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RADAR/RADIOMETER COMBINATION TO RETRIEVE CLOUD CHARACTERISTICS FOR ICING DETECTION

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1. INTRODUCTION

Remote measurements of cloud liquid water content (LWC) and characteristic droplet size (e.g., radar estimated size: RES) are required for quantifying potential aircraft icing hazard (Politovich, 1989; Politovich and Bernstein, 2002; Vivekanandan et al., 2001). During the 2004 Winter Icing and Storm Project (WISP04), research radars and radiometers were deployed at NCAR's Marshall experimental site near Boulder, Colorado to evaluate remote sensing techniques for characterizing cloud icing conditions. The dataset included radar and radiometer measurements.

The best case for single wavelength radar and two-channel radiometer-based retrievals was on March 10-11, when a shallow, fairly uniform stratus cloud in the temperature range of ~ -5 to -15^{o}C was observed. High liquid water content and little ice was found in the cloud. This cloud began with some patches of relatively high reflectivity (~10-20 dBZ) and snow showers at the ground. It then evolved to low (<-10 dBZ) reflectivity with lots of liquid, as evidenced by numerous pilot reports of icing in the Denver area. Strong ground clutter at S-band limits the usefulness of the data for a dual-wavelength application. Nevertheless, Ka-band radar reflectivity and radiometer measurements were available for retrieving cloud characteristics.

In this paper, we present retrievals for cloud LWC and RES from single frequency radar reflectivity and dual-channel radiometer measurements. Retrieval methods are reviewed in Section 2. The retrieval results and comparisons are presented in Section 3. A summary and discussion are given in Section 4.

2. METHODS

Cloud LWC and RES are retrieved from the radar and radiometer measurements using: (1) the Hitschfeld-Borden attenuation correction method, and (2) the constrained-gamma cloud drop size distribution (DSD) model. The Hitschfeld-Borden method uses an attenuation-reflectivity power-law relation and adjusts its coefficient with a path integrated attenuation (PIA) derived from radiometer measurements. The constrained-gamma cloud DSD method retrieves gamma DSD parameters from radar reflectivity and the PIA (path integrated attenuation). A constant scale parameter (N_0) and either a constraining relation between the shape (μ) and slope parameter (Λ) or a fixed μ are assumed.

At Ka-band, attenuation due to cloud and atmospheric gaseous components can be substantial. The measured radar reflectivity, Z_m, is

$$Z_m(r) = Z(r)\exp\left(-0.2\ln 10\int_0^r A(s)ds\right) \quad (1)$$

where Z is the expected reflectivity factor and A is the attenuation coefficient. Both A and Z are unknowns and they are related to measured reflectivity and absorption in the cloud. Range resolved attenuation is difficult to measure except when using a dual-wavelength radar technique (Vivekanandan et al., 1999). The total PIA can be estimated from dual-channel radiometer measurements of vapor path (VP) and liquid water path (LWP). The gaseous attenuation is estimated using the VP measurement.

2.1 Adjusted Hitschfeld-Borden method

The Hitschfeld-Borden method has been widely applied to space/air-borne radar remote sensing of rain [Meneghini & Kozu, 1990]. This method uses an attenuation-reflectivity relation, $A = \alpha Z^\beta$, to solve (1) for true reflectivity. The relation $A = 2.45Z^{0.704}$, which was derived for a cloud droplet spectrum (Vivekanandan et al. 1999), is used in this study.

When attenuation is large or an improper A-Z relation is used, the Hitschfeld-Borden solution to (1) becomes unstable. With total cloud attenuation as a constraint; however, the Hitschfeld-Borden solution can be adjusted to give stable results. The attenuation-corrected reflectivity is

$$Z(r) = \frac{Z_m(r)}{\left[1-0.2\ln 10\,\varepsilon\beta\int_0^r \alpha Z_m^\beta(s)ds\right]^{1/\beta}} \quad (2)$$

with

$$\varepsilon = \left(1-10^{-\beta\frac{PIA}{10}}\right)\Big/ 0.2\ln 10\,\beta\int_0^\infty \alpha Z_m^\beta(s)ds \quad (3)$$

and the adjusted A-Z relation becomes

$$A = \alpha\varepsilon Z^\beta . \quad (4)$$

For Rayleigh scattering, cloud LWC and attenuation are linearly related as

$$LWC = A/c \quad (5)$$

where the constant c= 1.15 dB km^{-1}/(g m^{-3}) for liquid cloud at a temperature of -5^{o}C.

The cloud characteristic droplet size, RES, is obtained from the ratio of the reflectivity factor and LWC (Vivekanandan et al., 2001).

$$RES = \left(\frac{Z}{LWC/(\pi\rho/6)}\right)^{1/3} \quad (6)$$

where ρ is the water density.

2.2 Constrained gamma drop size distribution (DSD) retrieval

Cloud characteristics can be retrieved by assuming a DSD model. The most commonly used DSD model is the gamma distribution, written as

$$N(D) = N_0 D^{\mu} \exp(-\Lambda D) \quad (7)$$

where the three parameters are: the concentration parameter N_0 , shape parameter μ, and slope parameter Λ. With the gamma DSD model (7), radar reflectivity and cloud attenuation are represented by the DSD parameters as

$$Z = N_0 \Lambda^{-7} \Gamma(\mu + 7) \quad (8)$$

$$A = \frac{\pi}{6} \rho c N_0 \Lambda^{-4} \Gamma(\mu + 4) . \quad (9)$$

To retrieve the three gamma DSD parameters, three independent measurements at every range gate are usually required. With single frequency radar reflectivity measurements and path integrated attenuation from radiometer measurements, further assumptions are needed.

It is usually assumed that N_0 is constant along the path and μ is fixed at a given value or a μ -Λ relation is used. Substitution of (8) and (9) into (1) yields the expression of estimated reflectivity, $\hat{Z}_m$. With the constrained condition PIA, gamma DSD parameters are solved from the measured reflectivity. Once the DSD parameters are known, LWC and RES can be obtained as

$$LWC = \frac{\pi}{6} \rho N_0 \Lambda^{-4} \Gamma(\mu + 4) \quad (10)$$

$$RES = \frac{1}{\Lambda} \left(\frac{\Gamma(\mu + 7)}{\Gamma(\mu + 4)} \right)^{1/3} . \quad (11)$$

These (above) two methods, the adjusted Hitschfeld-Borden method and the constrained gamma DSD retrieval method, are essentially similar when N_0 is constant and μ is fixed. Eliminating Λ from (8) and (9), we have

$$A = \frac{\pi}{6} \rho c N_0 \Gamma(\mu + 4) \left(\frac{Z}{N_0 \Gamma(\mu + 7)} \right)^{\frac{\mu+4}{\mu+7}} . \quad (12)$$

When N_0 is constant and μ is fixed at a value such that $\beta = \frac{\mu + 4}{\mu + 7}$, the DSD retrieval gives the same results as the adjusted Hitschfeld-Borden method since the coefficient α and N_0 are adjusted based on PIA.

3. COMPARISON BETWEEN RADAR AND AIRCRAFT RETRIEVALS

Figure 1 shows radar and radiometer measurements of liquid cloud on 11 March 2004. Figure 1a is the Ka-band radar reflectivity collected at 01:38:20 UTC at 14^o elevation, and Fig. 1b is the liquid water path and vapor path at 15^o elevation measured by Radiometrics's two-channel radiometer. The radiometer measurements lasted from 01:34:06 to 01:59:39 UTC. The measured vapor path is used to correct gaseous attenuation. The measured radar reflectivity and liquid water path are used to retrieve LWC and RES with the method presented in Section 2.1. The retrieved cloud LWC and RES are shown in Fig. 2. The LWCs around 0.2 g m^{-3} and RESs of 40 μm are reasonably in good agreement with in situ aircraft measurements from the University of North Dakota (UND) Citation.

The cloud LWC retrievals are compared with aircraft measurements as shown in Fig. 3. One ray of radar/radiometer retrievals at an azimuthal angle of 45^o from the north is plotted versus height. Aircraft measurements of LWC were collected by the CSIRO probe from 00:53:40 to 02:00:59 UTC. Only the data collected within 20 km of the radar are shown for the comparison. Considering differences in space, time, and sample volume size between the in-situ probe and remote measurements, this comparison is acceptable.

A simple error analysis can be performed when radar reflectivity measurement is the main source of uncertainty in the estimated cloud characteristics. With an assumption of reflectivity measurement error of 0.5dB, we find from (4) - (6) that the relative estimation error for LWC is 8.4% and the error for RES is1.2%. The relative LWC error can be inferred from the fluctuations in Fig. 3. The small RES error is because the errors in A estimates and that of Z are correlated and tend to cancel each other. It is noted that the model error and PIA constraint error can be larger than the error due to reflectivity estimation uncertainty.

4. SUMMARY AND DISCUSSIONS

In this paper, we have presented cloud characteristics retrievals from radar/radiometer measurements during WISP04. Both the adjusted Hitschfeld-Borden method and constrained gamma DSD retrieval are examined. It is shown that when N_0 is constant and μ is fixed the constrained gamma DSD retrieval can yield the same results as the adjusted Hitschfeld-Borden method. However, the DSD retrieval may have advantage for measurements with multi-parameters, such as dual-wavelength radar techniques.

The LWC and RES cloud characteristics were retrieved from radar/radiometer measurements for a liquid cloud case. The retrievals of LWC are comparable to in-situ measurements. Further verification of remotely retrieved parameters with in-situ measurements will be conducted. The comparison of the radar-retrieved variables with additional aircraft observations is in progress.

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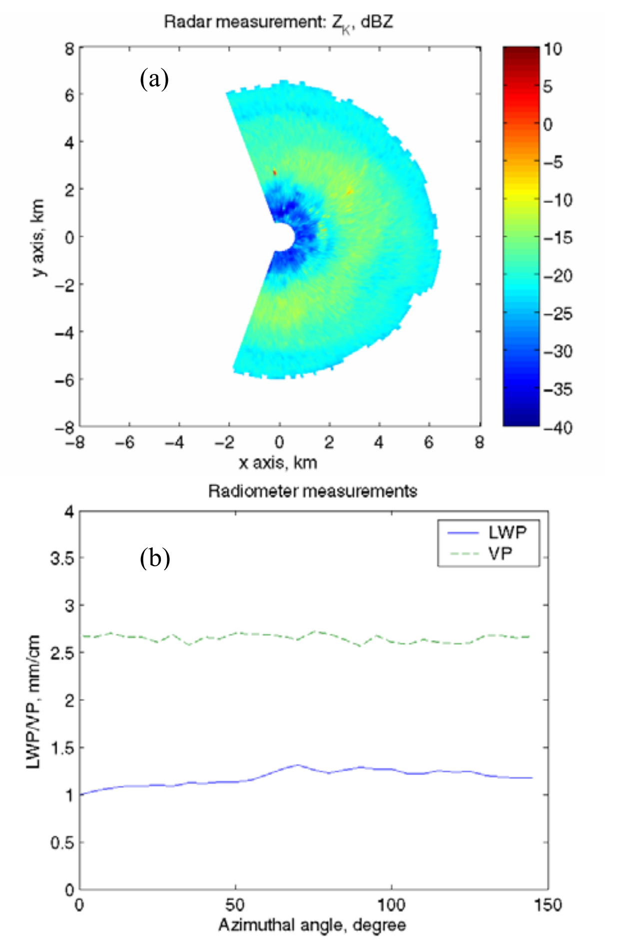

Figure 1: Radar/radiometer measurements of cloud. (a) Ka-band radar reflectivity on 03/11/2004 at 01:38:20 UTC, and (b) radiometer measured liquid water path and vapor path for a period from 01:34:06 to 01:59:39 UTC.

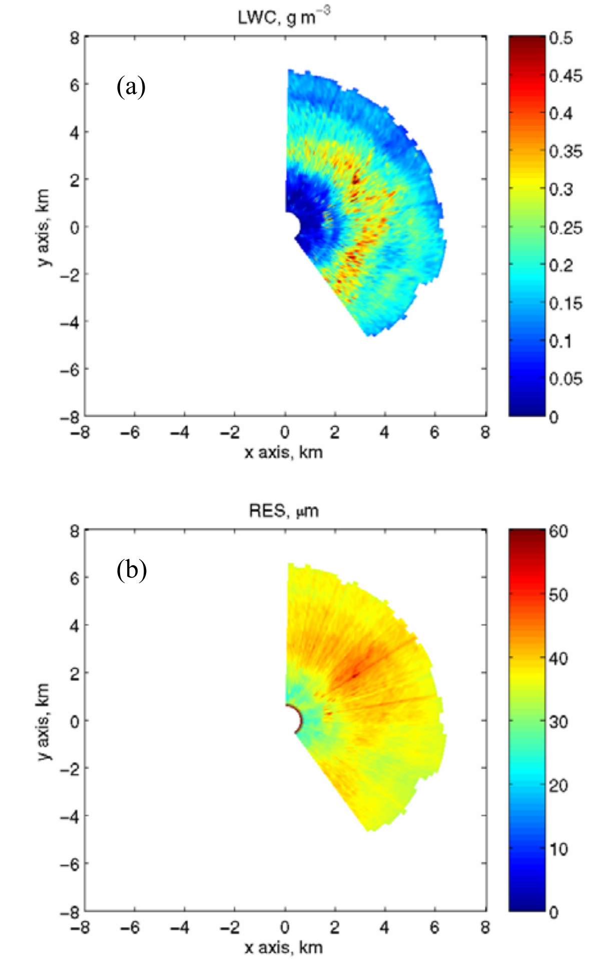

Figure 2: Radar/radiometer retrievals of liquid water content and radar estimated size. Data were collected on 03/11/2004 at 01:38 UTC near Boulder, Colorado.

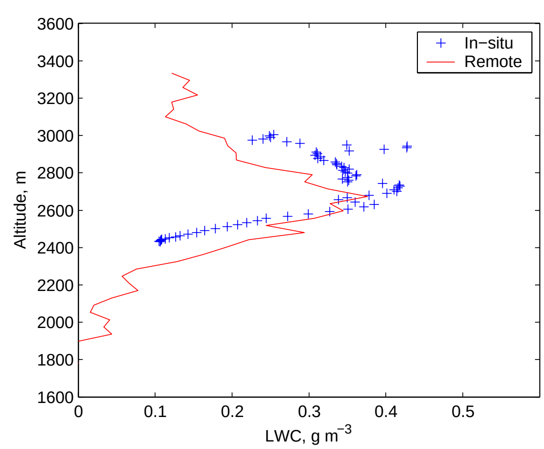

Figure 3: Comparison of liquid water content between radar/radiometer retrievals and in-situ measurements. In-situ measurements are from a CSIRO liquid water probe on board the UND citation research aircraft.