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Comparison of radar/radiometer retrievals of stratus cloud liquid-water content profiles with in situ measurements by aircraft

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Abstract. In situ sampling of cloud droplets by aircraft in Oklahoma in 1997 is used to evaluate a ground-based remote sensing technique for retrieving profiles of cloud liquidwater content. The technique uses vertically pointing measurements from a high-sensitivity millimeter-wavelength radar and a collocated dual-frequency microwave radiometer to obtain height-resolved estimates of the liquid content of stratiform clouds. Comparisons with the aircraft measurements are made for 16 overpasses through thin cloud layers within a 1.5-km radius of the remote sensor site. Over a range of liquid-water contents from 0.04 to 0.57 g m 3 the mean difference between the aircraft and the radar/radiometer values was 0.02 g m-3, and the maximum difference was 0.09 g m -3. Although the number of comparisons is limited, these results suggest that the ground-based estimates may be sufficiently accurate for many scientific purposes.

1. Introduction

Although most meteorological radars lack the sensitivity to detect small cloud droplets, recent advances in millimeterwavelength "cloud' radars provide new opportunities for monitoring the properties of non-precipitating clouds by remote sensing. These high-sensitivity radars can reveal the reflectivity and velocity structure of most clouds within the range of several kilometers of the radar with remarkable detail. However, tire problem of retrieving the microphysical features of clouds from these observations is not straightforward because the radar actually measures a moment of the Doppler velocity distribution which is related to the sixth power of droplet diameter, rather than to either the diameter itself or the cloud liquid-water content.

A number of procedures have been developed recently to estimate the microphysical features of clouds from millimeterwave radar observations alone. (In this article we restrict our attention to liquid-water clouds; retrievals for ice clouds arc described in other studies [e.g., *Matrosov,* 1997]). For example, *Sassen and Liao* [1996] employed a numerical cloud model to obtain a useful relationship between radar reflectivity and liquid-water content. *Fox and Illingworth* [1997] proposed an empirical power-law relation between reflectivity and water content for marine stratocumulus based on extensive aircraft in situ samples. Such simple relations may be quite useful in a large-scale climatological sense but may also be quite inaccurate for individual cloud cases. *Gossard et al.* [1997] approached the problem by using radar measurements of the full spectrum of measured Doppler vertical velocities with deconvolution adjustments for the effects of atmospheric turbulence. However, the procedure is complicated, and many radars do not routinely record the full Doppler spectrum. to addition, when the cloud droplets arc small, the fall velocity of the droplets may be smaller than the turbulent firtCtna60nS. and the errors in doing this kind of retrieval may be so large that the results are not useful.

In many situations, cloud microphysics may be retrieved more accurately by incorporating information from additional instruments. One such technique uses measurements of the path-integrated liquid-water content obtained with a microwave radiometer in combination with measurements of the first three radar Doppler moments, which arc routinely available from any Doppler radar. *Frisch et al.* [1995] developed this radar-radiometer technique for retrieving microphysical features of liquid-water clouds, such as stratus clouds. The method retrieves estimates of cloud droplet median size, total droplet concentration, and liquid-water content as a function of height. It was first applied to data from the Atlantic Stratocumulus Transition Experiment ASTEX 1992) in Portugal's Madeira Islands by the National Occanic and Atmospheric Administration Environmental Technology Laboratory (NOAA/ETL). Although the parameters retrieved by the method were reasonable for marine stratocumulus, there a were no coincident aircraft measurements in these clouds to evaluate the technique. In a later paper, *Frisch et al. [1998]* showed that the technique for liquid-water retrieval was more robust than originally reported in their *1995* paper, and other droplet distributions could be used, plus it was insensitive to bias in the radar calibration nor was it dependent on the spread of the droplet distribution. In a later paper, *Sassen et al., 1999]* described some validations of a modified *Frisch et al. [1995]* technique plus a discussion of the difficulty of intercomparing surfaced-based derived data with aircraft in situ data. In the present study

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we look at the method described by *Frisch et al. [1998]* for liquid water. In addition, there is more than one layer of stratus clouds, and these arc the first attempts to validate the liquid-water retrieval when there is more than one layer of clouds. New measurements at the Department of Energy's Atmospheric Radiation Measurement (ARM) program Cloud and Radiation Test Bed (CART) site in northern Oklahoma offer

Table 1. Characteristics of the Instruments

NOAA/K Radar	Microwave Radiometer	Forward Scattering Spectrometer Probe
Developed by NOAA/ETL Features, Doppler, full scanning, dual polarization Frequency, 35 GHz (8.7-mm wavelength, Kbarnd Beam width, 0.5' Height resolution, 37.5 m Temporal resolution, 0.3 s (raw), 3.0 s (processed data)	manufacturer, Radiometric, Inc. frequencies, 23.8 and 31.4 GHz beam width, 5' temporal resolution, *I* min	manufacturer, Particle Measuring Systems, Inc. droplet size range, 3-45 fan, nominal bin ,size centers in [his project, 4.2, 7.0, 15.0, 17.9, 21.4, 25.5, 29.8, 34.1, 38.3, 42.0, 48.9, 52.4 Am Temporal resolution, *1 s* aircraft speed, 100 m/s approx. corrected values of cloud liquid-water content which are derived from integration of FSSP droplet spectra, when drizzle drops are not present, have an accuracy of 34% *Baumgardner* 1983]

an opportunity to compare the ground-based remote sensing retrievals with concurrent aircraft in situ cloud sampling. The densely instrumented CART sites, described by *Stokes and Schwartz [1994],* include continuous, vertically pointing observations with dual-frequency microwave radiometers and, more recently, with a new radar, known as the millimeter-wave cloud radar (MMCR), which is described by *Moran et al. [1998].* These are the appropriate instruments for application of the *Frisch* et *a1. [1998]* technique.

2. Review of the Radar-Radiometer Retrieval Method for Liquid-Water Profiles

For nondrizzling stratus clouds, *Frisch* et *al. [1995, 1998]* showed that vertical profiles of cloud liquid-water content could be retrieved using measurements of radar reflectivity and the vertically integrated liquid-water path measured with a microwave radiometer. The *Frisch* et *al. [1998]* paper showed that the technique is more robust than originally reported both because the initial assumption of a lognormal droplet size distribution can be relaxed and the liquid-water content retrieval is independent of the radar's exact absolute calibration. They showed that if the droplet concentration and the spread of the size distribution are unknown and constant with height and if the moments of the cloud droplet distribution function can be related in such a manner that

$$< r^6 >= k^2 < r^3 >^2 \tag{1}$$

then the liquid-water content $\mathbf{q_p}$ at any height h_p is

$$q_p = Q \frac{Z_p^{1/2}}{\sum_{j=1}^{j=M} Z_j^{1/2} \Delta h} \tag{2}$$

In (1), *k is* an arbitrary constant, *r is* the cloud droplet radius, and the bracket denotes a moment of the radius distribution, in this case it is the third and sixth moment of the particle size distribution. In (2), *j is* the radar range gate number index used for the summing over all gates, Q is the vertically integrated Liquid-water path, Z_j, is the radar-reflectivity factor at gate j, Z_p is the reflectivity at range gate p, M is the number of the highest gate in cloud, *)h is* the gate length, and $\mathbf{q_p}$, is the retrieved liquid water at the radar range gate p.

The assumptions that the droplet concentration and spread are constant with height, used in the derivation of *(2)*, are reasonable approximations for marine stratus, based on measurements by Slingo el *al. [1982]. Frisch* et *al. [1998]* found good agreement in the relationship between the sixth moment of the radius and the square of the third moment (equation (1)) using droplet distribution measurements from around the world obtained by *Pinnick* et al. [1983].

3. Results From the Oklahoma Measurement

As part of an ARM Cloud Intensive Operating Period (IOP) in April *1997,* **NOAA/HTL** operated its **NOAA/K,-band** cloud radar at the Oklahoma CART site. This radar's ability to detect norprecipitating clouds has been demonstrated on numerous field projects *[Manner and Krop flu, 1993].* Data from this "visiting" radar and archived data from the CART site permanent dual-frequency microwave radiometer were used to retrieve microphysical properties of stratus and altostratus clouds over the site. Numerous flights through the clouds by the University of North Dakota Citation research aircraft provided in situ sampling of the cloud droplets for assessing the remote sensing retrievals. The Citation Forward Scattering Spectrometer Probe (FSSP) was the primary instrument used for the droplet measurement; liquid-water content and in situ estimates or radar reflectivity were computed from its mea sured size spectra. Other probes onboard indicated the presence (or absence) and size of ice crystals plus precipitating liquid water droplets. Basic characteristics of the three instruments are shown in Table 1.

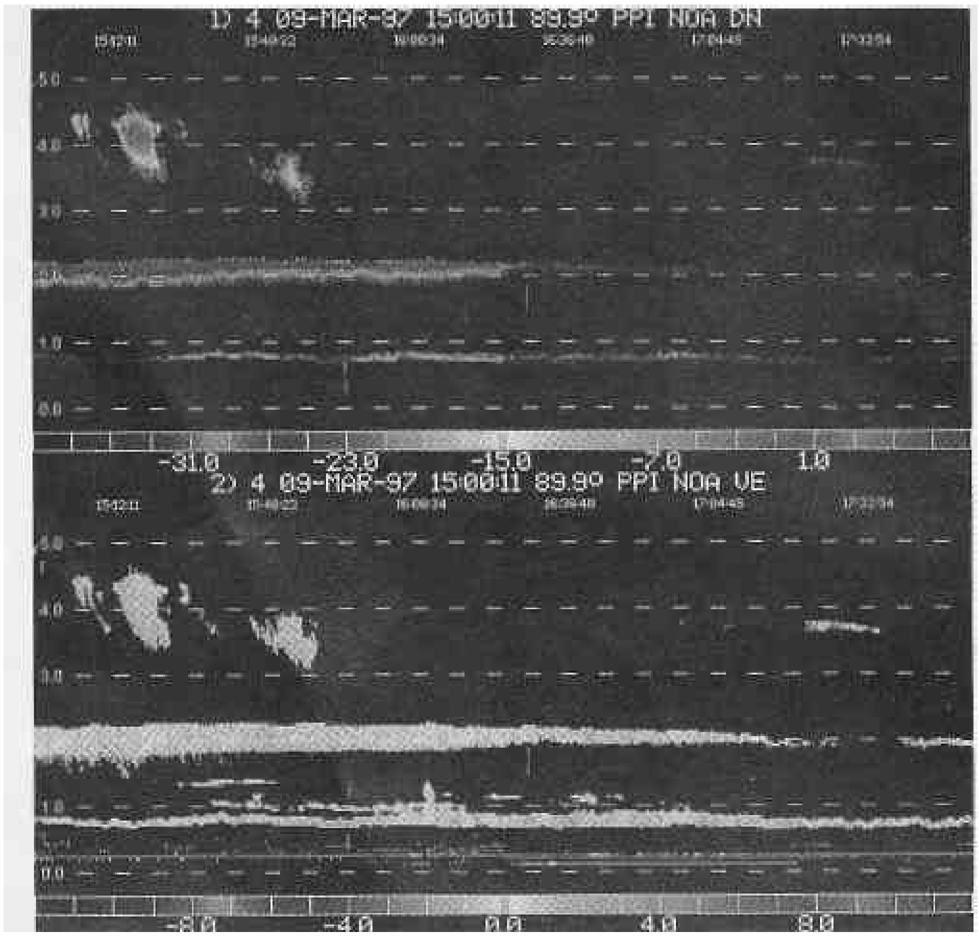

Figure 1. Time-height images of radar reflectivity (dBZ units; and vertical velocity (m s $^{-}$) for the aircraft comparison time period on April 9. 1997. The horizontal axis spans 3 hours; the vertical axis in each panel spans 0-5 km of height above ground level. The top display is radar reflectivity; the bottom is the radar Doppler shift.

Although the radar/radiometer retrievals were attempted on several days with support from the Citation aircraft, the radar cloud data on most days suffered from contamination by insects and other noncloud particulates in the boundary layer. This is a common warm-season problem for low-altitude radar observations al continental locations. Whereas the NOAA/K radar polarization data provide a means for identifying the presence of the insects, it is not currently sufficient for subtracting their contribution to the observed cloud reflectivities. Therefore we selected the only day (April 9, 7997) from the IOP when these complicating factors were not present. Thin stratus and altostratus layers persisted for almost 3 hours on this day, while the Citation made numerous horizontal passes through the cloud layers at different heights as well us a few ascending and descending spiral profiles through the clouds over the CART site. Time-height images of the radar observations of reflectivity and vertical velocity are shown in Figure 1. Data from the Citation FSSP were used for periods when the aircraft was horizontally within 1.5 km of the radar. The aircraft-indicated pressure-altitude heights, however, are subject to considerable uncertainty and have been adjusted by 2-5 radar gate lengths (75-200 m) in order to attain a closer match in the alignment of the shapes of the aircraft-derived and radar-measured reflectivity profiles before the liquid-water content comparisons were conducted. Figure 2 shows an example of one such adjusted profile from an aircraft spiral ascent. along with the corresponding radar profile. In this case, reflectivities computed from the aircraft FSSP data were some what larger than those observed by the radar. *These r*eflectivities were calculated from the sixth moment of the droplet spectra. As shown by *Frisch et* al. [1998], the radar-radiometer microphysical retrieval of liquid-water content is independent of the radar's absolute calibration, so the indicated reflectivity, differences arc of no consequence for the retrieval. The thick nesses of the two cloud layers indicated by the remote and in situ sensors were essentially identical.

Comparisons of the cloud liquid-water content values retrieved by the radar/radiometer technique with those sampled in situ by the aircraft arc shown in Figure 3 for numerous horizontal passes and a few short spirals of the Citation over the radar on this day. Each point represents several seconds of FSSP data as the aircraft passed within 1.5 km of the radar. In all, there were 16 times that met the 1.5 km criteria that we could use for comparisons. The result shown in Figure 3 suggests a linear relation with close agreement between the ground-based *retrievals and* the in situ measurements. The mean difference between the aircraft and the radar/radiometer

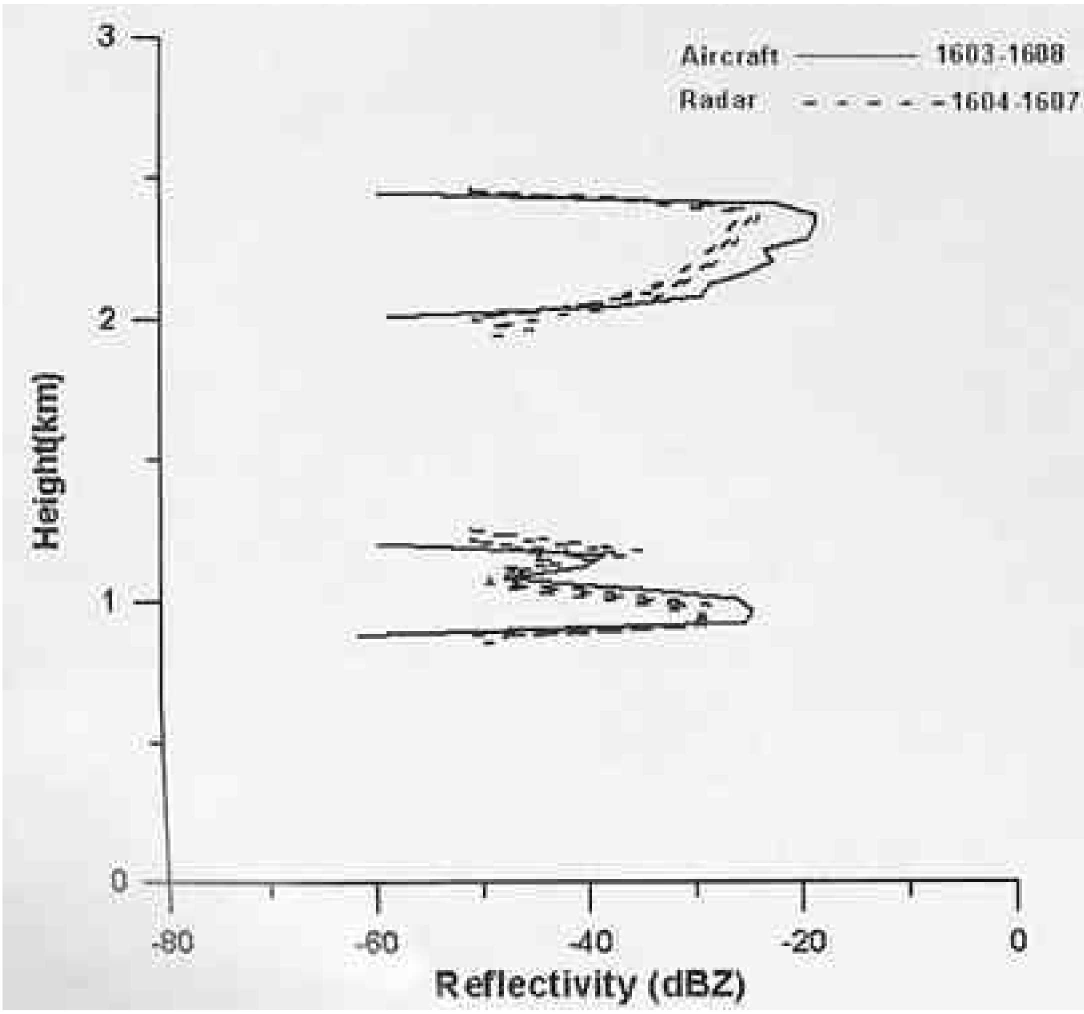

Figure 2. Radar and vertically adjusted aircraft FSSP profiles of reflectivity. This particular aircraft profile was adjusted by about 200 m to align the profile patterns.

values is 0.02 g m-', and the extreme difference is 0.09 g m^{-3}. A linear least squares fit to these data has a correlation coefficient of 0.96. No points depart by more than 0.05 g m^{-3} from the fit line, and the standard error of estimate is 0.03 g m^{-3}. The slope of the fit line indicates that the radar/radiometer retrievals tended to underestimate the liquid-water content, especially at the larger liquid values. Nevertheless, accuracies such as these estimating height-resolved cloud liquid-water contents from ground-based instruments would probably be acceptable for most scientific purposes. In addition, during some of these comparisons, there were two layers of stratus cloud present, which indicates the retrieval should work for more than one layer of stratus cloud.

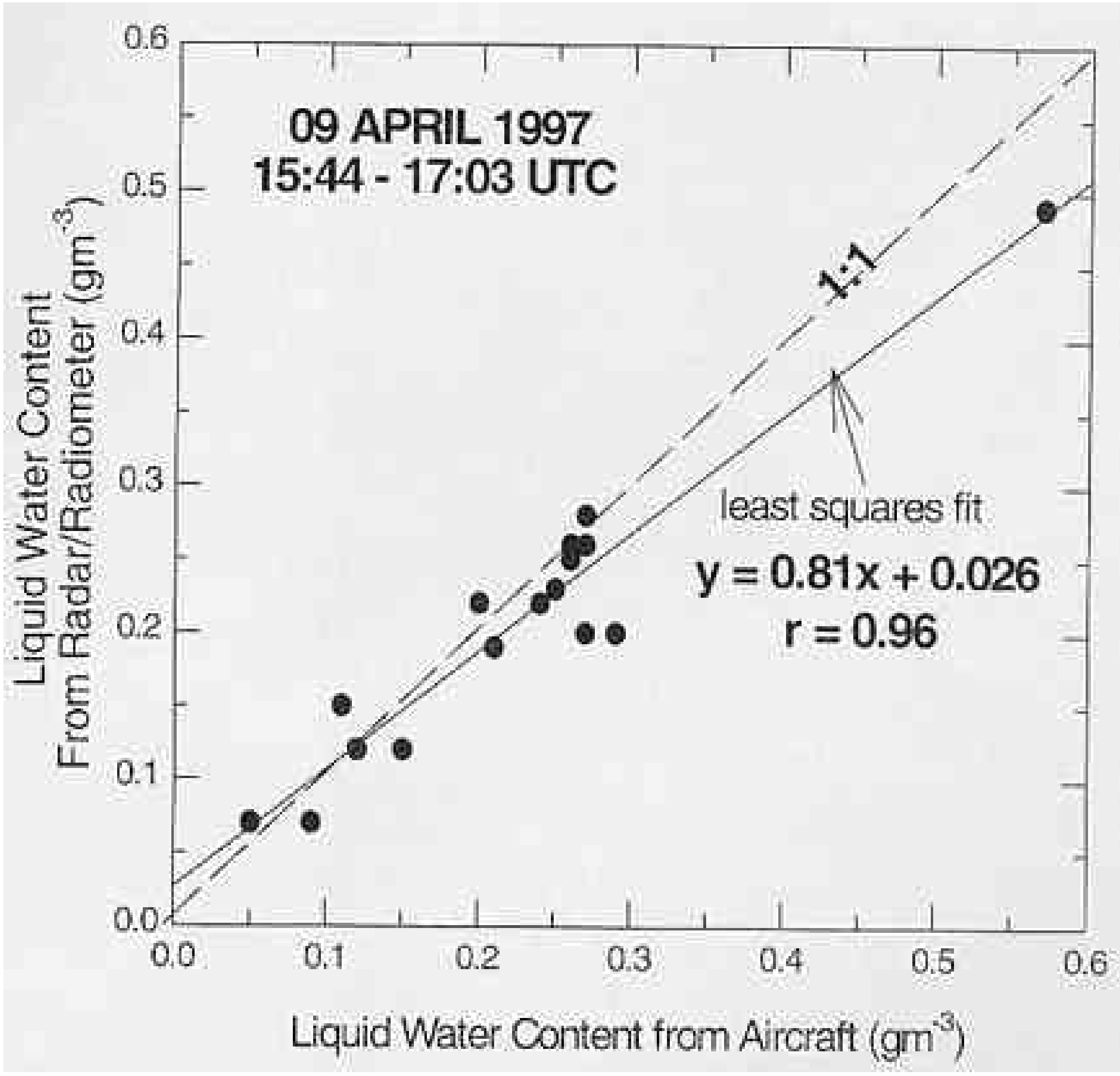

Figure 3. Comparisons of radar-radiometer liquid-water content retrievals with FSSP -measured liquid-water concentration. The dashed line is the linear least squares fit to the data points. Each point represents a different overpass by the aircraft within a 1.5-km radius of the remote sensor site

4. Summary and Conclusions

The radar/radiometer liquid-water retrieval technique of Frisch etal. [1995] was tested using observations of thin strains and altostratus cloud layers in Oklahoma. The vertical profiles of liquid-water content within the cloud layers were estimated from millimeter-wave cloud radar and microwave radiometer observations. Comparison of these retrieved profiles with those measured concurrently with in situ sampling by aircraft on 16 overpasses showed a maximum difference of less than 0.1 g m^{-3} and typical differences of less than 0.05 g m^{-3}. Considering various sources of error, including instrumental error, the different aircraft and remote sensor sampling volumes, and the horizontally inhomogeneous nature of clouds, the agreement is good. This leads support to tile usefulness of the radar-radiometer technique for estimating cloud liquid-water content profiles from the ground, as is being implemented by the ARM program, al least under some circumstances. There are some problems with these comparisons. The difference in the calculated reflectivity and that of the radar is a cause for concern, not so much for the liquid-water retrieval but for other applications. This difference can be due to the radar calibration, errors in the FSSP measurement of droplet spectra, or horizontal inhomogenities in the clouds. In addition, there is the bias in the comparisons, which could be due to a bias in the radiometer measurements of liquid water. Both of these effects need to have further study. The current comparison is for only one day. Additional in-situ verifications of the retrieval technique arc needed to establish more thoroughly the accuracy and limitations of the remote sensor method. Unfortunately, in the Oklahoma data set, all other case study days suffered from contamination of the radar observations by insect echoes in the lower altitudes. It is desirable to repeat the Oklahoma experiment in winter, or in other locations, such as marine environments or the arctic, to obtain more uncontaminated cases for comparison. Meanwhile, new methods, such as a wavelet analysis, arc being investigated to remove the contribution of insect echoes from the radar reflecivities measured in low-altitude clouds at the Oklahoma CART site. lf successful, this would allow wider application of the radar/radiometer technique to most continental sites.

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