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A Comparison of Cloud Attenuation Models Using Measured Cloud Data

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Abstract

Simultaneous measurements of surface atmospheric parameters and cloud liquid water are used to test and compare the accuracy of three different cloud models.

1. Brief Review of Cloud Attenuation Models

Numerous models for predicting the attenuation of electromagnetic waves propagating through clouds were developed over the years from a variety of theoretical and empirical methods. Cloud modeling for the purposes of assessing attenuation can be divided into essentially three different catagories: 1) attenuation is computed by using a Rayleigh approximation to Mie scattering theory [Gunn, East, 1954], [Staelin 1966], [Liebe, Manabe, Hufford, 1989]; 2) attenuation is directly correlated to surface absolute humidity [Altshuler, Marr, 1989]; 3) Meteorological data and computations are used to determine cloud liquid and then attenuation is computed using a slightly modified version of the catagory 1 models described above. [Slobin, 1982], [Dintelmann, Ortgies, 1989].

Although their mathematical form and predictions vary over a fairly large range, a parameter common to all models is the liquid water content of the cloud. Unfortunately, this fundamental parameter is also the most difficult to predict and to measure.

A detailed comparison of five prominent cloud models developed over the last forty years shows good agreement at frequencies below 40 GHz for light to medium clouds conditions [Gerace, Smith, 1990]. However, for heavy to very heavy clouds and frequencies above 10 GHz, the models diverge from each other.

The recent availability of radiometric measurements of atmospheric parameters and the worldwide availability of surface atmospheric measurements have inspired the development of new cloud attenuation models. These new models strive to relate surface atmospheric measurements to cloud attenuation. The overall underlying assumption is that the liquid water content of clouds is in some way related to the water vapor present at the earth's surface.

This paper describes how three of these new cloud models perform on a cloud event that was *in no way related* to the empirical data used to develop the models. The preliminary results presented below are an attempt to qualitatively verify both the mathematical cloud models (types 2 and 3) and the latest methods available for extracting data from an independent cloud event. A complete statistical analysis is forthcomming when we complete our analysis using cloud data measured at numerous sites worldwide.

We begin by introducing the Altshuler-Marr, Dintelmann-Ortgies, and GSW cloud attenuation models and briefly discussing a method for measuring cloud liquid water. We then present our methods for comparing the models along with graphical results. The results are also cross checked with the well established Slobin cloud models [Slobin, 1982].

2. Altshuler Model

By correlating data of absolute surface humidity with measurements of zenith cloud attenuation in the Boston area, Altshuler derived the following empirical model for a nominal cloud temperature of 10°C [Altshuler, 1989]:

$$\alpha=\left[-0.0242+0.00075\lambda+\frac{0.403}{\lambda^{1.15}}\right](11.3+\rho) \quad (1)$$

where

α=zenith attenuation (dB)
λ=wavelength (mm)
ρ=surface water vapor density (g/m^3)

To account for elevation angles other than 90 degrees, eq. 1 must be multiplied by the following:

$$D(\theta)=\begin{cases} csc(\theta) \\ \left[(a_e+h_e)^2-a_e^2\cos^2(\theta)\right]^{\frac{1}{2}} \\ \quad -a_e\sin(\theta) \end{cases} \quad (2)$$

where

θ = elevation angle
a_e = effective radius of the earth (4/3 earth taken as 8497 km)
h_e = 6.35-0.302ρ effective cloud height (km)
ρ = surface absolute humidity (g/m^3)

While the Altshuler model is primarily an empirical model the next model is more appropriately classified as a semiempirical model.

3. Dintelmann-Ortgies Model

Using standard meteorological equations along with radiometer attenuation and concurrent meteorological measurements, Dintelmann and Ortgies derived the following semiempirical model for cloud attenuation prediction [Dintelmann, Ortgies, 1989]:

$$M=\rho_o\frac{T_o}{T}\left(1-\frac{\kappa-1}{\kappa}\frac{gH}{RT_o}\right)^{\frac{\kappa}{\kappa-1}}-3.82 \quad (g/m^3) \quad (3)$$

where

M = cloud liquid water (g/m^3)

T_0 = surface temperature

T = cloud temperature

ρ_0 = surface water vapor density (g/m^3)

κ = the ratio of the specific heat of water at constant pressure to the specific heat of water at constant volume (approximately = to 4/3)

g=acceleration of gravity (9.8 m/s^2)

R=gas constant for air (approximately 287 J/K-Kg)

H = height of the 0 degree isotherm (m)

The height of the 0 degree isotherm can be approximated by:

$$H=0.89+0.165(T_o-273) \tag{4}$$

where

T_o = Surface Temp. (K)

Then the attenuation through the cloud can be computed using an equation Dintelman borrowed from [Slobin, 1982]:

$$\alpha=\frac{4.343\cdot 10^{0.0122(291-T)-1}}{\lambda^2}\cdot 1.16M \tag{5}$$

where α is now in dB/km, T is the cloud temperature in Kelvin, and λ is the wavelength in centimeters.

To obtain the total attenuation through the cloud, Dintelman used radiometer measurements to obtain the following empirical formula for the cloud vertical extent:

$$\Delta=0.15-0.023M+0.0055M^2 \quad (km) \tag{6}$$

where M is the cloud liquid in g/m^3.

Inherent in this model is the assumption that clouds form around the 0°C isotherm. The next model attempts to refine the Dintelmann-Ortgies model by including a calculation aimed at predicting more accurately the altitude of cloud formation.

4. GSW Model

The altitude at which the actual water vapor density exceeds the saturated water vapor density for the temperature and pressure at that point is called the lifting condensation level. The GSW (initials of authors' last names) model assumes that this is the altitude at which clouds begin to form. The model can be described as follows:

The initial version of the GSW model assumes a linear adiabatic temperature lapse rate of 6 deg C per kilometer:

$$T(h)=T_o-\gamma T$$

$$\gamma=6^\circ/Km \tag{7}$$

Then a vertical saturated water vapor profile can be computed as follows:

$$\rho_s=\frac{e_s}{RT} \tag{8}$$

where e_s is the water vapor pressure and is given by the following formula due to [Nordquist, 1973]:

$$e_s=10^x \quad where$$

$$x=c_1-1.3816e^{-7\cdot 10^{p_1}} +8.1328e^{-3\cdot 10^{p_2}} -\frac{2949.076}{T} \tag{9}$$

where

$$p_1=11.344-0.0303998T \tag{10}$$

$$p_2=3.49149-\frac{1302.8844}{T} \tag{11}$$

$$c_1=23.832241-5.02808\log(T) \tag{12}$$

Now a vertical water vapor profile can be computed as follows:

$$\rho(h)=\rho_o\frac{T_o}{T}\left(1-\frac{\kappa-1}{\kappa}\frac{gh}{RT_o}\right)^{\frac{\kappa}{\kappa-1}} \tag{13}$$

One can compute the lifting condensation level by equating equations (8) and (13) and solving for the height, h. This is where the saturation vapor density equals the actual vapor density and is most likely the altitude at which the cloud begins to form.

Above the lifting condensation level, water vapor continues condensing as long as the actual vapor density exceeds the saturated vapor density. Loosely based on actual measurements of total integrated cloud liquid water and typical values of cloud liquid water densities, an estimate of the cloud liquid water content can be computed as follows:

$$M=\rho(h')-\rho_s(h') \tag{14}$$

where h′ is the altitude at which $\rho = 1.25\ \rho_s$.

Then cloud attenuation can be computed using equations 5 and 6 with equation 6 modified by multiplying all of the coefficients by a factor of ten. This factor of ten will most likely be refined as we average in more data sets from various sites to improve our model.

Next, we describe a method for measuring the amount of liquid water in a cloud.

5. Cloud Liquid Water Measurements

Radiometer measurements of atmospheric absorption at two frequencies, a water vapor sensitive frequency and a cloud liquid water sensitive frequency (say 20.6 and 31.65 MHz), can lead to a determination of total integrated cloud liquid water, L [Westwater, 1978]. The computation can be summarized as follows:

$$L=\frac{(-\kappa_{Vu}f_{l}+\kappa_{Vl}f_{u})}{(\kappa_{Vl}\kappa_{Lu}-\kappa_{Vu}\kappa_{Ll})} \quad (15)$$

where

$$f_{v}=-\tau_{dv}-\ln\left[\frac{(T_{mr}-T_{bv})}{(T_{mr}-T_{bb})}\right] \quad (16)$$

for v = l, u

where

κ_{Vu} = path averaged absorption coefficient of vapor at the upper liquid water sensitive frequency, u.

κ_{Lu} = path averaged absorption coefficient of liquid at the upper liquid water sensitive frequency, u.

κ_{Vl} = path averaged absorption coefficient of vapor at the lower water vapor sensitive frequency, l.

κ_{Ll} = path averaged absorption coefficient of liquid at the lower liquid water sensitive frequency, l.

T_{mr} = mean radiating temperature

T_{bb} = cosmic background "big bang" brightness temperature (2.8 K)

T_{bv} = measured value of the microwave brightness temperature at frequency, v.

τ_{dv} = dry absorption at frequency, v.

Measurements of cloud liquid water using the above algorithm are currently being made by the Wave Propagation Laboratory (WPL) of the National Oceanic and Atmospheric Administration (NOAA) at San Nicolas Isand, CA, and Denver Colorado. We are now intensively analyzing data that was collected throughout the 1980s. The results in this report are based on data taken in July 1984.

6. Method of Comparison

Figure 1 depicts our method of comparison. Using surface atmospheric measurements taken in Denver CO, cloud liquid water contents

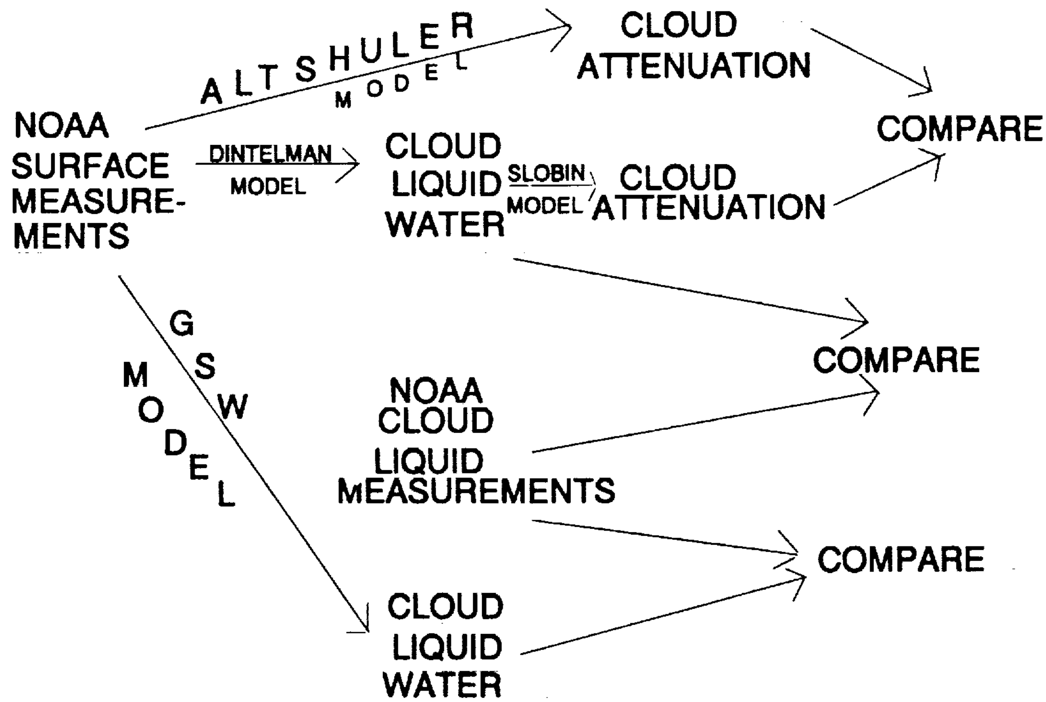

Figure 1. Method of Comparison

computed using the Dintelmann-Ortgies and GSW models were compared to measurements of cloud liquid present at the time the surface measurements were recorded. Attenuation predicted by the Altshuler model was compared to that predicted by the Dintelmann-Ortgies model (via the Slobin approximation discussed above).

7. Results.

A time series of the surface measurements taken during a sample cloud event is shown in figure 2. Figure 3 shows a comparison of the Dintelmann predictions to NOAA's measurements of cloud liquid water. Figure 4 shows a similar comparison for the GSW model. Note that the order of magnitude of the total integrated liquid (cm) for all three models is correct. However, the shape of the curves agree qualitatively only

during the last half of the three hour measurement period. Also note that the Dintelmann-Ortgies model predicts high liquid water content (g/m^3) and low vertical cloud extent as compared to the Slobin models described in figure 5. But the two effects sort of cancel each other out when computing the total integrated liquid (cm) because the units conversion from g/m^3 to cm is as follows:

$$M\left(\frac{g}{m^3}\right)=\frac{10M\,(cm)}{\Delta(Km)} \tag{17}$$

where M is the cloud liquid and Δ is the extent of the cloud.

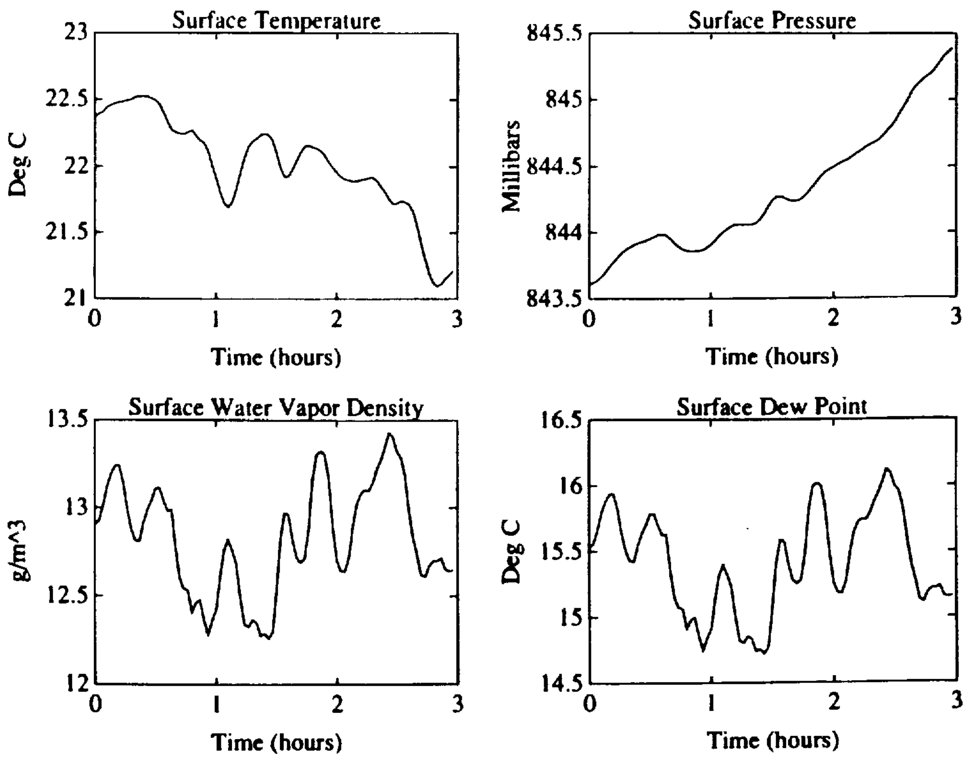

Figure 2. Surface Measurements of Atmospheric Parameters During the Cloud Event.

The GSW predictions are a little closer to the Slobin models but also exhibit some disagreement during the first half of the time period.

All of this probably points to some physical phenomena that is not being accounted for in these simple "state equation" models. Improvements in modeling the vertical temperature profile, for example, might help matters. We are currently using simultaneous measurements of vertical temperature gradients and cloud liquid to improve the model.

It is also of interest to note that the GSW model predicts the lifting condensation level to be a kilometer or so below the zero degree isotherm as shown in figure 6. We are now analyzing measurements of the lifting condensation level to improve cloud base altitude predictions.

A striking result is shown in figure 7. Although the Altshuler and Dintelmann-Ortgies models were derived quite differently, they predict almost identical cloud attenuation time series patterns during the cloud event. Note however that the absolute magnitudes and the dynamic range of the patterns do differ.

8. Continuing Work

The complexity of cloud physics and the lack of

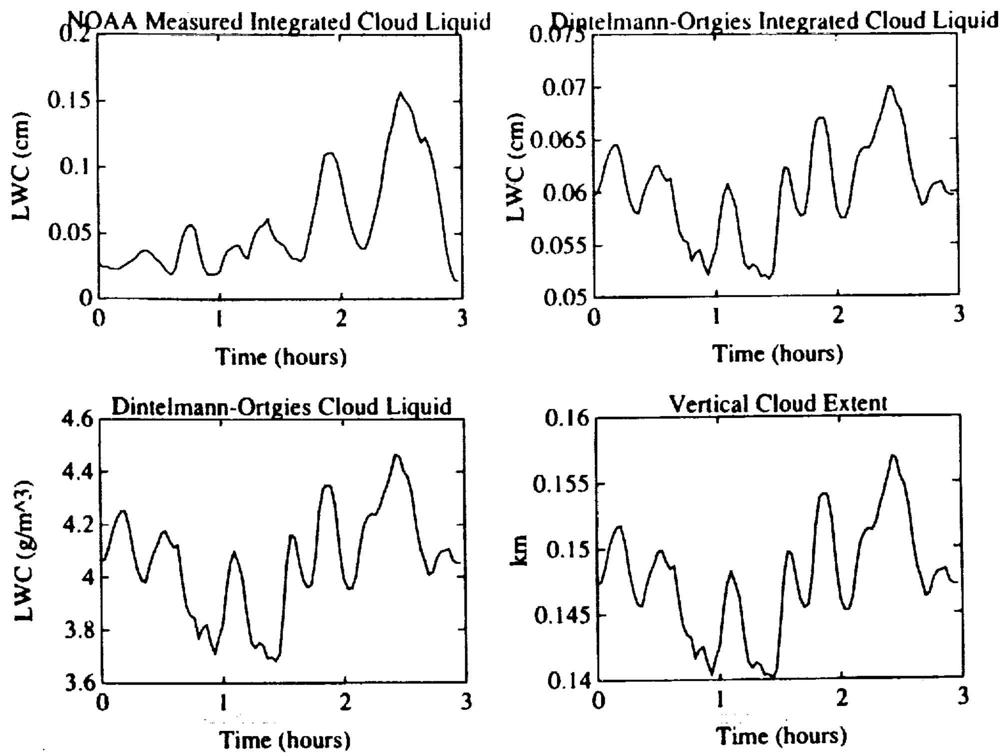

Figure 3. Cloud Liquid and Vertical Cloud Extent Predicted by Dintelmann-Ortgies Model and NOAA Measurements of Cloud Liquid.

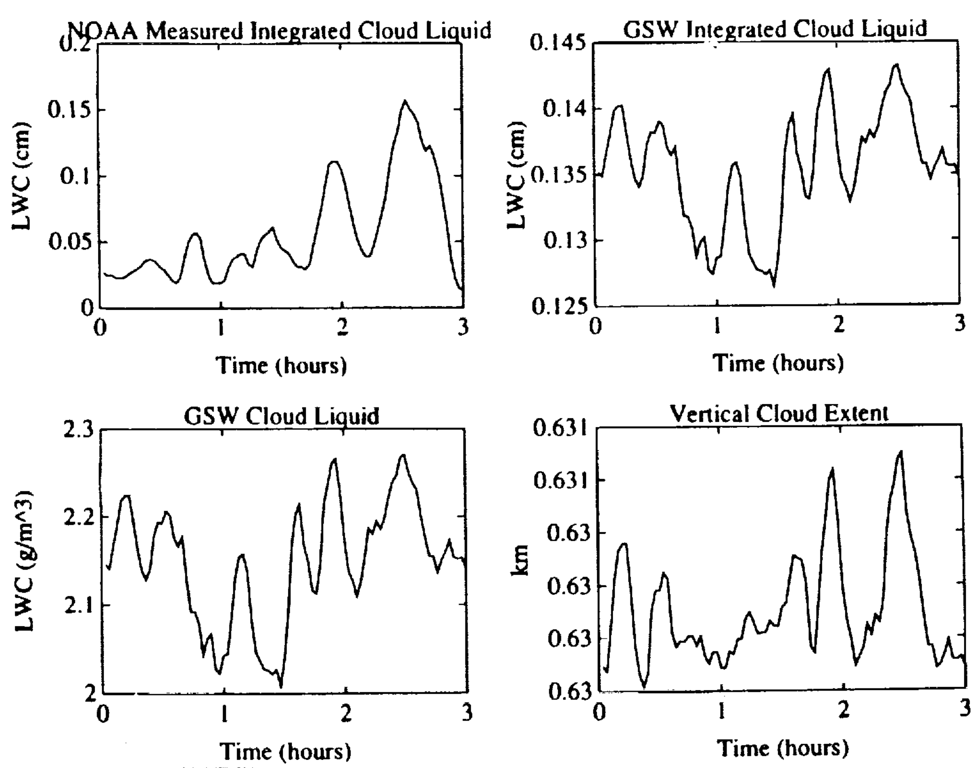

Figure 4. Cloud Liquid and Vertical Cloud Extent Predicted by GSW Model and NOAA Measurements of Cloud Liquid.

Sample Clear-Air and Cloud Models With Associated Zenith Microwave Effects

Case	Lower Cloud Density (g m^{-3})	Lower Cloud Base (km)	Lower Cloud Top (km)	Lower Cloud Thickness (km)	Upper Cloud Density (g m^{-3})	Upper Cloud Base (km)	Upper Cloud Top (km)	Upper Cloud Thickness (km)	10 GHz T (K)	10 GHz A (dB)	20 GHz T (K)	20 GHz A (dB)	30 GHz T (K)	30 GHz A (dB)	40 GHz T (K)	40 GHz A (dB)	50 GHz T (K)	50 GHz A (dB)
								Clear	*Air*									
1	...	...	...	...	...	...	...	...	3.05	0.049	14.73	0.232	13.76	0.219	23.20	0.383	78.14	1.481
								Light,	*Thin Clouds*									
2	0.2	1.0	1.2	0.2	...	...	...	...	3.22	0.052	15.37	0.242	15.20	0.242	25.67	0.424	81.17	1.545
3	...	...	...	...	0.2	3.0	3.2	0.2	3.28	0.053	15.60	0.247	15.72	0.252	26.55	0.441	82.22	1.572
								Light	*Clouds*									
4	0.5	1.0	1.5	0.5	...	...	...	...	4.12	0.066	18.80	0.298	22.84	0.367	38.53	0.646	96.63	1.892
5	...	...	...	...	0.5	3.0	3.5	0.5	4.50	0.073	20.24	0.326	26.01	0.430	43.73	0.758	102.57	2.067
								Medium	*Clouds*									
6	0.5	1.0	2.0	1.0	...	...	...	...	5.27	0.084	23.12	0.370	32.29	0.529	54.05	0.934	114.68	2.342
7	...	...	...	...	0.5	3.0	4.0	1.0	6.06	0.098	26.06	0.428	38.57	0.660	63.97	1.168	125.42	2.708
								Heavy	*Clouds*									
8	0.5	1.0	2.0	1.0	0.5	3.0	4.0	1.0	8.25	0.133	34.10	0.566	55.40	0.970	89.96	1.719	153.47	3.569
9	0.7	1.0	2.0	1.0	0.7	3.0	4.0	1.0	10.31	0.166	41.42	0.700	70.06	1.271	111.21	2.254	174.40	4.404
10	1.0	1.0	2.0	1.0	1.0	3.0	4.0	1.0	13.35	0.216	51.97	0.900	90.17	1.722	138.36	3.055	198.77	5.656
								Very	*Heavy Clouds*									
11	1.0	1.0	2.5	1.5	1.0	3.5	5.0	1.5	19.66	0.326	72.67	1.338	126.26	2.708	181.57	4.908	232.20	8.395
12	1.0	1.0	3.0	2.0	1.0	4.0	6.0	2.0	26.84	0.457	94.35	1.864	159.18	3.891	214.08	6.912	251.92	11.682

Cases 2-12 are clear air and clouds combined.

Figure 5. Slobin Cloud Models [Slobin, 1982].

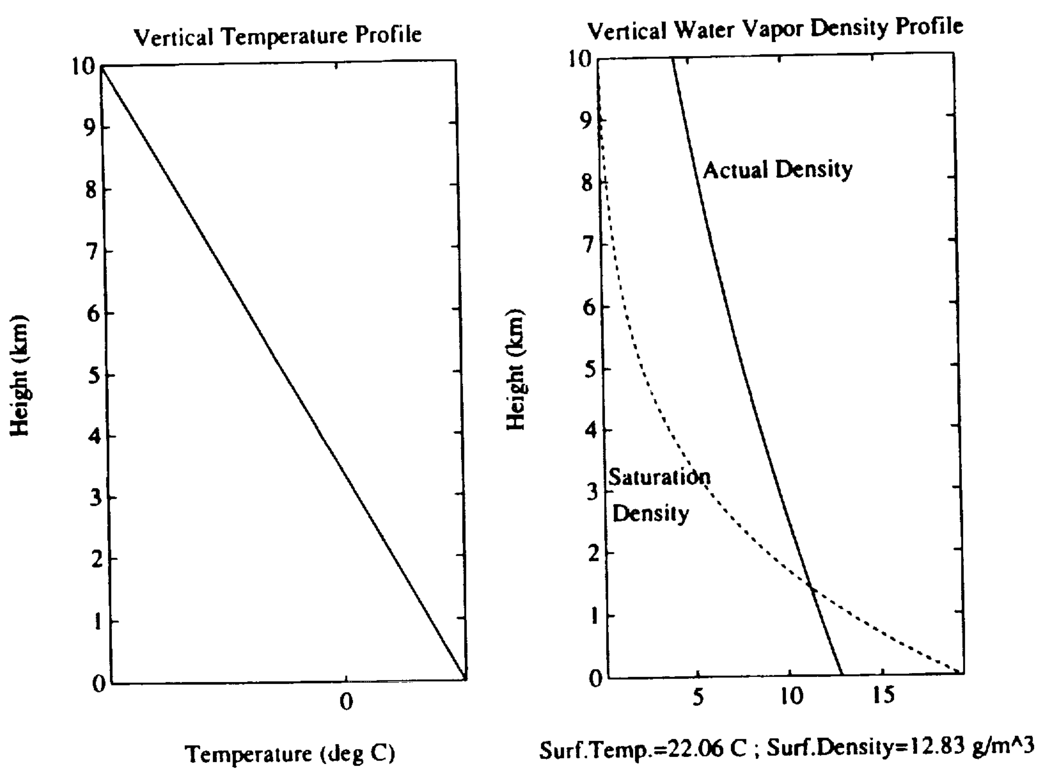

Figure 6. Vertical Profiles of Temperature, Saturation Water Vapor Density, and Actual Water Vapor Density as Predicted by the GSW Model.

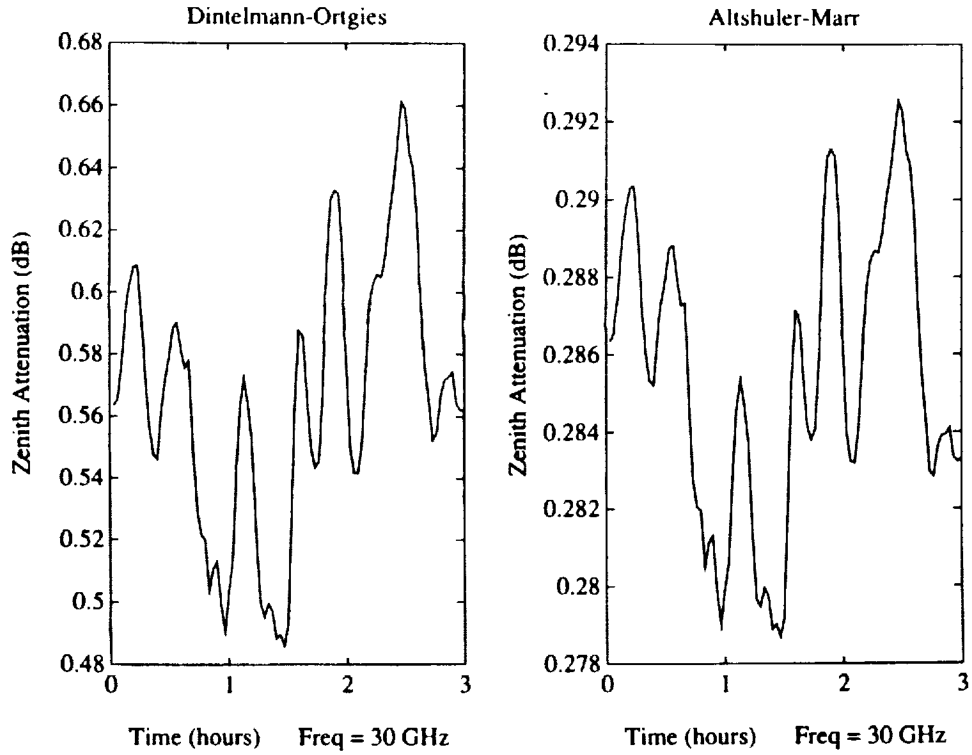

Figure 7. Comparison of Zenith Attenuation Predicted by the Dintelmann-Ortgies and Altshuler-Marr Models.

measured data has always hampered cloud liquid research. Now as data begins to trickle in, we are seeing the beginnings of a new cloud liquid science--a blend of theory and experiment. The models presented here are a building block toward the understanding of cloud attenuation. As we continue working with more data sets at various locations, we are seeking to improve temperature profiling and condensation level predictions. Gradually we hope to incorporate and validate more detailed cloud physics to describe the condensation and mixing processes associated with clouds. We openly welcome your critiques and ideas.

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