Ice Cloud Extinction Retrieval Using Ground-Based and Airborne Millimeter-Wave Cloud Radar Measurements

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Introduction

The National Aeronautics and Space Administration (NASA) CloudSat program will utilize a spaceborne W-band (94-GHz) cloud radar to provide the first global survey of cloud distributions and their seasonal variations (Li et al. 1994; Stephens et al. 1998). However, cloud measurements at this frequency are affected by extinction from atmospheric gases, clouds, and precipitation. Although Sassen and Liao (1996) predicted that extinction from cirrus clouds is small, it can be significant for precipitating cirrus and aggregated particles. Reflectivity errors caused by attenuation have a direct impact on ice mass content estimation (Atlas et al. 1995; Sekelsky et al. 1999).

During the 1998 DC-8 Cloud Radar Experiment, ice and precipitating cloud data were collected by the 33-GHz/95-GHz Cloud Profiling Radar System (CPRS) operated by the University of Massachusetts (UMass), and by the 95-GHz Jet Propulsion Laboratory (JPL)/UMass Airborne Cloud Radar (ACR) (Sadowy et al. 1997) installed in a nadir-viewing configuration on NASA's DC-8 research aircraft.

Previous work used combined airborne and ground-based 95-GHz radar measurements to estimate the extinction and rain rate in precipitation (Li et al. 1999). Our present analysis uses the same dual-radar technique to retrieve the lower-level extinction in ice clouds. Mie scattering is measured by comparing Ka-band (33-GHz) and W-band (95-GHz) measurements. For a given particle size distribution, Mie scattering can be related to hydrometeor median volume diameter. Initial analysis shows that the attenuating ice cloud regions exhibit Mie scattering at W-band and that extinction rates are a function of Mie scattering. This indicates that W-band extinction may be dominated by scattering losses from large particles.

Methodology

Dual-Radar Method

By using ground-based and airborne 95-GHz radars, measurements of the same cloud and precipitation volumes are made from opposing viewing angles. Without a priori knowledge of hydrometeor micro-physical properties, the dual-radar method combines the collocated upward-looking and downward-looking radar profiles to retrieve the true radar reflectivity and atmospheric extinction (Li et al. 1999; Sekelsky et al. 1999; Li et al. 2000). Extinction due to atmospheric gases is estimated from local soundings. Therefore, extinction in ice clouds is obtained by subtracting extinction due to atmospheric gases from total atmospheric extinction.

Compared to extinction caused by rain or water clouds, extinction in ice clouds is small. For example, W-band extinction for a rain rate of 1 mm/hr is 0.70 dB/km, while the maximum extinction rate that we have measured in ice cloud is 0.28 dB/km. Therefore, measurements of attenuation are sensitive to radar calibration and water vapor and oxygen absorption as discussed by Li et al. (1999). The dual-radar method has the advantage of measuring this weak extinction. Because both the upward-looking and downward-looking radars experience the same extinction for a given range resolution cell, we obtain twice the two-way total path attenuation by comparing radar measurements at the top and the bottom of the ice cloud. This larger quantity allows more accurate estimation of the extinction rate.

DWR and Mie Scattering

Dual wavelength ratio (DWR) is a measure of Mie scattering and is defined as the ratio of the co-polarized reflectivity at two different frequencies. For radars operating at 33 GHz and 95 GHz

$$DWR_{Ka,W} = 10 \log (Ze_{33}/Ze_{95})$$

DWR is a function of the size, number, and type of Mie scatters observed. It has been used to estimate effective hydrometeor size (Lhermitte 1987; Matrosov 1993; Sekelsky and McIntosh 1996; Sekelsky et al. 1999). Figure 1 illustrates the relationship between $DWR_{Ka,W}$ and median volume diameter for medium-density ice-air spheres using a first order Gamma distribution. For Rayleigh scatters, $DWR_{Ka,W}$ approaches a constant value of -1.04 dB, where Ze_{33} and Ze_{95} are expressed as water equivalent reflectivity.

Radar Measurements

On June 26, 1998, the airborne ACR and ground-based CPRS observed deep ice clouds and precipitation. Figure 2 shows raw and attenuation-corrected radar reflectivity profiles at 20:42 Universal Time Coordinates (UTC). The lines labeled ‘ACR’ and ‘CPRS W-band’ represent radar measurements before attenuation correction. The true W-band reflectivity (dash-dot) is retrieved using the dual-radar method. Ice cloud extinction at Ka-band is assumed negligible, and Ka-band extinction from humidity and precipitation in the lower atmosphere is corrected using a cloud-top matching technique demonstrated by Sekelsky et al. (1999). However, for this data, the airborne radar measurements are substituted for

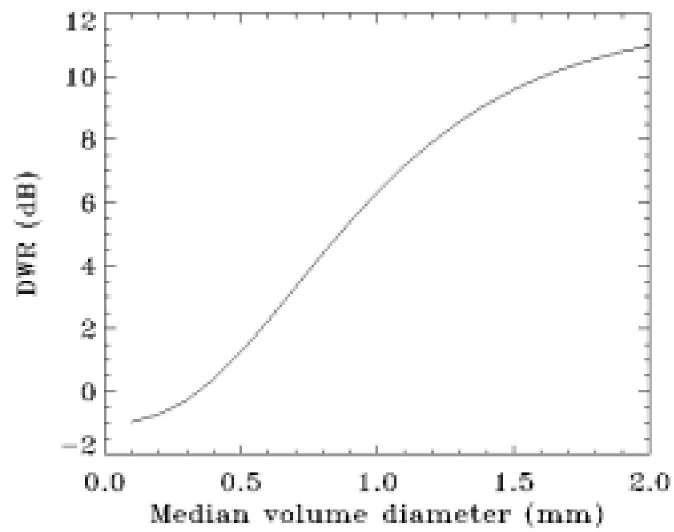

Figure 1. A simplified relationship between DWR $_{Ka,W}$ and median volume diameter modeled by a first order Gamma distribution for spherical snow particles with mass density of 0.5 g/m^3.

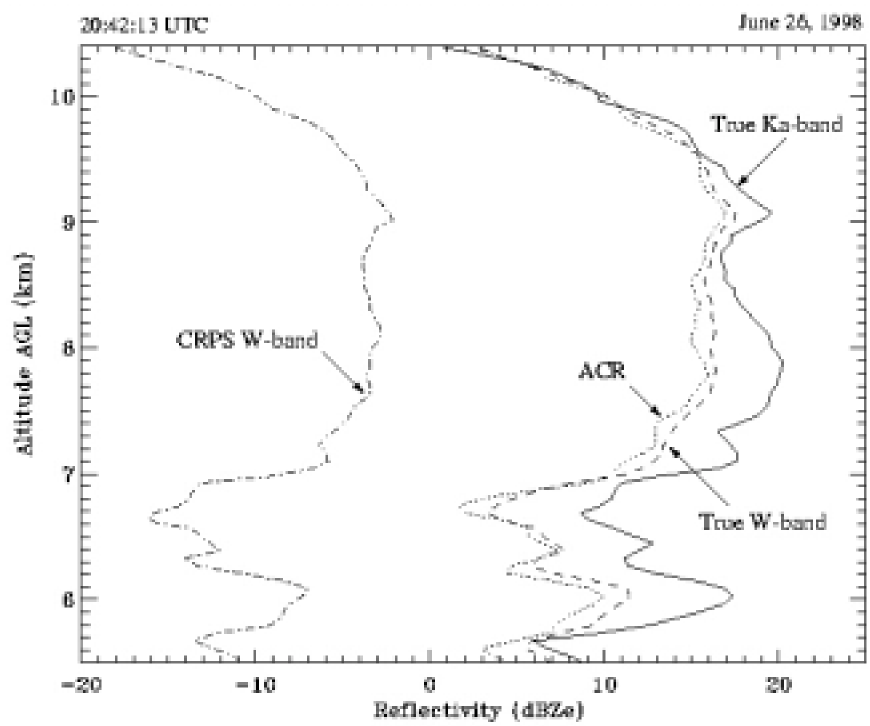

Figure 2. ACR (dotted) and CPRS W-band (dash-dot) radar reflectivity profiles above the freezing level before attenuation correction. The unattenuated W-band reflectivity (dashed) is retrieved using the dual-radar method. We assume that Ka-band (solid) extinction in the ice cloud is negligible.

the unattenuated low-frequency radar data. In order to match the sampling volume in the ice cloud region, ACR, CPRS W-band, and CPRS Ka-band data were averaged for 0.4, 8, and 4 seconds, respectively. These averaging times are based on aircraft motion, horizontal wind speed, and antenna beamwidth.

W-band extinction due to atmospheric gases is calculated using local sounding data, and it is subtracted from the total extinction. The remaining extinction must therefore be due to hydrometeors. Figures 3a and 3b plot DWR $_{Ka,W}$ and particle median volume diameter for the data shown in Figure 2. The ice particle median volume diameter is derived using DWR $_{Ka,W}$ measurements and model results shown in Figure 1. It indicates two distinct extinction rates of 0.08 dB/km above 8.7 km and 0.28 dB/km below 8.7 km, which is consistent with the change of DWR $_{Ka,W}$ shown in Figure 3a and the change of ice particle median volume diameter shown by Figure 3b. These data indicate that larger particles correspond to higher DWR $_{Ka,W}$ and higher extinction rates.

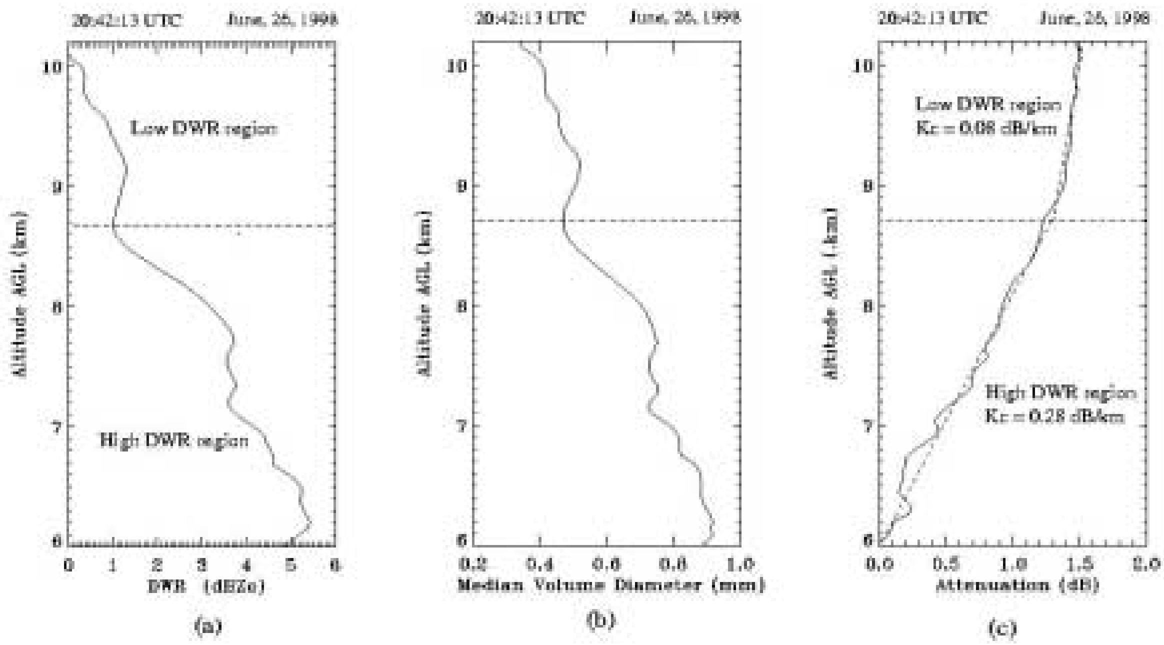

Figure 3. Results derived from the data shown in Figure 2. (a) The dual wavelength ratio $DWR_{Ka,W}$. (b) Ice particle median volume derived from $DWR_{Ka,W}$ and the simplified model data presented in Figure 1. (c) Two-way cumulative ice cloud extinction at W-band shows two distinct extinction rates above and below 8.7 km, which corresponds to a temperature of –23°C measured by local radiosonde.

Figure 4 shows the statistical results of 18 aircraft overpasses of the ground-based system between 20:05 UTC and 23:59 UTC on June 26, 1998. Figure 4a shows the layer averaged one-way ice cloud extinction rate at W-band versus the layer averaged W-band true reflectivity. The relationship between ice cloud extinction rate K_c and radar reflectivity Z_e is modeled as power law (Sassen and Liao 1996). After fitting data points with a power law relation, we obtain $K_c = 0.0138Z_e^{\ 0.796}$. Figure 4b shows the layer averaged K_c versus layer averaged DWR $_{Ka,W}$, and Figure 4c plots the layer averaged K_c versus median volume diameter.

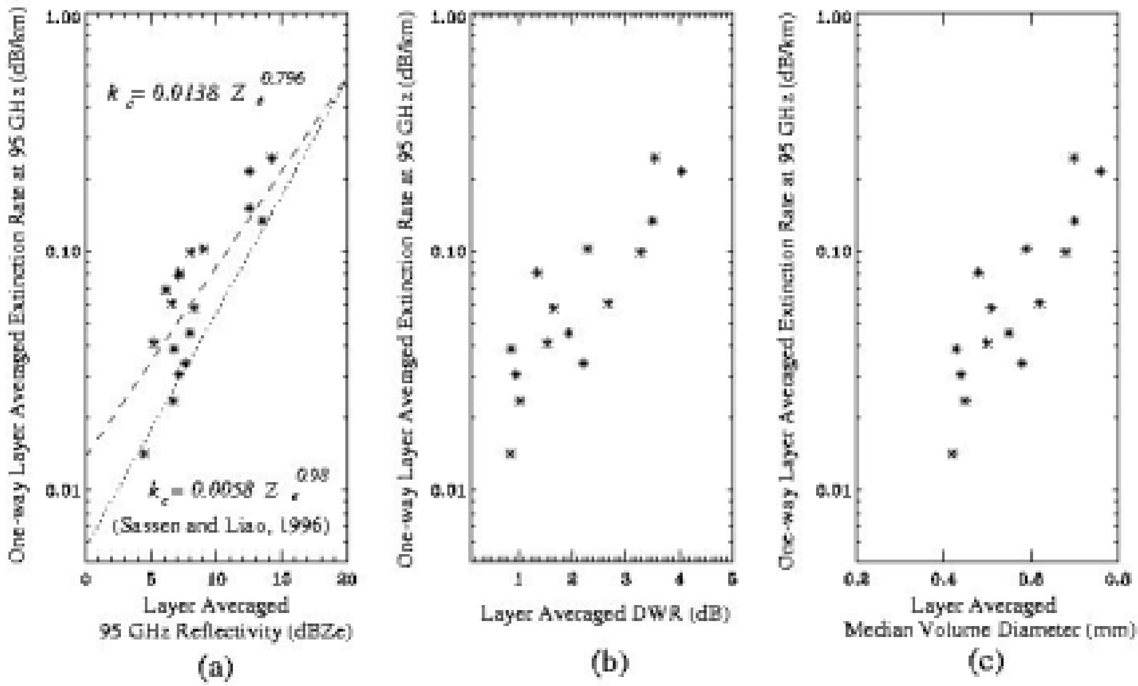

Figure 4. Statistical results from 18 overpass measurements. (a) Layer averaged one-way ice cloud extinction rate versus layer averaged W-band unattenuated reflectivity. These data points are fitted to a power law relation (dashed line), $K_c = 0.0138\ Z_e^{0.796}$. The relationship derived by Sassen and Liao for cirrus is also plotted for comparison (dotted line). (b) Layer averaged one-way ice cloud extinction rate versus layer averaged $DWR_{Ka,W}$, which shows that extinction increases with $DWR_{Ka,W}$. (c) Layer averaged one-way ice cloud extinction rate versus layer averaged median volume diameter.

Summary

Ice cloud extinction rate is retrieved using simultaneous upward-looking and downward-looking W-band cloud radar measurements. Dual-wavelength ratio derived from Ka-band GHz and W-band radar data provides an estimation of median volume diameter D_0. The correlation between K_c and D_0 suggests that W-band extinction is dominated by scattering from large particles.

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