Observed Extinction by Clouds at 95 GHz

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Abstract: Measurements of backscattered power were made in maritime stratus with a 95 GHz pulsed radar mounted on an aircraft. The aircraft also carried probes for the in situ characterization of the cloud composition in terms of liquid water content (LWC) and size distribution of the hydrometeors. Horizontal flight segments of 5-10 km length over which the LWC was relatively uniform were selected for analysis. Mean values of LWC ranged from 0.05 to 0.8 g/m^3. The dominant part of the LWC came from droplets < 50 μm diameter, while the radar backscatter was dominated by drizzle drops > 50 μm. By assuming that the uniformity in cloud composition observed to exist along the flight line also prevailed to 1-2 km distances to the side of the flight path, and after correcting for extinction by water vapor, the observations yielded an extinction coefficient of 4.6 dB/km per g/m^3 of cloud water. This result agrees well with theoretical predictions and constitutes the first direct test of those calculations.

I. INTRODUCTION

The W-band frequency range has proven to be suitable for airborne cloud radars. The combination of compact radar size, higher sensitivity and narrow beamwidth achievable with relatively small antennas allow high resolution cloud measurements to be obtained from airborne

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platforms [1-4]. Even though attenuation by atmospheric gases is relatively small, water clouds produce significant attenuation at this frequency range. Attenuation effects are readily discernible in data collected with W-band radars and detract from the advantages mentioned earlier.

The importance of attenuation is illustrated in the sample image shown in Fig. 1. This image represents the 95 GHz radar reflectivity field in a stratus cloud detected with a horizontally pointing beam at 750 m altitude on September 16, 1995 off the central coast of Oregon. The uncorrected image (Fig. 1a) reveals an obvious decrease in reflectivity with distance away from the radar. After a correction based on the results presented in the paper (Fig. 1b) shows a more realistic reflectivity field.

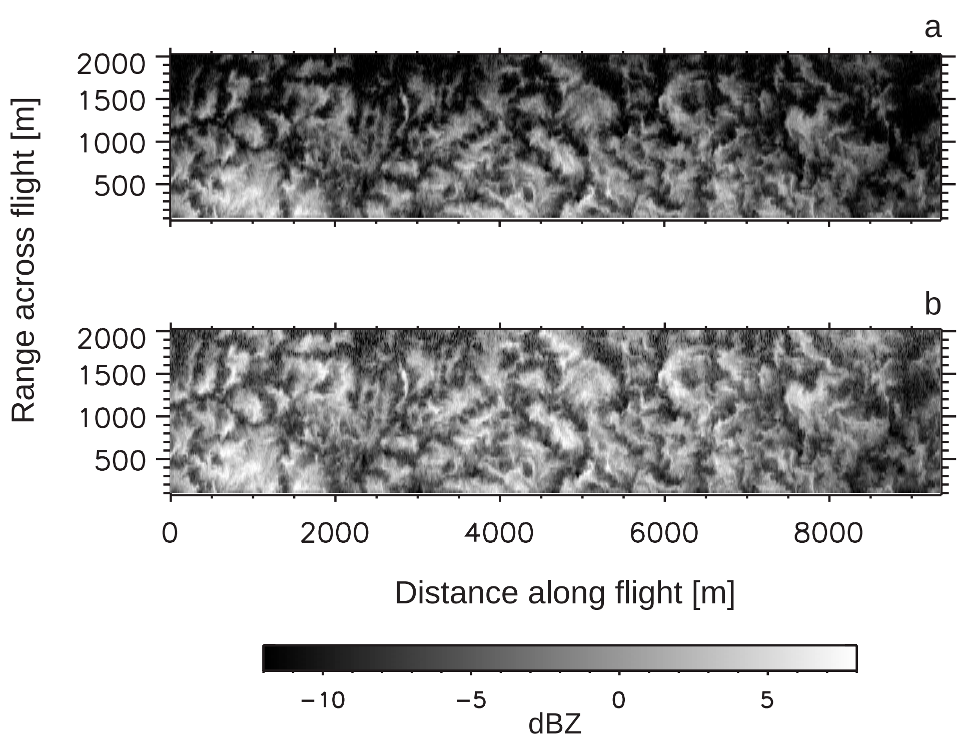


Figure 1. Horizontal look of radar HH reflectivity in maritime stratus off the Oregon coast: (a) – no attenuation correction, (b) – 2 dB/km one-way attenuation correction applied.

Theoretical estimates of the extinction coefficients for millimeter wavelengths have been derived by several authors[4-7] with comparable results. However, to our knowledge, no direct empirical tests of these predictions have been reported prior to this work. The purpose of this paper is to present a set of measurements of the extinction coefficient in liquid clouds that were obtained at 95 GHz, along with simultaneous and co-located cloud measurements of drop-size distribution, liquid water content, temperature, and pressure. We also compare the observed rates with theoretical predictions.

II. OBSERVATIONAL SYSTEM

The University of Wyoming KingAir research aircraft is equipped with a 95 GHz dual-polarized pulsed Doppler radar and a full range of instrumentation for in situ measurements of state parameters, air motions, and for the observation of hydrometeor type, concentration and size. Main parameters of the radar are given in Table 1, the specifications of the in situ instrumentation used for this study are summarized in Table 2. More detailed descriptions of the radar and of the in situ instrumentation can be found in [1,2].

Table 1. Wyoming Cloud Radar specifications.

Transmitted frequency	94.92 GHz
Peak output power	1.6 kW
Pulse duration	100ns – 0.5μs
Pulse repetition frequency	1-20 kHZ
Antenna: gain	49 dB
beamwidth	0.7°
Polarization	H, V
Doppler processing	pulse pair, FFT

Table 2. Characteristics of instrumentation used for this study on the KingAir aircraft.

Variable	Instrument	Range	Resolution	Accuracy
Air temperature	Reverse flow	-50 to 50°C	0.006°C	0.5°C
	Rosemount 102	-50 to 50°C	0.006°C	0.5°C
Static pressure	Rosemount 1501	0-1080 mb	0.003 mb	0.5 mb
Liquid water content	CSIRO hot wire	0-3 g/m^3	0.0003 g/m^3	0.2 g/m^3
	FSSP calculated			30%
Particle spectra	PMS FSSP100	0.5-45 µm	0.5-3 µm	
	PMS OAP-1DC	12.5-187.5 µm	12.5 µm	
	PMS OAP-2DC	25-800 µm	25 µm	
	PMS OAP-2DP	200-6400 µm	200 µm	

For this study, the radar was operated with a fixed horizontal, side-looking beam. Combined with the aircraft motion this yielded reflectivity maps from horizontal sections across the clouds. The transmitted power was horizontally polarized. Radar range resolution perpendicular to the flight direction was 30 m while along-flight resolution was approximately 5 m, determined by the averaging applied.

The combination of in situ and radar measurements from the same aircraft have unique advantages for the study of microwave attenuation. The minimum separation of in situ and radar sample volumes is only 60 m (set by the far field of the radar antenna) which is negligible in comparison with the sizes of the observational domains. A further benefit of the airborne system for this work was the capability to obtain data from horizontal sample planes over the ocean, in stratus and at low altitudes, and thereby to take advantage of the uniformity of conditions prevalent in these clouds.

III. ATTENUATION BY VAPOR AND WATER CLOUDS

Water vapor and oxygen are the main atmospheric gases that contribute to the absorption of microwaves. Even though W-band radars work in one of the water vapor transmission windows, absorption due to water vapor can exceed 1 dB/km at some temperatures and humidities found in the lower troposphere.

The result of a semi-theoretical model for water vapor extinction coefficients for microwaves below 100 GHz is [7, p.271]:

$$k_{H_2O} = 2 f^2 \rho \left(\frac{300}{T}\right)^{\frac{3}{2}} \gamma_1 \left[\left(\frac{300}{T}\right) e^{-\frac{644}{T}} \frac{1}{\left(494.4 - f^2\right)^2 + 4 f^2 \gamma_1^2} + 1.2 \times 10^{-6} \right], \quad \text{dB/km},$$

where f is the microwave frequency (GHz), ρ is water vapor density (g/m^3), T is temperature (°K) and γ_1 is spectral linewidth (GHz). Extinction coefficients in this paper refer to one-way attenuation. Figure 2 shows the extinction coefficient calculated from this equation for 95 GHz and water vapor at saturation. For 900 mb and for temperatures in the vicinity of 10°C the one-way attenuation by water vapor is 0.6-0.7 dB/km.

Clouds consisting of water droplets cause further attenuation. The extinction rate in clouds depends on the size distribution, density and shape of the hydrometeors. The general solution for absorption (and scattering) at W-band microwaves is obtained from the Mie approximation. On the other hand, for clouds consisting of randomly distributed, spherical droplets less than 100 μm diameter, the 95-GHz microwave absorption can be adequately described by the Rayleigh approximation [5-7].

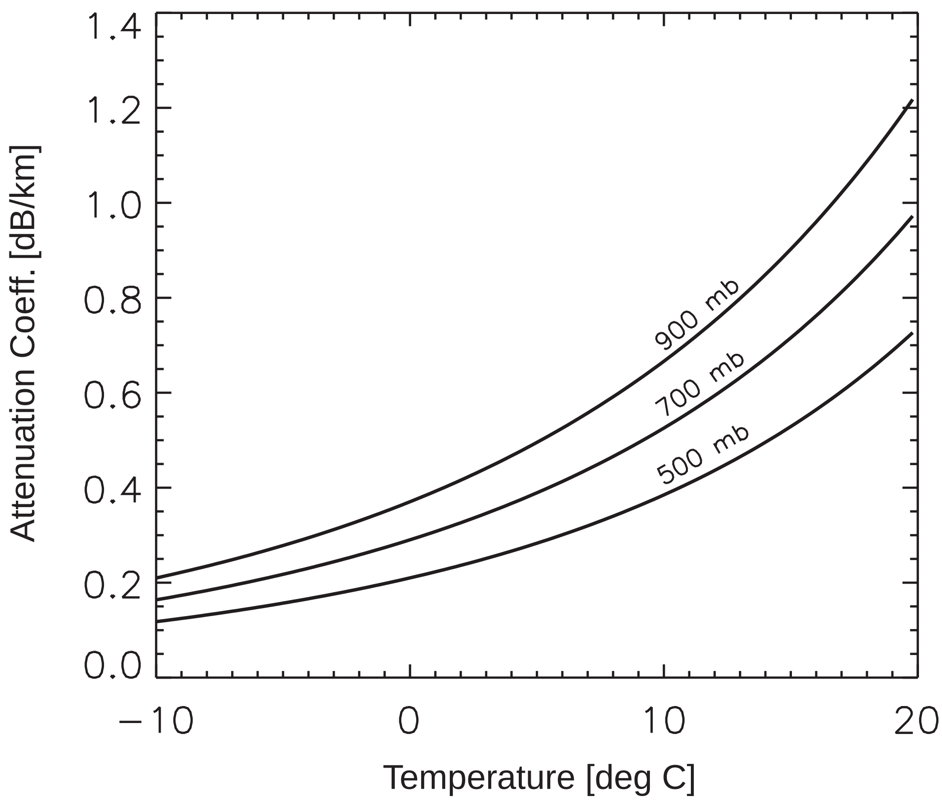


Figure 2. Attenuation by water vapor at saturation for 95 GHz microwave frequency.

We use the approximation $\alpha = wa\theta^b$, dB/km, given in [6], where w is the liquid water content (LWC) in g/m^3, $\theta = 300 / T$ (°K), $a = 3.73$ and $b = 2.81$ for 95 GHz. This model compares favorably with the full Mie calculations presented in [5]. For example, at 10°C, Lhermitte [5] calculated 4.2 dB/km per g/m^3 of liquid water attenuation and Liebe et al. [6] using the Rayleigh approximation obtained 4.4 dB/km. The predicted extinction coefficient per g/m^3 LWC for clouds alone, and for the total attenuation including cloud and water vapor are shown in Fig. 3.

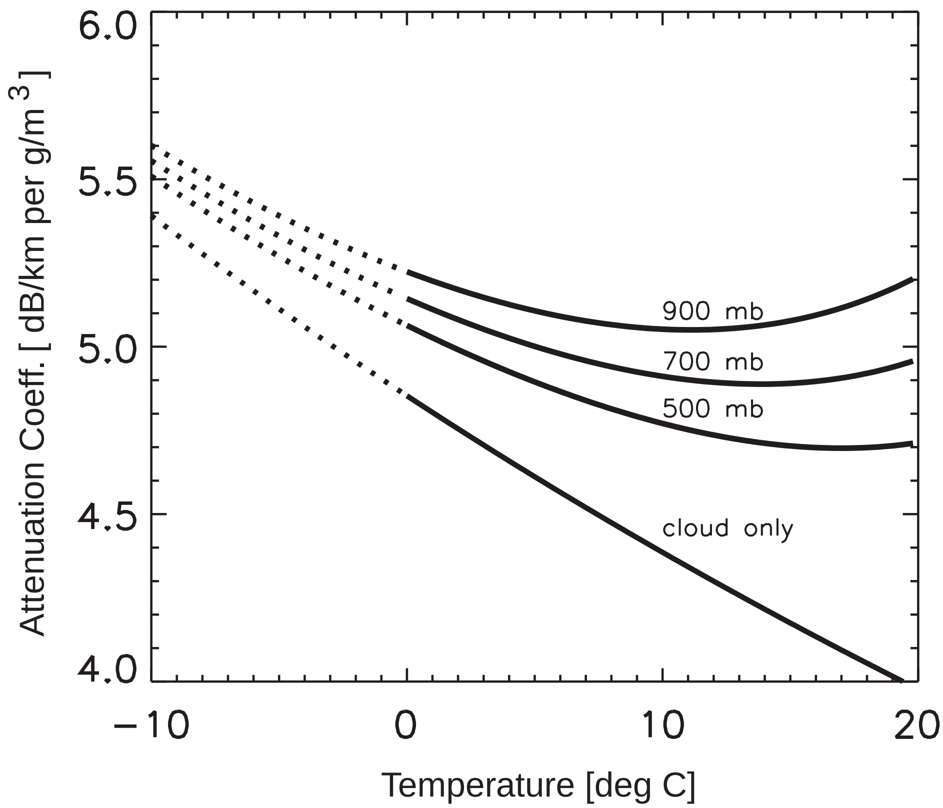


Figure 3. Calculated attenuation by cloud and vapor at 95 GHz.

IV. MEASURED ATTENUATION AT 95 GHz

A. Cloud Characteristics

The data processed for this analysis were collected in stratus clouds of 150 m to 300 m vertical depth off the coast of Oregon, during September 1995. A detailed analysis of the cloud characteristics is given in [3]. The clouds consisted of unbroken layers in the area of the observations, about 50 km offshore. Horizontally-averaged LWC increased monotonically from cloud base to near cloud top. Light drizzle with dropsizes <300 μm diameter was present in all cases. Flight segments of 5 to 10 km length at constant altitudes are used in the analyses; regions were selected that exhibited the lowest degree of fluctuations in LWC and in dropsize distributions. Figure 4a shows a representative example of the observed LWC for one data segment, with each point in the graph representing LWC averaged over 9-10 m horizontal distances. The standard deviation of these LWC values is 29% of the mean. The size distribution of drops averaged over the same data segment is given in Fig. 4b.

The steep slopes of the observed size distributions past the major modes have important consequences for this study. First, a predominant portion of the LWC, 83% in the example shown, resided in droplets smaller than 50 μm diameter. This is the size indicated by a dotted vertical line in Fig 4b. The mass-median diameter for the dominant part of the LWC was <20 μm in all cases. The 50 μm limit is often used to separate cloud droplets of negligible fall velocity from drizzle drops. Thus, the microwave attenuation was dominated by cloud droplets, not by drizzle, in the cases studies. Second, there was sufficient drizzle in the clouds to produce reflectivity variations much in excess of that due to cloud droplets, i.e. the patterns shown in images such as Fig. 1 were caused by variations in the concentrations and sizes of drizzle drops. The combination of these two factors provided a relatively uniform attenuating medium with superimposed backscatter from larger drops which by themselves contributed little attenuation. If the LWC had an uneven distribution such as that of the reflectivity field, the noisiness of the range dependence of mean reflectivity would have degraded the accuracy of the derived attenuation values significantly.

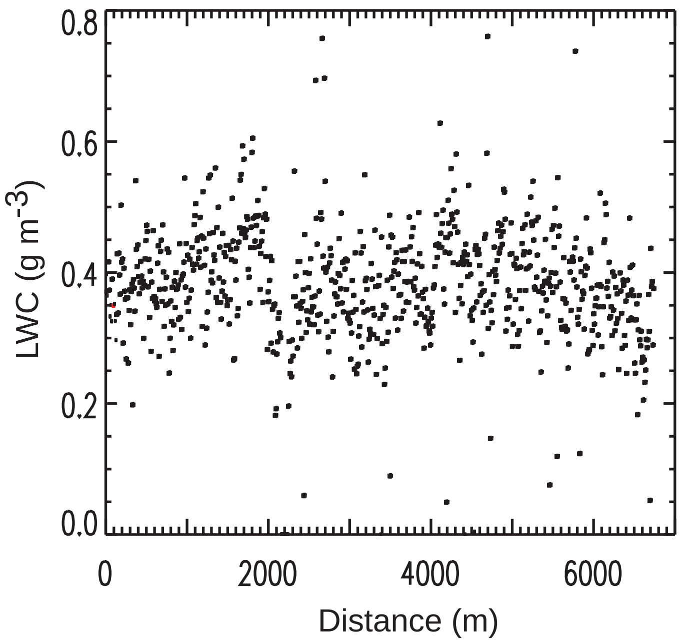
Mean values of the LWC for the 13 data segments analyzed ranged from 0.05 to 0.8 g/m^3, with corresponding changes in mean drop sizes. Temperatures were between 10° and 13°C; the pressure level of the observations was near 900 mb for all cases.

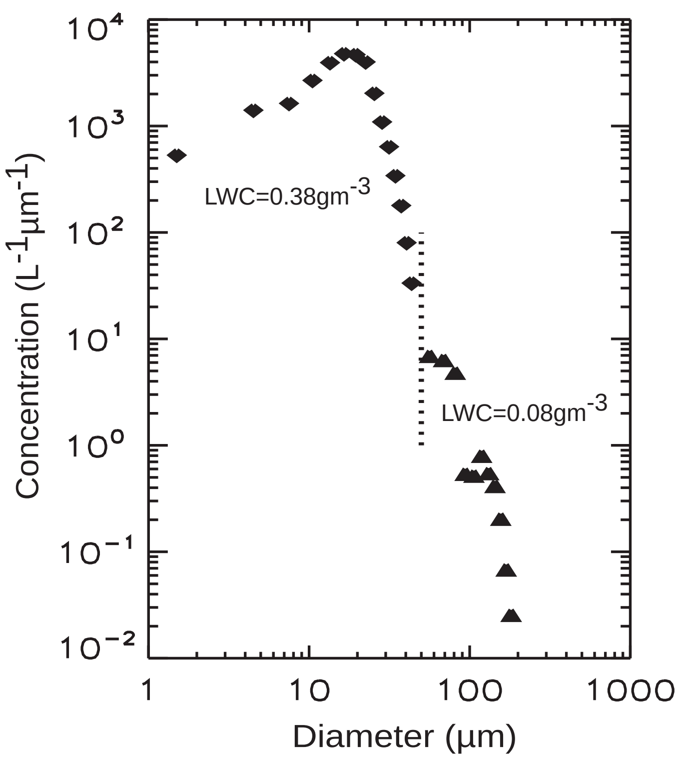
B. Data Processing

The estimate of the extinction coefficient was derived from the reflectivity measurements based on the assumption that the LWC fields were isotropic in horizontal planes, i.e. having the same mean in the direction perpendicular to the flight track as along the flight track. This homogeneity was required to extend to 1-2 km distances from the flight track, whereas the observed homogeneity along the flight tracks extended over 5-10 km distances. Also, other flight legs were usually available to ascertain that there were no significant gradients in cloud characteristics in any direction near the study region. The reflectivity images such as those in Fig. 1 also support the assumption of isotropy.

Thirteen data segments totaling 37 minutes (~200 km) of flight through clouds were chosen for processing.

First, to avoid excessive noise contribution the data were thresholded with three standard deviations of the noise signal. Second, since the average signal decreases with range, the maximum distance along the radar beam included in the analysis was determined by requiring that noise points account for no more than 10% of the total points at the furthest range gate. Next, for every range gate up to the maximum range, the average reflectivity over all profiles in the data segment was calculated. Finally, an exponential fit was calculated using the average reflectivity for all allowed range gates; the slope of this fit yielded the observed two-way attenuation for the case (Fig 4c). Correlation coefficients were required to be >0.9 for the result to be accepted. In addition the stability of the slope was examined by performing the fitting procedure over different numbers of range gates up to the maximum range.


0.8
0.6
0.4
0.2
0.0
LWC (g m-3)
0
2000
4000
6000
Distance (m)


10⁴
10³
10²
10¹
10⁰
10⁻¹
10⁻²
Concentration (L-1μm-1)
LWC=0.38gm-3
LWC=0.08gm-3
1
10
100
1000
Diameter (μm)

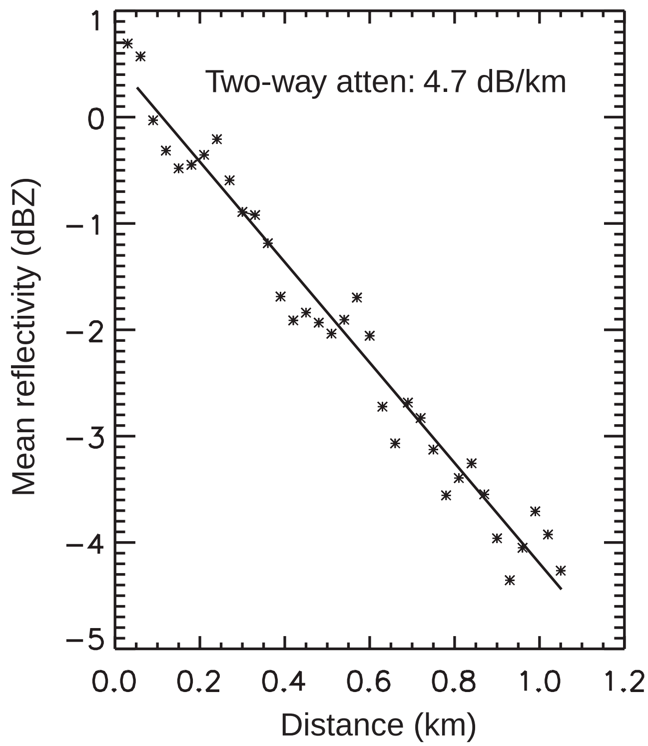


Figure 4. Data samples of LWC (a), particle size distribution (b), and two-way attenuation determined from the rate of decrease of the mean reflectivity with horizontal distance (c). Data were collected on September 16, 1995 between 23:00:29 and 23:01:44 UTC off the central coast of Oregon.

C. Results

One-way attenuation values obtained from 13 flight segments are shown in Figs. 5 and 6. The individual points in Fig. 5 indicate the LWC values for which attenuation was evaluated. A linear fit between the extinction coefficient and the measured LWC is indicated by the dotted line; this line yields an extinction coefficient of 4.6 dB/km per g/m^3. The linear correlation coefficient is close to 0.9. The full line in this figure represents the 4.4 dB/km per g/m^3 extinction predicted in [6]. The y-intercept of the fitted line represents the contribution made by water vapor absorption.

The scatter of points in Fig. 5 is one indication of the precision of the empirical attenuation determinations. While most points fall within <0.5 dB/km of the best fit line, there are two outliers showing significant discrepancies. No clear reason can be assigned to this discrepancy at this time; it is most likely a result of unusual cloud droplet spectra and accompanying errors in the derived LWC’s.

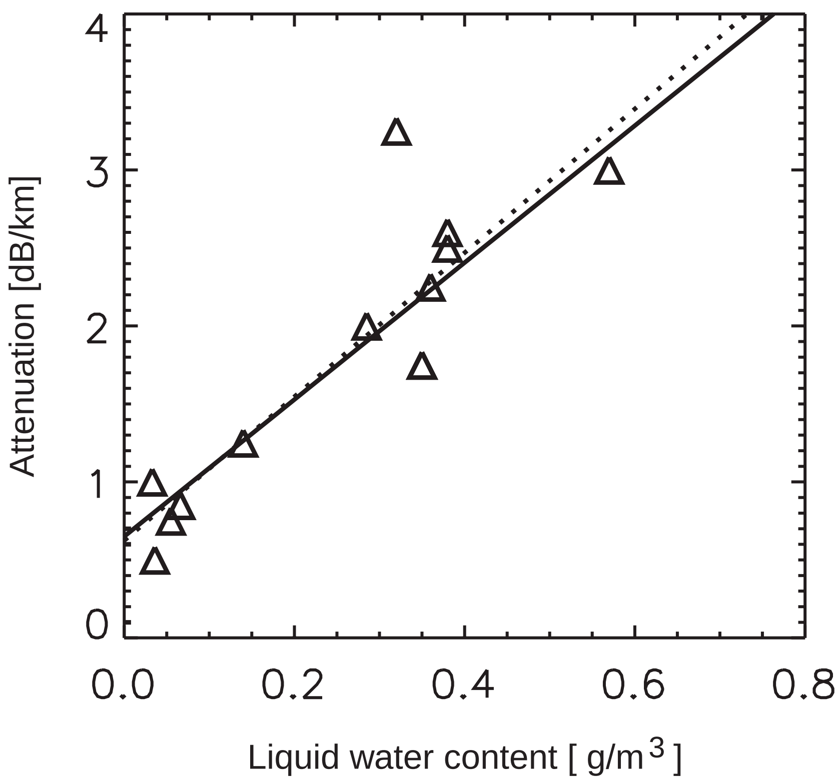


Figure 5. Linear fit of measured attenuation (dotted line, 0.62+4.6∗LWC) and Liebe et al [6] model (solid line, 0.65+4.4∗LWC).

Measured and calculated attenuations for individual cases are compared in Figure 6. Agreement between theory and observation is comparable to the scatter exhibited by the measurements.

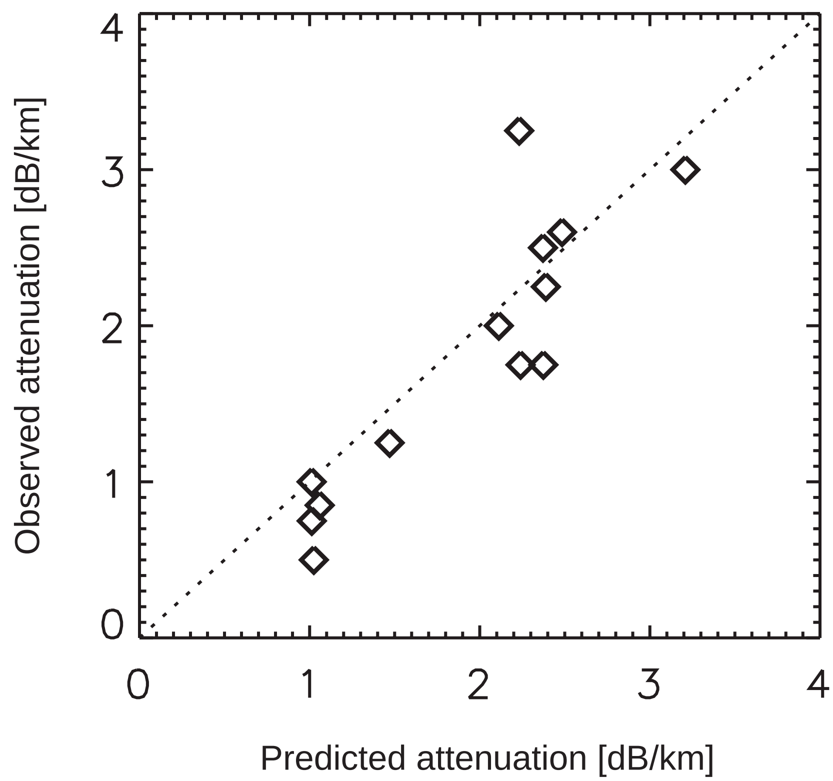


Figure 6. Comparison of measured and calculated attenuation for 13 cases in Oregon stratus.

IV. CONCLUSIONS

Measurements of 95-GHz microwave attenuation were obtained in maritime stratus clouds consisting of cloud droplets < 50 μm diameter and with drizzle drops of < 300 μm diameter. For temperatures around 10°C and pressures close to 900 mb, the one-way attenuation in dB/km was found to be linearly dependent on LWC, expressed by the relationship: *0.62 + 4.6∗LWC*, where 0.62 dB/km represents absorption by water vapor. The measured extinction coefficient of 4.6 dB/km per g/m^3 is within 5% of the value predicted in [6]. The 0.62 dB/km value for vapor absorption is also in within 5% of the value derived for 900 mb and 10°C from the equation given earlier and shown in Fig. 2. This confirmation of the vapor absorption and of the theoretical attenuation estimates for liquid water, for at least one set of pressure and temperature conditions, and for the range of LWC encountered in this study, provide support for the use of those estimates.

We derived the extinction coefficient from measurements in clouds in which the dominant source of reflectivity patterns was the variation in the concentration of drizzle drops, while these drops contributed little to the total attenuation. In other words, local variations in extinction due to LWC were much smaller than the reflectivity patterns that are exemplified by Fig. 1. The method of evaluation we employed would be subject to further errors if the reflectivity and LWC fields were not decoupled in the sense indicated above.

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