Observations of Attenuation Due to Liquid-bearing Stratocumulus Clouds over Ottawa Using a Ground-Based Profiling Radiometer

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Abstract—Statistics on the attenuation due to non-precipitating, liquid-bearing overcast stratocumulus (Sc) clouds over Ottawa during the daytime are presented in this paper. Time series of Sc cloud attenuation are extracted from the brightness temperature data and retrievals from a ground-based multifrequency profiling radiometer. Frequencies of interest are 30 and 51.25 GHz; four elevation angles between 15 and 90 degrees (zenith) are considered. Both the MPM '93 and Rosenkranz models are used to assess gaseous absorption using retrieved profiles "topped up" with the closest in time radiosonde data from a local station. Since most of the clouds in the data set contain some supercooled liquid, these extracted cloud attenuation data are compared to predictions from various dielectric constant models for pure liquid water using both the contemporaneously-retrieved liquid water path data and temperature at the cloud base as inputs.

***Index Terms*—Attenuation measurement, clouds, microwave radio propagation, microwave radiometry.**

I. Introduction

CLOUD attenuation is one of the propagation impairments that become increasingly important to assess for reliable satellite communications in the Ka-band and above. All cloud attenuation models found in the literature use as input a limited number of macrophysical parameters like cloud thickness and horizontal extent, or a few microphysical parameters such as liquid water path or cloud liquid water density. These parameters are not routinely measured by weather stations. In this context, the Communications Research Centre Canada (CRC) in Ottawa has developed a method to extract cloud attenuation from sky brightness temperatures and retrieved atmospheric profiles measured by a multifrequency profiling radiometer (Radiometrics TP/WVP-3000) deployed at CRC. This instrument uses 12 channels, five in the K-band between 22.235 and 30 GHz for water vapour profiling, and seven in the V-band between 51.25 and 58.8 GHz for temperature profiling.

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It also features an infrared radiometer (operating between 9.6 and 11.5 μm) that measures the zenith cloud base temperature T_{ir}. The profiling radiometer can retrieve vertical profiles of temperature, humidity, and cloud liquid water every minute from the surface up to 10 km in height. It also retrieves both the liquid water path *(L)* and the water vapour path *(V)* continuously. The radiometer has automated elevation-angle scanning capability (currently looping through 15º, 27.45º, 45º and 90º).

II. Data set of low-lying stratiform, liquid-bearing clouds over Ottawa

A. Background and Motivation

The data set is composed of sky brightness temperatures and vertical profiles retrieved when non-precipitating liquid-phase and mixed-phase overcast stratocumulus (Sc) clouds were present over CRC between April 2005 and April 2006 during the daytime. According to the land cloud climatology of Warren and Hahn [1], stratocumulus clouds are among the most frequently occurring liquid-bearing types over a 5-degree by 5-degree box that includes the Ottawa area. Moreover, some of the cloud macro- and micro-physical properties measured over Ottawa are compared to the 6-year climatology of midlatitude low-level continental clouds from the ARM Southern Great Plains (SGP) Central Facility, Oklahoma, reported in [2]. To the best of our knowledge, this 6-year climatology is the only one available in the literature.

There are clearly differences in climate between CRC in Ottawa and the SGP Facility in Oklahoma. For example, winters are shorter and less rigorous in Oklahoma (with negligible snow depth) than those in Ottawa. Moreover, the annual mean temperature in Oklahoma City near the SGP Facility is higher than in Ottawa. However, a comparison of the CRC results with those from the SGP site increases the confidence in the data retrieved by CRC's profiler. A good agreement is found between the two locations for yearly averages of daytime liquid water path, cloud base and cloud top heights but differences are found in seasonal averages for these parameters, likely due to the above-mentioned dissimilarities in climate between northern Oklahoma and eastern Ontario.

B. *Criteria Used in the Data Set*

The data set used in this paper consists of the author's daytime observations of overcast Sc in the sky above the profiling radiometer deployed at CRC. The key criteria used to create the data set reflect much those used in [2]:

1) No mid-level clouds overlie the Sc. The shape of the retrieved relative humidity profile provides the necessary evidence to identify such cases.
2) The total cloud amount is either 7 or 8 octas (overcast).
3) The measured cloud base heights of Sc are less than 2 km, consistent with the WMO definition in temperate regions [3].
4) Cloud top heights computed using CRC's cloud detection algorithm [4] are less than 4 km (as in [2]).
5) The retrieved liquid water path is less than 1 mm. Higher values for L are inevitably observed during rainy periods or in advance of rain or drizzle episodes when large liquid water drops aloft have not yet reached the surface and wetted the profiler radome. These large drops rescatter radiation, increasing the brightness temperatures over what would be measured from thermal emission alone [5]. The profiler neural network was trained with absorption models only.
6) Cloud observations during precipitation – either rain, drizzle or even light snow – are omitted.
7) Retrieved L values (L_{retr}) are rejected if they are superadiabatic, i.e., if the ratio $|L_{ad} - L_{retr}| / L_{ad} > 0.1$ where L_{ad} is the estimated adiabatic liquid water path [6].
8) All of the 457 profiles selected satisfy all of these criteria. Retrieved L values range from 0.05 mm to 0.55 mm, very much like those found in [2]. More details on the Sc data set can be found in [7].

III. Extraction method for cloud Attenuation

Frequencies of interest are 30 GHz and 51.25 GHz, given their range and sensitivity to cloud liquid. The method used to extract time series of cloud attenuation from time series of total attenuation derived from sky brightness temperature (T_b) data is as follows:

1) The total attenuation A_{tot} due to gases and clouds is calculated using the well-known relationship [8]:

$$A_{tot} = 10\, log_{10}\left(\frac{T_{mr} - T_c}{T_{mr} - T_b}\right) \quad (dB) \qquad (1)$$

where T_{mr} is the effective medium temperature (K) and T_c is the cosmic microwave background temperature, usually assigned a value of 2.73 K. The effective medium temperature is computed using the Rosenkranz 2007 model [9] with composite (retrieved plus radiosonde) profiles as input data. The retrieved cloud liquid profiles from the surface up to 4 km are also taken into account in the computation of T_{mr}.

2) Both the Rosenkranz 2007 [9] and the MPM'93 [10] models are used to assess gaseous absorption A_g. Input data for these models consist of retrieved profiles of temperature and humidity (from the surface up to 10 km) and reconstructed pressure profiles (0-10 km) obtained by solving the hydrostatic equation for thin layers of moist air. All of theses retrieved profiles are "topped up" with the closest in time radiosonde profiles from the Maniwaki station (WMO 71722) from 10 km up to the altitude at which the radiosonde balloon punctured (typically around 30 km).
3) Attenuation due to non-precipitating clouds $A_c(t)$ at a time *"t"* is given by $A_c(t) = A_{tot}(t) - A_g(t)$.
4) All profiler retrievals are computed based on zenith measurements of sky brightness temperatures (T_b). Measurements of slant T_bs cannot be exactly concurrent with zenith retrievals of liquid water path. Thus, natural cubic spline temporal interpolation of L, $A_g(t)$ and T_{mr} is used to estimate slant $A_c(t)$ at times when non-zenithal measurements of T_bs take place. The liquid water path L at a given elevation angle θ is estimated by multiplying this interpolated value of L by the cosecant of θ.

IV. Predictions From Two Gaseous Absorption Models at 30 and 51.25 GHz Under Clear Sky Conditions

As a check of the extraction method outlined above, a comparison was made between measured and modeled A_g using 1721 retrievals under clear sky conditions (i.e., 100% free from visible cloud) during the same period (April 2005-April 2006). At 30 GHz, the Rosenkranz 2007 model has the lowest bias and RMS error compared to observations ($A_{tot} = A_g$ under clear sky) at the four elevation angles considered (15°-90°); at 51.25 GHz, the MPM '93 model provides the closest match to the observations (i.e., has the lowest bias and RMS error). This approach is used to select the most accurate gaseous absorption model because CRC does not routinely launch radiosondes. Moreover, the Maniwaki radiosonde station does not issue METARs. It may be interesting to note that Hewison *et al.* [11] drew similar conclusions on these two gaseous absorption models (more precisely, Rosenkranz '98 [12]) at 30 and 51.25 GHz by comparing *modeled* brightness temperatures from radiosondes launched in clear skies with *measured* brightness temperatures from a co-located TP/WVP-3000 during the Temperature, Humidity and Cloud (TUC) experiment.

V. Cloud Attenuation Modeling

A. *Current ITU-R Recommendation (P.840-3)*

The ITU-R recommends that the attenuation due to clouds at a given elevation angle θ for a given exceedance probability *"p"* be computed using [13]:

$$A_c(p,\theta) = \frac{K_l L(p)}{\sin\theta} \quad (dB) \qquad (2)$$

where K_l is the specific attenuation coefficient (dB/km)/(g/m^3) and $L(p)$ is the reduced liquid water path in mm. Coefficient K_l is currently based on the MPM '89 cloud module [14] and assumes that the cloud liquid is at 0°C. We use this physical model (2) with the contemporaneously-retrieved time series of non-reduced liquid water path and the measured temperature at the cloud base *(T_{ir})* – instead of the standard reference temperature of 0°C – as inputs to compute time series of predicted cloud attenuation.

B. Predictions from Various Dielectric Models for Absorption Due to Supercooled Cloud Liquid

Comparison tests with the original MPM '89 formulation [14] showed an overestimation compared to the measured cloud attenuation data. Thus, predictions for K_l from other dielectric models for liquid water were compared. Fig. 1 shows the results of such a comparison at 30 GHz for a wide range of temperatures using the following models: MPM '89 [14]; both the standard (quadratic) and the exponential formulations for the first relaxation frequency γ_1 [15] presented in the model of Liebe, Hufford, and Manabe [16]; the model of Rosenberg [17]; and the model of Meissner and Wentz [18]. In order to cover the full range of K_l values found in Fig. 1, predictions from both forms of the Liebe '91 model [16], as well as from the model of Meissner and Wentz, are compared.

Significant departures among models are visible in Fig. 1 for temperatures lower than -10°C. A similar behavior is observed at 51.25 GHz. Above 0°C the dielectric properties of liquid water can be adequately measured in the laboratory and a good number of measurements have been made over a wide range of microwave and millimeter-wave frequencies [16]. However the situation is less clear for supercooled liquid water. Nonetheless some laboratory data taken at about -8°C were used in the development of the Rosenberg model, according to [19]. Moreover, the model of Meissner and Wentz for pure liquid water used laboratory measurements at 9.61 GHz in the range between -21°C and 32°C as described in [20].

C. Abundance of Supercooled Liquid in Our Sc Data Set

In light of the above, we assessed the abundance of supercooled liquid in our data set of Sc. In 66% of the sampled clouds, all liquid was supercooled, since the cloud base temperatures were at or below freezing level. The cumulative distribution function of cloud base temperatures ranges between -10°C and 19°C, with a mean of -1.7°C, a median of -3.5°C and a standard deviation of 6.7°C. Fortunately, differences between dielectric models are not too large for temperatures higher than -10°C (see Fig. 1). Finally, by combining the cloud vertical structure as per the algorithm expounded in [4] with the contemporaneous temperature profiles, it was found that only 11% of the cloudy profiles found in the data had all liquid at temperatures above 0°C.

VI. Results and Discussion

A few representative results will now be presented. Cumulative distribution functions (CDFs) of measured and modeled cloud attenuation A_c at 30 GHz for 27.45° and 90° are shown in Figs. 2 and 3, respectively. The Rosenkranz 2007 model was used to assess both gaseous absorption and T_{mr}. Since periods of no Sc clouds are omitted, the vertical scale in Figs. 2 and 3 represents conditional probabilities when Sc clouds are present. Figs. 2-3 show a good general agreement but bias and RMS errors are larger for slant A_c than for zenith A_c. The conditional CDF of measured and modeled cloud attenuation at 51.25 GHz for 27.45° is presented in Fig. 4. Gaseous absorption was assessed using the MPM '93 model in Fig. 4, whereas the Rosenkranz 2007 model was once again used to assess T_{mr}. Slant A_c values of up to 1.2 dB and 3.2 dB are measured at 30 GHz and 51.25 GHz, respectively.

At both 30 and 51.25 GHz, the ITU-R model used in conjunction with the exponential formulation for γ_1 (Liebe '91) yields the lowest bias and RMS errors compared to measured (extracted) A_c. Predictions from both the Meissner and Wentz model and the standard formulation for γ_1 were very close since our data set contains only moderately supercooled cloud liquid.

The cosecant elevation angle of the ITU-R model performs fairly well but with increasing error as the angle is decreased. A reduction factor is needed at low angles.

Our extraction method will also be tested with a data set of overcast, non-precipitating, liquid-bearing altocumulus clouds over Ottawa.

Finally, some aircraft data from supercooled (especially for $T < -10$°C) stratiform clouds over Ottawa from the C3VP project (http://c3vp.org) will provide an independent measurement of cloud liquid (despite some temporal and spatial variability [19]). Comparison of these *in situ* data with contemporaneously-extracted cloud attenuation data from our profiler appears to be a practical way to assess the accuracy of various dielectric models for supercooled liquid water [16]-[18] given the dearth of suitable laboratory data.

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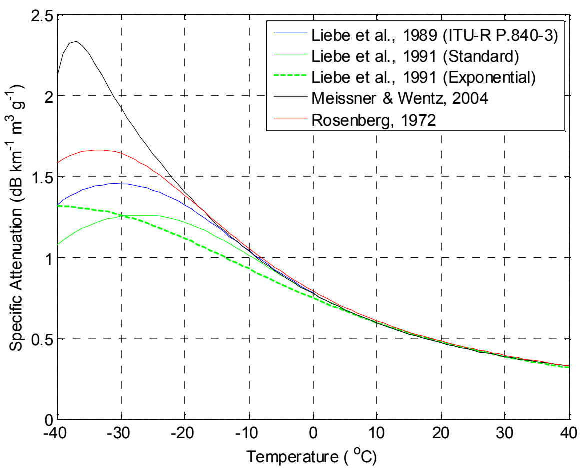

Fig. 1. Predictions for specific attenuation coefficient K_l from different dielectric models for cloud liquid water [14], [16]-[18] at 30 GHz for a wide range of temperatures. Significant departures among models are visible for supercooled liquid below -10°C. Similar behavior is observed at 51.25 GHz.

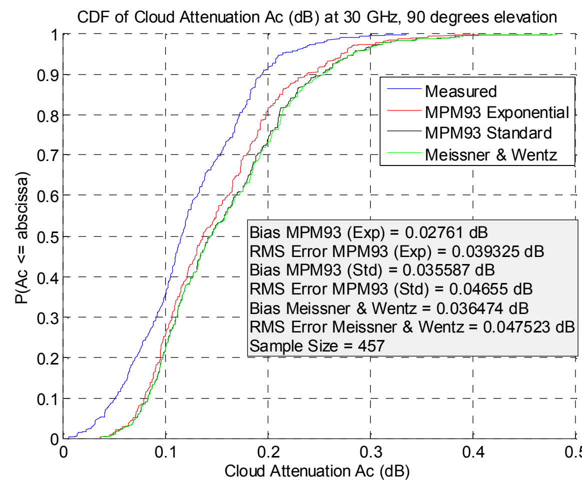

Fig. 3. Conditional CDF of measured (extracted) cloud attenuation at 30 GHz, 90°, for daytime Sc (April 2005-April 2006). Also shown are predictions of the ITU-R cloud attenuation model with K_l computed with both forms of the Liebe '91 model as well as the Meissner and Wentz model.

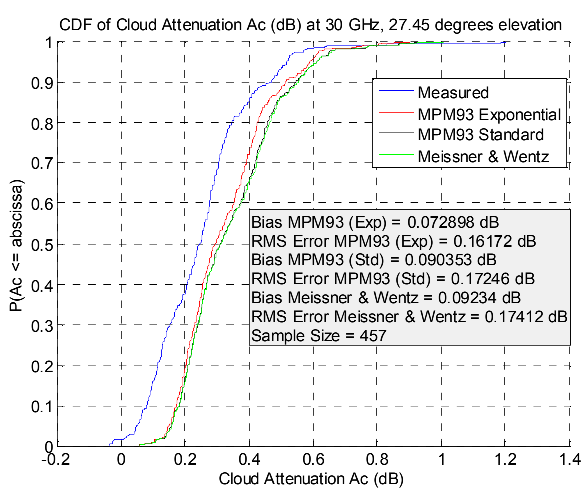

Fig. 2. Conditional CDF of measured (extracted) cloud attenuation at 30 GHz, 27.45°, for daytime Sc (April 2005-April 2006). Also shown are predictions of the ITU-R cloud attenuation model with K_l computed with both forms of the Liebe '91 model as well as the Meissner and Wentz model. The vertical scale represents conditional probabilities when Sc are present.

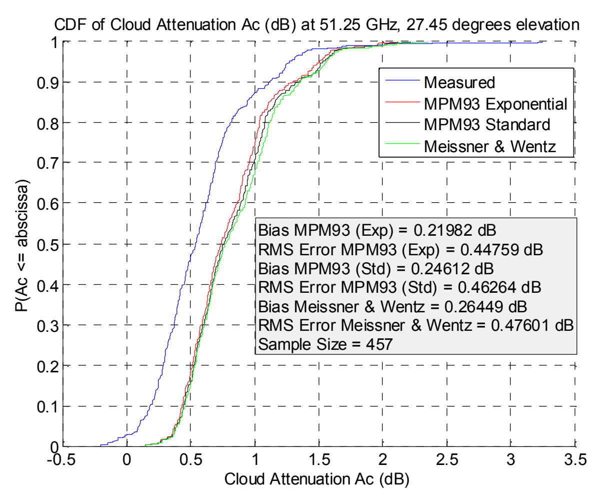

Fig. 4. Conditional CDF of measured (extracted) cloud attenuation at 51.25 GHz, 27.45°, for daytime Sc (April 2005-April 2006). Also shown are predictions of the ITU-R cloud attenuation model with K_l computed with both forms of the Liebe '91 model as well as the Meissner and Wentz model.