Ice Water Content (IWC) Retrieval from Cirrus Clouds Using Millimeter-Wave Radar and *In-Situ* Ice Crystal Airborne Data

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Abstract —-**Data collected in March 2000 during the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Cloud Intensive operational period (Cloud IOP) at the Cloud and Radiation Testbed (CART) site in Lamont, Oklahoma was used to retrieve the ice water content (IWC) of cirrus clouds. In situ measurements of ice particles were collected using the National Center for Atmospheric Research (NCAR) Video Ice Particle Sampler (VIPS), which flew on the University of North Dakota (UND) Citation research aircraft. Ground-based vertical radar profiles were collected using the University of Massachusetts (UMass) 33GHz/95GHz Cloud Profiler Radar System (CPRS). The equivalent radar reflectivity at Ka band (33GHz) from both sensors was compared in a previous study [8]. In this work, IWC was calculated for both sensors using variable density model for the ice crystals. The IWC derived from the measured VIPS data was compared with several IWC models. The model from Liao and Sassen, 1994 resulted in closer agreement with the observed data. This model used a density which is a function of ice crystal's diameter.**

Keywords: Cirrus clouds, millimeter wave, equivalent reflectivity, particle size distribution

1. INTRODUCTION

Cirrus clouds play an important role in the balance of Earth's energy dynamics. In order to validate their representation in global circulation models used for climate research and weather forecasting we need to obtain global data on the vertical structure of ice water content (IWC) in clouds [1].

To evaluate the accuracy of the current climate models, precise millimeter-wavelength radar measurements of clouds microphysical properties for developing the cloud parameterization are needed. Several experiments have been performed in the past two decades to improve the understanding of the relationship between microphysical and radiative properties of cirrus clouds (FIRE-I, FIRE-II and ARM). To accomplish this radar and in-situ measurements had been analyzed and compared, e.g. Chandrasekar, Bringi and Strapp have documented comparisons for graupel and hail [2].

Appropriate radars for studying clouds such as cirrus clouds are millimeter wavelength radars like the UMass Cloud Profiler Radar System (CPRS), because they are sensitive enough to study particles smaller than one millimeter. For the in-situ measurements the NCAR Video Ice Particle Sampler (VIPS) was used. The CPRS operating frequencies are 33 and 95 GHz, which is near to the atmospheric window making it useful for studying the microphysical properties of clouds [3]. Although Rayleigh approximation is applicable at 35GHz, in this work we used the full Mie equations to calculate the backscattering from individual crystals. Data from both instruments were obtained on March 2000 from the ARM experiment at the Southern Great Plains (SGP) site in Oklahoma [4].

2. EXPERIMENT SETUP

Data from March 13, 2000 was used because good matching in time and space in the presence of cirrus clouds was found. The flight pattern for that day was a series of legs at various altitudes like the portion of the flight shown in Fig.1.b, and an overhead view of the flight is shown in Fig.1.a. The ice particle data was collected using an instrument called Video Ice Particle Sampler (VIPS) and given by A. Heymsfield from the National Center for Atmospheric Research (NCAR). This is an airborne instrument that flies inside cirrus clouds, and takes samples of the cirrus cloud particles sizes up to 5 μm in size. The VIPS have an electro-optical and imaging unit that is in charge of collecting data, and another part designated to record data. Equivalent reflectivity obtained from data from the CPRS is shown in Fig.2 and in this case the blue line in the mid section of the figure is the path of the plane at the same time that the radar collected the information. The matched data was compared using traditional methods such as assuming Mie backscattering from the ice bullets; the backscatter was calculated as a function of the wavelength, diameter and density. The equation that was used to calculate the equivalent reflectivity for the VIPS data is:

$$Z_e = \frac{10^{12}\lambda^4}{4\pi^4 |K_w(\lambda)|^2} \int_0^{D_{max}} \xi_b(D,\lambda,\rho) N(D) D^2 dD \quad [mm^6 m^{-3}] \tag{1}$$

Where ξ_b is the Mie backscattering coefficient, K_w is the dielectric factor and *N(D)* is the particle's size distribution.

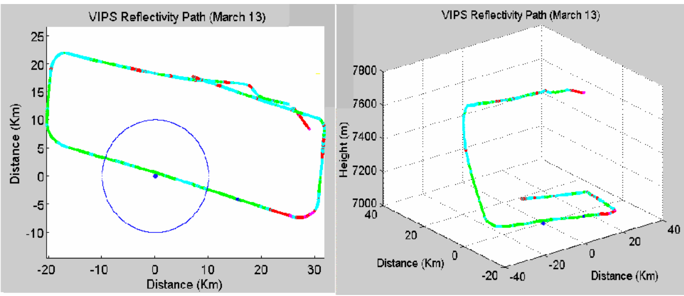

Figure 1 a) Overhead view of the VIPS flight track pattern for March 13, 2000. The blue dot at (0, 0) indicates the position of the CPRS radar, the blue circle is only a reference for data that were spatially closed between sensors. b) Is the same as a) but in three dimensions to show variation in altitude.

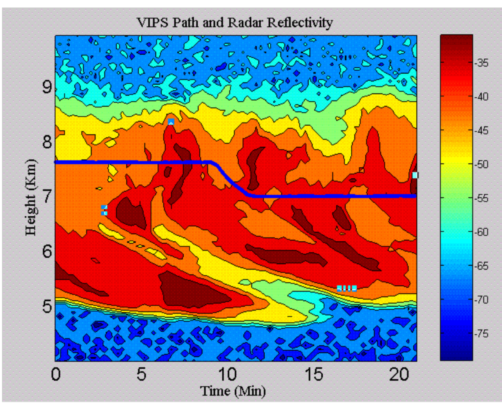

Figure 2 CPRS reflectivity plot versus time showing the trajectory of the airplane through the cirrus cloud.

The density of the ice particles has been shown that have a big effect in the backscattering [5]. The density of the ice particles vary as a function of its dimensions and in cirrus clouds it has been found that the dominant crystal type found in cirrus clouds is the bullet rosette, with an average of five bullets per rosette. Different crystal structures are more dominant in a cirrus cloud depending of the diameter. Particles of less than 100µm are more likely to have a spherical shape [6]. Each bullet has a longitude relation, *L* (mm), versus wide, *w* (mm), (twice times the apothem) for temperatures between –18º and –20 ºC given by [7−11]:

$$w = 0.25 L^{0.7856} \quad \text{[mm]}, \tag{2}$$

for bullets with $L \leq 0.3$ mm, and

$$w = 0.185 L^{0.532} \quad \text{[mm]}, \tag{3}$$

for bullets with $L \geq 0.3$ mm.

In this way the equations were determined for the bulk density, ρ, of the bullet, considering the solid ice density as 0.9 g cm-3 and using the volume of ice in individual crystals

$$\rho = 0.78 L^{0.0038} \quad (\text{g cm}^{-3}) \tag{4}$$

As the Wiener's theorem states the complex index of refraction, *m*, depends of the bulk density when dealing with dry ice particles:

$$m = \frac{2 + n_i^2 + 2 f_i \left(n_i^2 - 1\right)}{2 + n_i^2 + f_i \left(-n_i^2 + 1\right)} \tag{5}$$

where f_i represents a non-dimensional fraction of the volume of air and ice and it is defined as:

$$f_i = \frac{\rho}{\rho_i} \tag{6}$$

with ρ_i as the solid ice density (0.9 g cm-3) and where n_i is the complex index of refraction of solid ice which is different for every frequency (33 and 95 GHz). Using the above equations, we obtained an index of refraction for each bullet size [5]. The new complex indexes of refraction in our case are used to calculate the backscattering efficiency using Mie theory. This was done by converting the length *L* of a bullet shaped particle to diameter of a sphere. Finally this backscattering efficiencies and the particle size distribution from the VIPS are used to calculate the equivalent reflectivity; which are then compared to the equivalent radar reflectivity obtained by the CPRS.

3. DATA AND EQUIPMENT

3.1. UMass Cloud Profiling Radar System (CPRS)

CPRS operates at 33 and 95 GHz frequencies and in this experiment the radar was operating in a vertically looking position so that it was looking at zenith at all times. From this data we used the range (distance to the radar), the time of the measurement and the equivalent reflectivity. A contour plot from the CPRS data to represent the radar reflectivity is shown in Fig.2 with the horizontal axis as time and the vertical as height. Also data of both channels (33 and 95 GHz) is shown in Fig.3, clearly showing that the 95GHz data is corrupted due to saturated reflectivity values. For further details on the system the reader is referred to reference [8].

3.2. NCAR Video Ice Particle Sampler (VIPS)

This device uses an electro-optical instrument used to collect and record a continuous sample of cloud particles down to 5µm. The data we have from this instrument is in table format. From here were used the altitude of the airplane, the diameters and concentration of particles *N(D)* per cubic meter present for this diameters. Data was aligned in time and space.

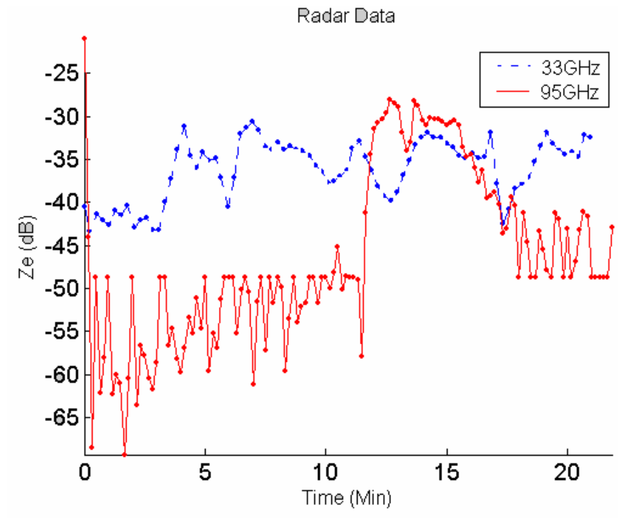

Figure 3 Time trace of the data showing the radar reflectivity of the two channels of CPRS data during the time when the airplane over flew over the radar. The 95 GHz channel shows a miss-operation during this time, therefore only 33GHz data was used in this work.

3.3 Ice Water Content (IWC) retrieval

Ice water content for the VIPS data was calculated with the following equation:

$$IWC = \frac{\pi}{6}\sum_{d=d_0}^{\infty}\rho(D)N((D)D^3 \qquad (7)$$

were $\rho(D)$ is the density of the particle, $N(D)$ is the particle size distribution and D is the diameter of the particles. Also the following relationships of IWC at 33GHz were applied to the in-situ data: IWC=0.097$Z_e^{0.596}$, IWC=0.064$Z_e^{0.58}$ (Atlas et al. 1995), IWC=0.15$Z_e^{0.84}$ (Liao and Sassen 1994, for $\rho=0.07D^{-1.1}$), IWC=0.027$Z_e^{0.78}$ (Liao and Sassen 1994)[1]. A plot using all of this relationship is shown in Fig.6.

4. Results

A comparison between backscattering using Mie theory and bullet shaped particles (using DDA) are shown in Fig.4, here the upper line is for Mie backscatter and the one a little bellow is the result using DDA, both for a constant density of $\rho= 0.916\ g{*}cm^{-3}$ as can be seen the difference is negligible at 33GHz. The comparison for in situ and radar measurements is shown in Fig.5, were the CPRS data is represented by a red cut line and the VIPS data is represented in blue solid line. The data was gathered in the same interval of time, and a green line represents the distance between instruments. The root mean square (RMS) difference value for the equivalent reflectivity was calculated for data with a distance of 10 and 5km between instruments using the following equation:

$$Ze_{RMS} = \sqrt{\frac{(a_1-b_1)^2+(a_2-b_2)^2+(a_3-b_3)^2+\ldots+(a_n-b_n)^2}{n}} \qquad (8)$$

Where a_n is the equivalent reflectivity from the CPRS in dBZ, b_n is the equivalent reflectivity from the VIPS also in dBZ, and n is the total number of points used in the calculation. The resulting RMS for a distance up to 10km between instruments the difference is 4.673 dBZ and for a distance up to 5km the difference is 1.311dBZ. As was mentioned before, the IWC was calculated and plotted for the VIPS data using some relationships and equation 7; and in Fig.7 the IWC using equation 7 and the best relationship IWC=0.15$Z_e^{0.84}$ were compared for the time in which the radar and the VIPS were better matched.

5. Conclusions

The equivalent reflectivity obtained for both instruments compare favorably when both instruments were close in time and space, and the RMS values obtained are smaller when the points compared are closer (See Fig. 5). Also the IWC calculated for the in situ data matched with IWC relationship for density equal to $\rho=0.07D^{-1.1}$, this is the IWC=0.15$Z_e^{0.84}$ (See Fig.6 and 7). Finally, at 33GHz the effect of the shape in the calculation of the backscattering efficiency is negligible, but the density has a strong effect on this calculation.

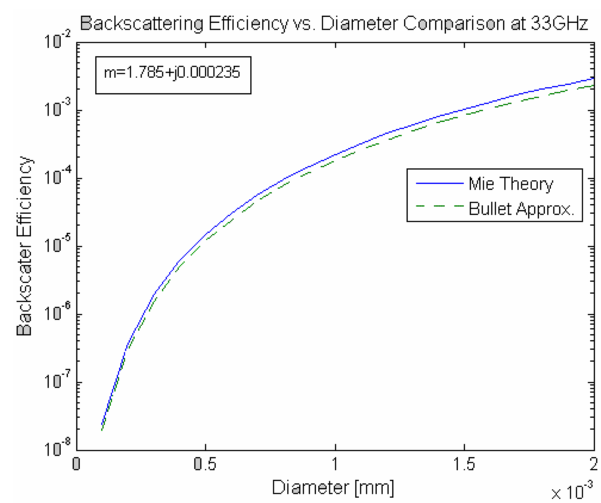

Figure 4 Backscattering efficiency as a function of diameter calculated at 33GHz for a ice with constant density (index of refraction m=1.785+j.00235 at 33GHz).

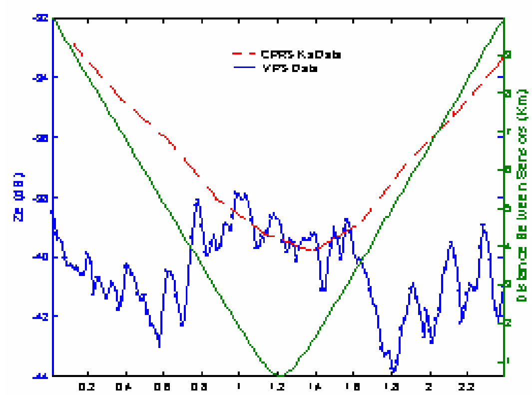

Figure 5 Plot showing on the left scale the radar reflectivity from the CPRS and the computed reflectivity from the VIPS particle size distribution and on the right the distance between the radar and the airplane position.

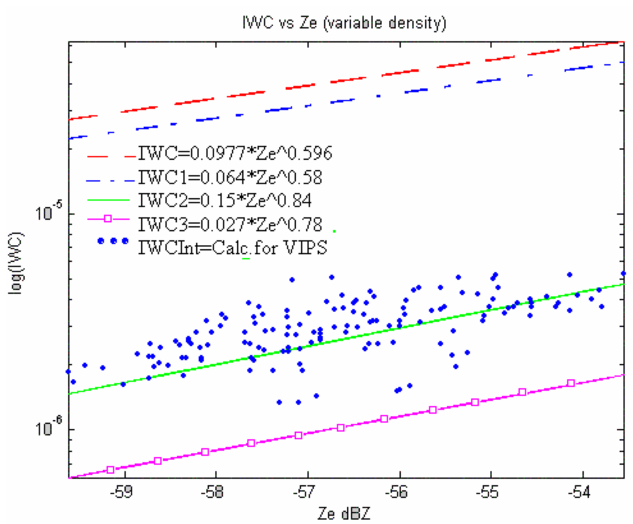

Figure 6 Various IWC models applied to the in-situ data using variable density (ρ(D)=0.07D^-1.1).The blue dots represent the IWC obtained for the VIPS data.

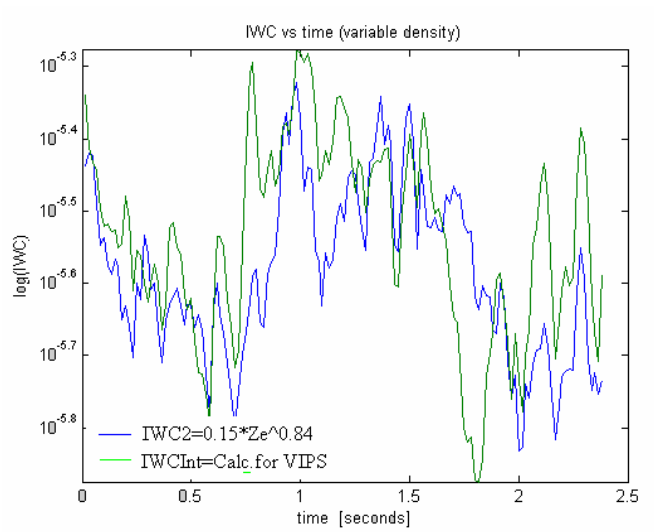

Figure 7 Comparison of IWC versus time for the IWC2 model and the IWC calculated using equation 7 using variable density (ρ(D)=0.07D^-1.1).

6. Future Work

To find operable radar data for both channels (even if the space matching is not good with the VIPS), this in order to make calculations for the 95GHz data. Also we want to retrieve the particle size distribution from the radar data to compare it with the VIPS data.

Acknowledgements

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References

[1] C. Liu, and A. Illingworth. "Toward more accurate retrievals of Ice Water Content from Radar Measurements of Clouds". Journal of Applied Meteorology. Vol.39, 1999.

[2] A. El-Magd, V. Chandrasekar, V. Bringi, W. Strapp. "Multiparameter Radar and in situ Aircraft Observation of Graupel and Hail". *IEEE Transactions on geoscience and remote sensing , vol. 38, no.1 January 2000.*

[3] S. M. Sekeslky, and R. E. McIntosh, "Cloud Observations with a Polarimetric 33 GHz and 95 GHz radar". *Meteor. Atmos. Phys.*, vol. 58, pp. 123-140, 1996.

[4]http://www.arm.gov/docs/iops/2000/sgp2000sprcloud/afteriop_cloud2000.html

[5] J.Villa, S.L. Cruz-Pol, and S.M. Sekelsky, "*Modeling, Simulation and Comparison Study of Cirrus Clouds Ice Crystals*", SPIE 9th International Symposium on Remote Sensing, Crete, Greece, 2002.

[6] G. M. MacFarquhar, T. Nousiainen, M. S. Timlin, S. F. Iacobellis, R. C. J. Somerville."*Use of In-Situ observations to characterize cloud microphysical and radiative properties: application to climate studies*". Thirteenth ARM Science Team Proceedings, Broomfield, Colorado, March 31-April 4, 2003.

[7] A. J. Heymsfield, "Ice crystal terminal velocities". *J. Atmos. Sci.,* 29, pp. 1348-1357, 1972.

[8] J. Morales, Trabal, J., , Cruz-Pol, S. and,. Sekelsky, S. M., "Cirrus Clouds Millimeter-Wave Reflectivity Comparison with In-Situ Ice Crystal Airborne Data", SPIE 04, Hawaii, Nov 8-12, 2004.