Comparison of Radar/Radiometer Retrievals of Stratus Cloud Liquid Water Content Profiles with In Situ Measurements by Aircraft

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Introduction

Although most meteorological radars lack the sensitivity to detect small cloud droplets, recent advances in millimeter-wave cloud radars provide new opportunities for monitoring the properties of non-precipitating clouds by remote sensing. The problem of retrieving the microphysical features of clouds is not straightforward, however, because radar actually measures a moment of the Doppler velocity distribution, which is related to the sixth power of droplet diameter, rather than to the diameter itself, or to the cloud liquid water content (LWC).

Sassen and Liao (1996) used a cloud model to get a relationship between the reflectivity and cloud liquid water. Fox and Illingworth (1997) proposed a simple empirical power-law relation for LWC of stratocumulus clouds based on radar reflectivity alone, which may be quite useful in a large-scale climatological sense but may be quite inaccurate for individual cases. Gossard et al. (1997) approached this problem by using millimeter-wave radar measurements of the full spectrum of vertical velocities with deconvolution adjustments for the effects of atmospheric turbulence. But the procedure is complicated, and many radars do not routinely record the full Doppler spectrum. In some situations the problem can be resolved more simply by incorporating information from additional instruments. One such technique uses measurements of the path-integrated liquid water measurement obtained with a microwave radiometer in combination with measurements of the routinely available Doppler moments.

Frisch et al. (1995) developed this radar-radiometer technique for retrieving microphysical features of liquid water clouds, such as stratus, using collocated, vertically pointing millimeter-wave radar and microwave radiometer. This method, which retrieves estimates of cloud droplet median size, total droplet concentration, and LWC as a function of height, was first applied in the Atlantic Stratocumulus Transition Experiment (ASTEX) of 1992 in Portugal's Madeira Islands. Although the retrieved parameters were reasonable for marine stratocumulus, there were no coincident aircraft measurements of these clouds to evaluate the technique. New measurements at the U.S. Department of Energy's (DOE's)

Atmospheric Radiation Measurement (ARM) Program's Cloud and Radiation Testbed (CART) site in northern Oklahoma, however, offer an opportunity to compare the ground-based remote sensing retrievals with concurrent aircraft in situ cloud sampling.

Radar-Radiometer Retrieval Method

The technique is described in detail by Frisch et al. (1995) with extensions by Frisch et al. (1998). They show that the profile of LWC through a stratus cloud can be expressed as

$$q_l(z_j) = \frac{Q_l Z^{1/2}(z_j)}{\Sigma_{i-l}^{i=N} Z^{1/2}(z_i)\Delta z} \tag{1}$$

where q_l is the LWC at height z_j, Q_l is the total path-integrated LWC measured by the Microwave Radiometer, Z is the radar reflectivity factor measured by the millimeter-wave radar, j is the range gate (height) index, N is the number of layers in the cloud, and Δz is the gate thickness or height increment of the data. This result was based on assumptions that droplet number concentration and the spread of the drop size distribution are constant with height, which are good approximations for marine stratocumulus (e.g., Slingo et al. 1982). The method is being adapted to the ARM CART site measurements for routine retrievals of liquid cloud properties.

The Oklahoma Measurements

As part of an ARM Cloud Intensive Operational Period (IOP) in April 1997, the National Oceanic and Atmospheric Administration/Environmental Technology Laboratory (NOAA/ETL) operated its NOAA/K cloud radar at the Oklahoma CART site. This radar's ability to detect non-precipitating clouds has been demonstrated on numerous field projects (Martner and Kropfli 1993). Data from this visiting radar and from the CART site's permanent dual-frequency microwave radiometer were used to retrieve microphysical properties of stratus and altostratus over the site. Numerous overflights through the clouds by the University of North Dakota's Citation research aircraft provided in situ sampling of the cloud droplets for assessing the remote sensing retrievals. The Citation's Forward Scattering Spectrometer Probe (FSSP) was the primary instrument used for the droplet measurements; LWC was computed by integrating its measured size spectra. Other probes on board indicated the absence or presence and size of ice crystals. Basic characteristics of the three instruments are shown in Table 1.

Results

Although the radar/radiometer retrievals were attempted on several days with support from the Citation aircraft, the radar's cloud data on most days suffered from contamination by insects and other non-cloud particulates in the boundary layer. Whereas the radar's polarization data provide a means for identifying the presence of the insects, etc., we have selected for our initial analysis a day (April 9, 1997) when these complicating factors were not present. Thin stratus and altostratus layers persisted for almost three

Table 1. Characteristics of the instruments.

NOAA/K Radar	Forward Scattering Spectrometer Probe	Microwave Radiometer
Developed by: NOAA/ETL **Features**: Doppler, full scanning, dual-polarization Beam width **Wavelength**: 8.7 mm **Beam width**: 0.5 deg. **Height Resolution**: 37.5 m **Temporal resolution**: 0.3 s (raw), 3.0 s (processed data)	**Manufacturer**: Particle Measuring Systems, Inc. **Droplet size range**: 3-45 microns, nominal **Bin size centers in this 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 microns **Temporal resolution**: 1 s **Aircraft speed**: 100 m/s approx.	**Frequencies**: 23.8 and 31.4 GHz **Beam width**: 5 deg **Temporal resolution**: 1 min

hours on this day while the Citation made numerous horizontal passes through the cloud layers at different heights as well as a few ascending and descending spiral profiles through the clouds over the CART site.

Data from the Citation's FSSP were used for periods when the aircraft was within 1.5 km of the radar. The aircraft's indicated pressure-altitude heights, however, are subject to considerable uncertainty and have been adjusted by two to four radar gate lengths (75 m to 150 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 LWC comparisons were conducted. Figure 1 shows an example of one such adjusted profile from a spiral ascent, along with the corresponding radar profile. In this case, reflectivities computed from the aircraft's FSSP data were somewhat larger than those observed by the radar. As shown by Frisch et al. (1998), the radar-radiometer microphysical retrieval of LWC is independent of the radar's absolute calibration, so the indicated reflectivity difference is of no consequence.

Comparisons of the cloud LWC values retrieved by the radar-radiometer technique with those sampled in situ by the aircraft are shown in Figure 2 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. Considering various sources of error, including instrumental error, the hugely different aircraft and remote sensor sampling volumes, and the less than perfectly homogeneous nature of the clouds, the agreement is quite good. This lends support to the usefulness of the radar-radiometer technique for estimating cloud LWC profiles from the ground, at least under some circumstances.

Acknowledgment

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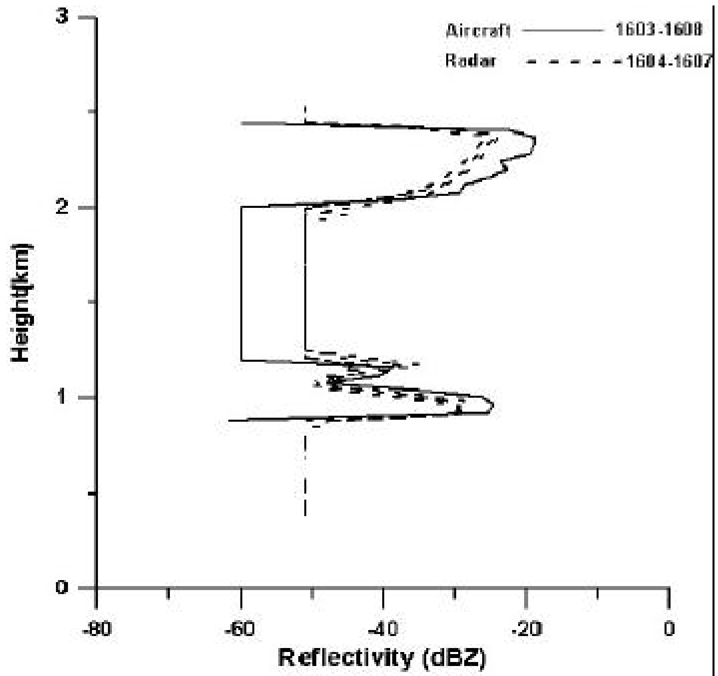

Figure 1. Radar and vertically adjusted aircraft FSSP profiles of reflectivity.

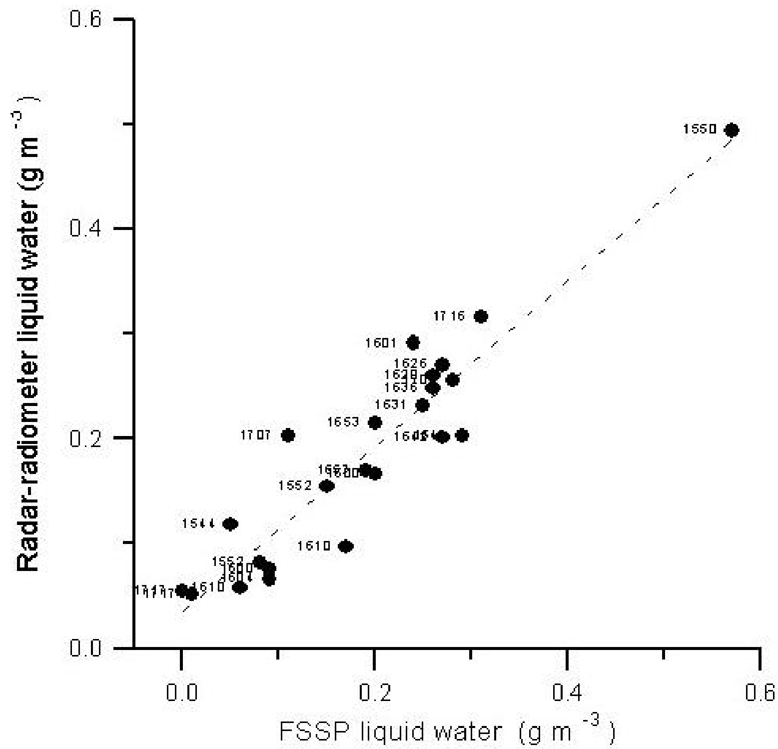

Figure 2. Comparisons of radar-radiometer liquid water concentration retrievals with FSSP-measured liquid water concentration.

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