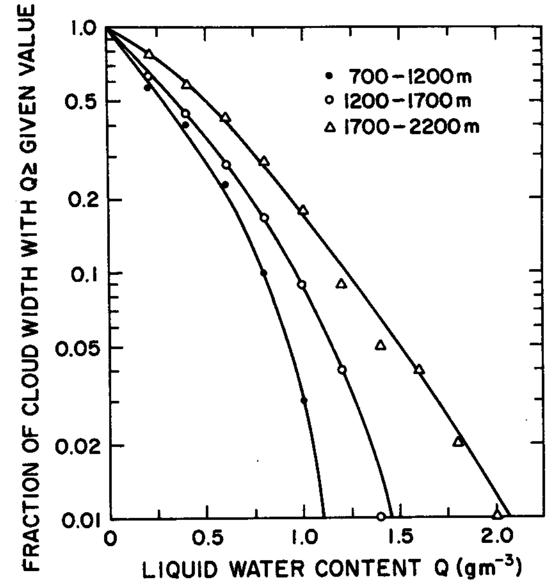

FIG. 3. Statistical analysis of the results of the direct measurements for three height ranges: 700–1200, 1200–1700, and 1700–2200 m. The standard error of the results for each of the mean curves is roughly 0.05 of the cloud width.

## 5. Results from radiometric measurements

### *a. General characteristics of data*

As would be expected from the King Air measurements, the radiometer data also showed evidence of marked variability of liquid water distribution. Observed brightness temperatures in clear sky conditions with the Electra aircraft at 300 m and the antennas in their normal position of looking 45° below the zenith were typically 35–40 K. Small to moderate clouds gave maximum brightness temperatures of 50–150 K, often with marked variations during the passage of the Electra below cloud base; large clouds, where light precipitation was known to be present, gave brightness temperatures up to 230 K. Typical records of brightness temperature are shown in Fig. 4. All show evidence of marked structure in the liquid water distribution with the last

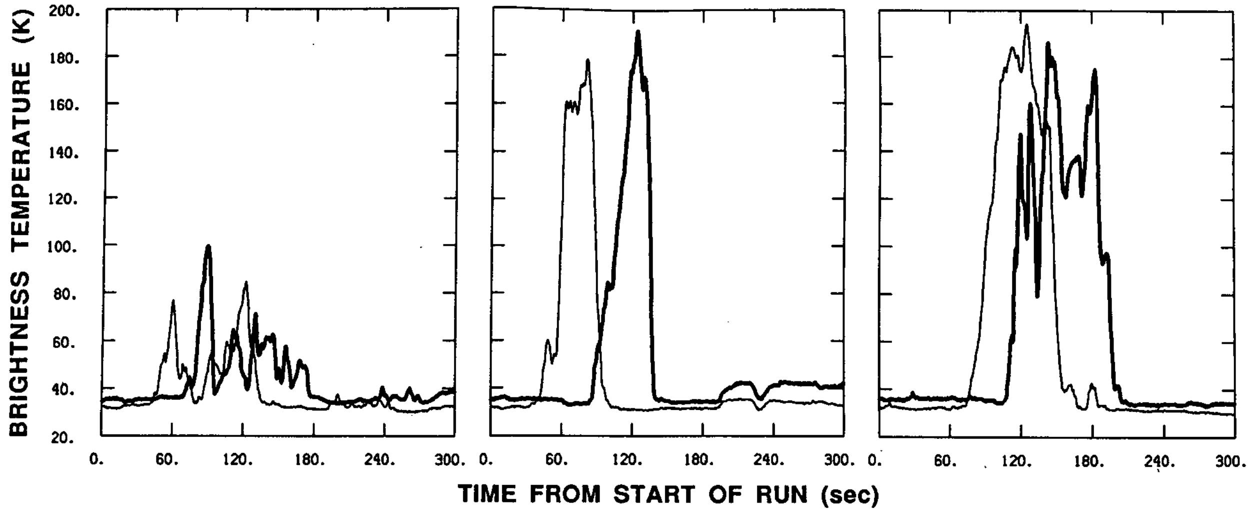

FIG. 4. Records of radiometric brightness temperature for three clouds. Thin and thick lines represent the signals from the forward and rearward pointing antennas respectively.

example indicating the presence of cells sloping towards the Electra as it approached the cloud.

### *b. Retrieval procedures*

Since there was no independent information regarding the size or position of the cloud under study relative to the Electra track, the process of retrieving the liquid water distribution from the radiometric data started by assuming a large field, typically 8 km wide and 5 km high, and a 1 km resolution. The fields used in all retrievals took cloud base to be at 600 m. Temperature and water vapor profiles in the cloud environment came from soundings made by the King Air from cloud base to about 4500 m and at higher levels from nearby rawinsonde data. Since no high level clouds were present on the three days under study, the 5 km deep field was clearly adequate. While only water clouds are "seen" by the radiometer, with the present procedure a retrieval is possible only if both radiometer antennas see all the cloudy areas in the total field. The mathematical procedure used in the retrieval process is described by Drake and Warner (1988). With the cloud position more or less determined, the field was narrowed, and 500 and then 300 or 250 m resolution retrievals were attempted. A typical result of this process is shown in Fig. 5.

Initially it was assumed that the whole field contained cloudy air saturated at the environmental temperature. When cloud was found in the retrieval to occupy only part of the field, the humidity was reduced in the areas showing zero liquid water to its clear air environmental level or, when an apparently cloud-free area was small, to a level between saturation and the environmental value. Another retrieval was then carried out with these humidity constraints which resulted in changes in the liquid water field. The process was repeated until a self-consistent pattern was obtained, which usually took three or four iterations, the adjustments becoming progressively smaller. On no occasion did large changes in amount or distribution of liquid water result at any stage in this process.

Many of the retrievals were not continued beyond a resolution of 500 m since this is the scale at which the King Air direct measurements were treated in the statistical analysis. Further, as was pointed out by Drake and Warner (1988) in the simulation study, there is a trade-off between spatial resolution and the accuracy with which the magnitude of the liquid water can be determined in the retrieval. For the size of cloud under investigation in this field program there seems little point in attempting retrievals to a resolution better than 250 m because the accuracy of the retrieval would, on the basis of the simulation study, then be about 0.2 g $m^{-3}$ in a cloud having a maximum liquid water content of 2 g $m^{-3}$.

### *c. Results from retrievals of liquid water distribution from radiometric data*

The retrievals shown in Fig. 5 were for a cloud for which the maximum radiometric brightness temperature was 100 K. Two other examples are shown in Fig. 6 for clouds showing maximum brightness temperatures of 65 and 150 K. The low brightness temperature example shown in Fig. 6a represents two or three small clouds as indicated. The diagonal line of liquid water starting at the bottom right-hand corner of the figure is clearly not real and is most probably due to changes in the distribution of water in the time interval between sighting the cloud by the forward and the rearward pointing radiometer antennas. The retrieval shown in Fig. 6b for a high brightness temperature cloud is for a 500 m resolution. Another retrieval

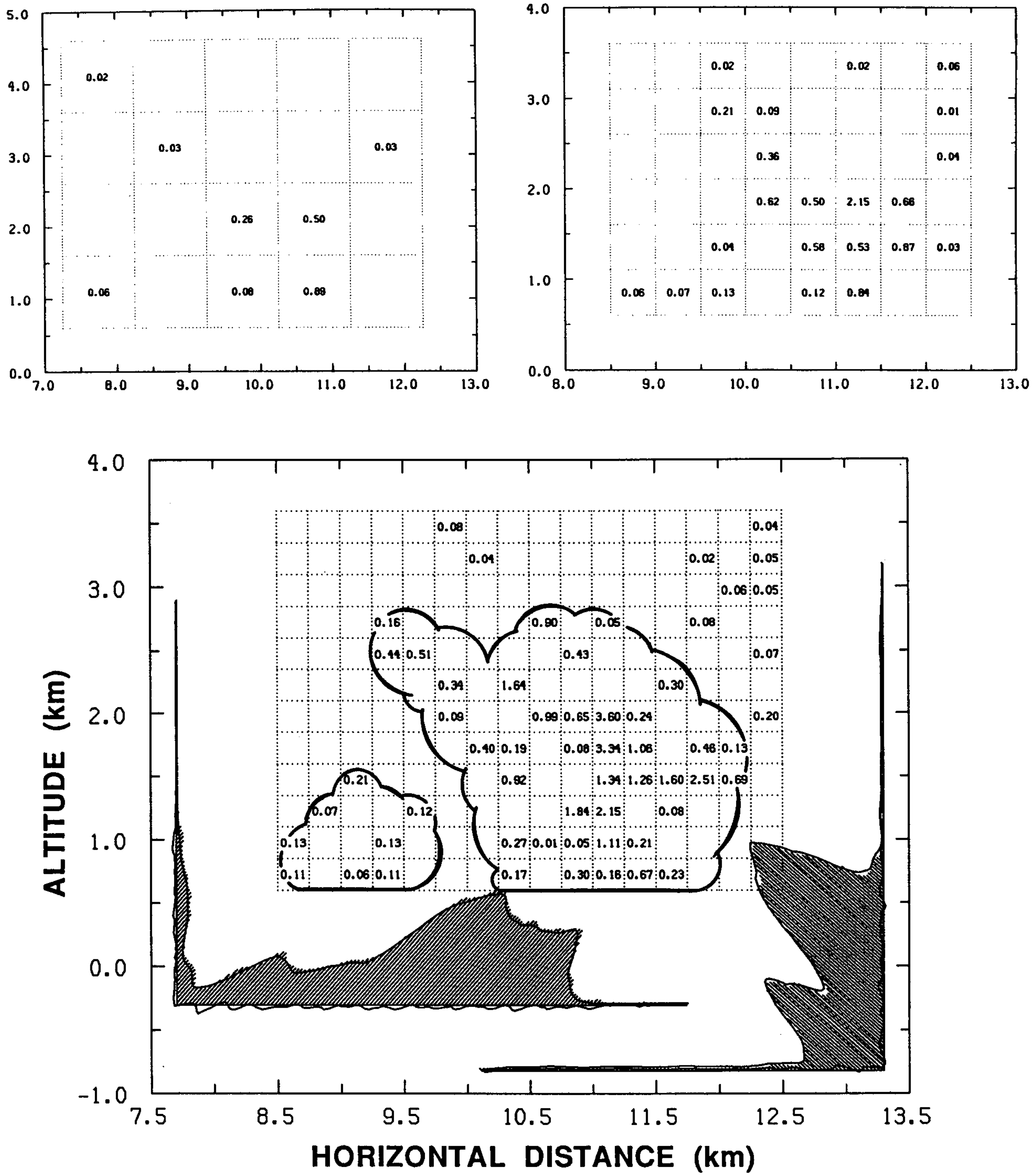

FIG. 5. Successive retrievals at 1000, 500 and 250 m resolution from radiometric measurements on a medium sized cumulus cloud. The numbers in each box represent the average liquid water content in g $m^{-3}$ for that box. A suggested cloud outline is indicated. The sloping vectors have lengths proportional to the brightness temperature observed after clear sky brightness (about 28 K) has been subtracted, and each vector points with the corresponding antenna direction toward the appropriate region of cloud where that temperature was observed. The curve at the top of the vectors is the brightness temperature calculated from the retrieved field. The curve at the bottom of the vectors represents the difference between measured and calculated quantities. The maximum brightness temperature detected by the antennas on this pass was 98 K.

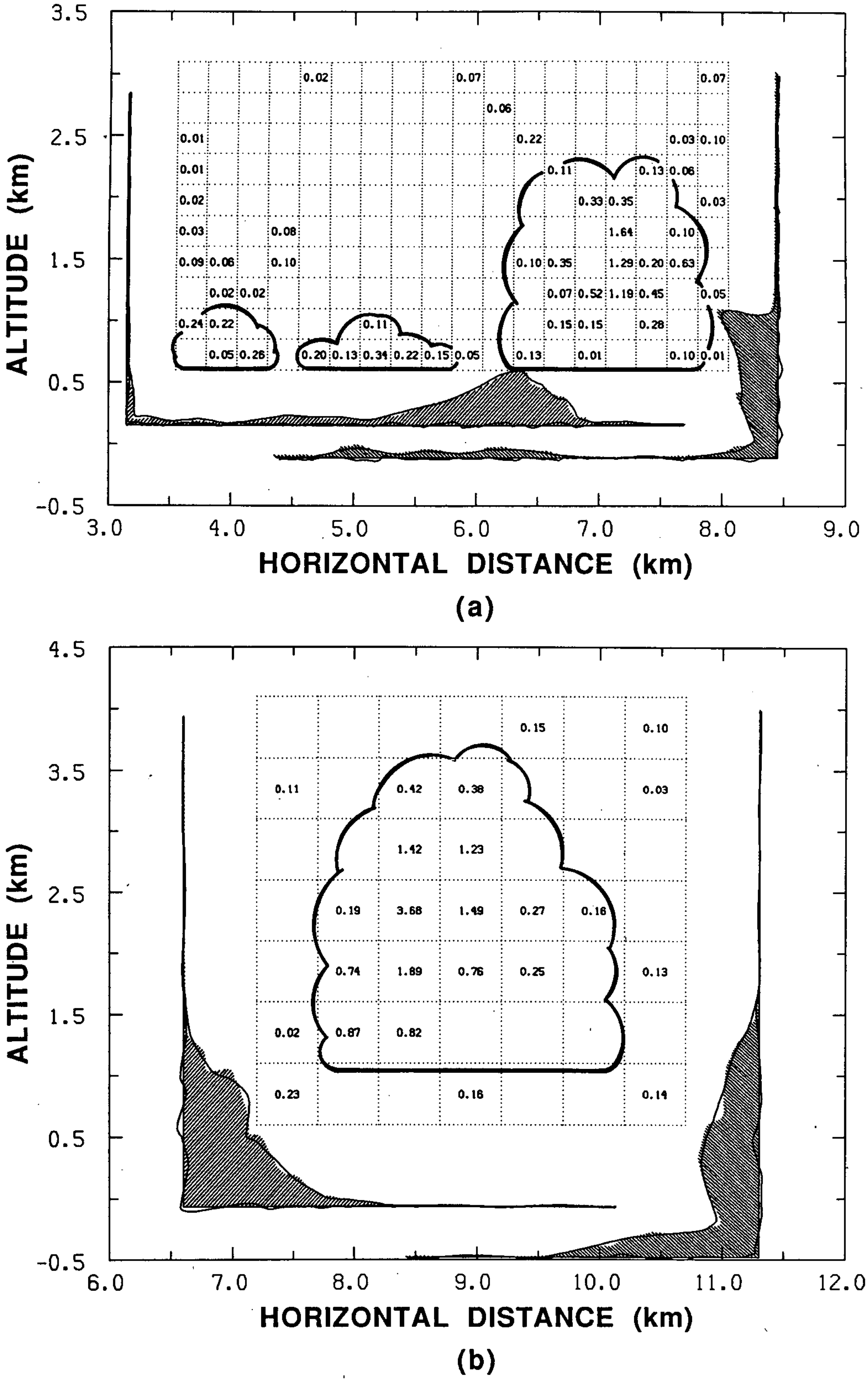

FIG. 6. Retrievals from brightness temperature measurements on small and large cumuli. See Fig. 5 for description of details.

was obtained for a 250 m resolution and gave smaller residual errors but a rather unrealistic-looking "cloud" with many zeros near cloud base and superadiabatic values of liquid water in the midlevels. The latter may have been due to the (undetected) presence of precipitation. During the study of another cloud on this day precipitation was observed by the Electra below cloud base and at midlevels by the King Air, which also observed moderate intensity radar echoes. Retrievals under these conditions showed strongly superadiabatic values of liquid water. Here there is no doubt that the cause was the presence of millimeter-sized liquid droplets in significant concentrations which emit, absorb, and scatter 31 GHz radiation at a rate greatly in excess of that due solely to their water content. The results from these retrievals were not considered in the statistical analysis described in the following section.

Approximately 500 radiometric measurements were used in each of the examples shown in Figs. 5 and 6. On the basis of the simulation studies reported by Drake and Warner (1988) rms errors of between 0.1 and 0.2 g m$^{-3}$ in retrieved values of liquid water would be expected. However, the assumption of temporal stationarity which applied in the simulation studies is clearly not valid for the clouds studied during the October–November field program, so no claims can be made regarding accuracy of individual values in the retrieved field. This matter will be discussed in more detail later.

### *d. Statistical analysis*

A statistical analysis was carried out on retrievals of liquid water distribution from radiometric data obtained during 40 passes below cumulus clouds. To conform to the analysis of the King Air data only information from the 500 m resolution retrievals was used. Before commencing the analysis a smoothing process was applied to the retrieved data by taking running means of the values appearing in the boxes in each 500 m deep row. This was done initially to make the data as similar as possible to that arising from the smoothed King Air records of liquid water. An example of the results of this process is shown in Fig. 7. The process had another advantage in that an objective criterion could be applied in deciding on the position of the cloud boundaries, which was often difficult when the retrieved field varied greatly from place to place. It was decided that if the liquid water in the smoothed data fell below 0.1 g m$^{-3}$ for two or more consecutive data points, it would indicate the end of one cloud and the possible start of another. Thus, for the record shown in Fig. 8, two clouds are counted. This parallels the procedure that was applied in treating the King Air data.

The results of the analysis, taking the mean of all results for the three days 7, 8 and 9 November, are shown in Fig. 9. The standard error of the mean fractions ranged from about 0.03 to 0.09 of the cloud width. There was a greater variation of the relationship on a daily basis than was the case for the King Air measurements, but the same trends occurred on all three days.

## 6. Intercomparison between datasets and discussion

A comparison between the direct observations of liquid water and those deduced from the radiometric data is given in Table 1 on the statistical basis described above. The three levels given are at about the center of each 500 m deep region into which the original data were subdivided.

As was remarked earlier, the King Air data were divided into 500 m deep ranges commencing at 700 m altitude in order to obtain a reasonable number of data points in each range, and the radiometric retrievals commenced at 600 m—the height of cloud base. Hence, if the liquid water gradient were adiabatic, we would expect the radiometric liquid water to be about 0.2 g m$^{-3}$ less than that observed by the King Air in each height range. Since the gradient is less than adiabatic we might expect a difference of about 0.1 g m$^{-3}$. This is indeed the difference between the sets of curves in Figs. 3 and 9.

In view of what has been said about the variability of the liquid water in space and time, the lack of coincidence between the King Air's position and the cloud region observed by the radiometer below cloud base, and the roll of the Electra during the traverse, the agreement between the two datasets is extraordinarily

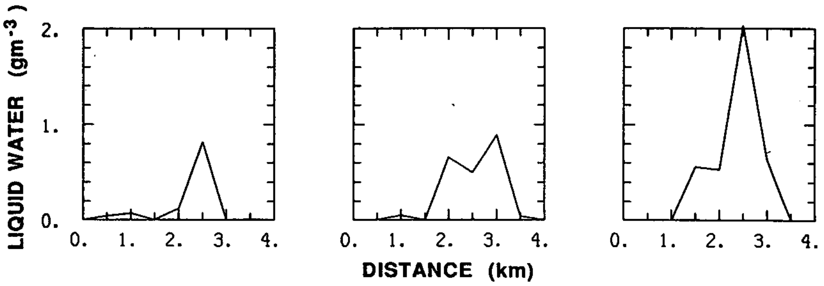

FIG. 7. Smoothed liquid water contents for the 600–1100, 1100–1600, and 1600–2100 m height ranges from the 500 m resolution retrieval shown in Fig. 5.

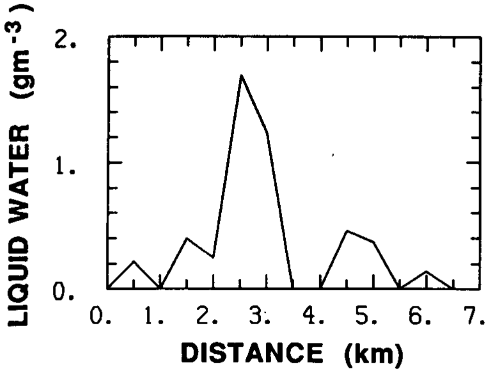

FIG. 8. Smoothed liquid water content for one height range of a retrieval. It was decided that two clouds were present here.

TABLE 1. Comparison between statistics of direct observations (KA) and retrievals from radiometer data (R) as percentage of cloud width for which $Q \geqslant$ given value. Note that the standard error of the curves from which the table was produced is about 5% of cloud width.

| | Level | | | | | |
|---|---|---|---|---|---|---|
| Liquid water $Q$ (g m$^{-3}$) | 900 m | | 1400 m | | 1900 m | |
| | KA | R | KA | R | KA | R |
| 0.25 | 54 | 45 | 60 | 56 | 75 | 68 |
| 0.50 | 28 | 18 | 35 | 30 | 50 | 42 |
| 0.75 | 12 | 6 | 19 | 16 | 30 | 25 |
| 1.00 | 3 | 2 | 8 | 8 | 17 | 14 |
| 1.25 | — | — | 3 | 4 | 9 | 8 |
| 1.50 | — | — | — | 2 | 5 | 4 |
| 1.75 | — | — | — | — | 2 | 2 |

good. The agreement is, of course, only on a statistical basis and then only for a spatial resolution of 500 m; indeed, only the choice of such a coarse resolution makes the intercomparison possible. An examination of the retrievals indicates clearly that at finer resolution the agreement between the datasets, even on a statistical basis, would be much worse.

The distribution of liquid water obtained from individual retrievals cannot be regarded as other than approximate, and the finer the resolution the worse the approximation will be. Similar comments would apply if an attempt were made to assemble results from the King Air measurements into a representation of the distribution of liquid water in any particular cloud. The measurements by the King Air are indeed true representations of the liquid water instant by instant during a traverse, but the longer it takes for the aircraft to traverse the whole cloud the less the justification in taking the liquid water trace to represent the distribution of water at one time. For retrievals from the radiometric data the situation is worse, in that the liquid water assigned to each box in the retrieved field depends upon brightness temperatures observed throughout the whole traverse below cloud base. In a changing situation considerable errors can occur in assuming stationarity and clearly the smaller the boxes the larger the errors.

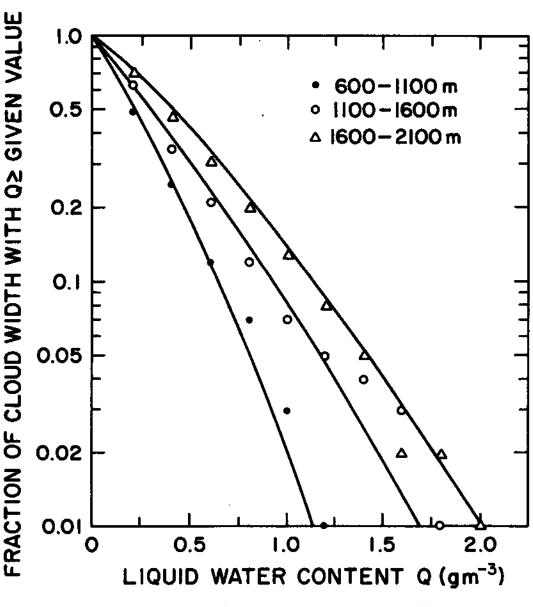

FIG. 9. Statistical analysis of liquid water deduced from radiometric data for three height ranges: 600–1100, 1100–1600, and 1600–2100 m. The standard error of the results for each of the mean curves is roughly 0.05 of the cloud width.

The clouds studied during the field program were highly variable, more so than for many reported cloud studies. For example, Warner (1955, 1973) reported relatively small changes in liquid water and microstructure over periods in excess of ten minutes for small to moderate cumuli. Cooper and Lawson (1984) report an approximately exponential decay of liquid water from the first sampling pass with a time constant of about 830 s for the relatively small cumulus congestus clouds sampled during the HIPLEX experiment. Schemenauer and Tsonis (1985) give a rather lower value, 560 s, for the time constant and suggest that the decay was linear rather than exponential. Cooper (1985) in reply still considers the exponential fit preferable and modifies the time constant to 700–780 s. Schemenauer and Isaac (1984) give the results of a study of cloud lifetimes in three different areas and find that the rate of change of liquid water content exceeded 0.1 g m$^{-3}$ min$^{-1}$ on 34 out of 102 occasions. They associate more rapid decay of correlation with the production of rain by either the warm or cold rain process. Malkus (1954) reported a consistent updraft pattern in trade wind cumuli, which must have been accompanied by a relatively steady distribution of liquid water, during the (considerable) time taken to make the observations. Hence, we have strong reasons to believe that for many, if not most, clouds, changes on scales of 100 m or more are small over periods of 2–3 min. For such clouds the radiometric technique would be readily applicable and, provided relative aircraft positions could be determined accurately enough, direct comparisons would be possible between the retrieved field of liquid water and in situ measurements.

## 7. Conclusions

A comparison has been made between in situ measurements of liquid water content in cumulus clouds and the values of liquid water deduced by mathematically inverting a series of measurements of radiometric brightness temperature. The radiometric observations were made from an aircraft flying below cloud base while a second aircraft penetrated the cloud at different levels. Because of the strong variability both in space and time of the liquid water in the clouds sampled and because of uncertainty in the relative position of the two aircraft, only a statistical comparison was possible and then only at a spatial resolution of 500 m. Agreement between the two datasets was excellent. For clouds having more normal variability the radiometric data could have been processed to yield a resolution of 250 m or better and a direct intercomparison could have been made with in situ observations.

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