Comparison of measured cloud reflectivity at 95 GHz with reflectivity simulations from hydrometeor particle size distributions.

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1. Introduction.

The presented study is performed within the Megha-Tropiques (MT) project. Megha-Tropiques is a French-Indian satellite devoted to improve our knowledge on the understanding of the processes linked to the tropical convection. The relevant instrument on the satellite for cloud studies is the MADRAS microwave imager with 9 frequencies (18.7 GHz to 157 GHz). Two aircraft measurement campaigns (MT1 over West Africa in 2010 and MT2 over the Indian Ocean in 2011) have been performed with the French Falcon 20 in order to improve cloud microphysics parameterization and precipitation retrievals from the satellite data. The presented study is using solely MT1 data. Onboard the French Falcon aircraft, the French Doppler radar RASTA (Radar Aéroporté et Sol de Télédétection des propriétés nuAgeuses; with a frequency of 95 GHz: Protat & Al. 2009), the Cloud Imaging Probe (CIP), the Precipitation Imaging Probe (PIP) and the 2D Stereo (2DS).

In situ CWC mass has not been measured directly. After image data processing two types of composite particle size distributions (hereafter PSD) have been derived. The representation of PSD is given as a function of the equivalent diameter of a disc corresponding to the crystal surface (hereafter Deq), the second type of PSD is presented as a function of the maximum length of the particle (Dmax). Both PSDs are calculated for a 1 s and 10 s time resolution (PSD are handled in 10 µm bin resolution from 50µm to 6400µm).

Determining the mass of a particle is very difficult when its shape is not known. Baker and Lawson, (2006) presented a relationship between particle mass and geometric parameters derived from 2D particle images. Schmitt and Heymsfield (2010) showed that the fractal dimensions of aggregates are related with their mass.

The estimation of IWC in MCS systems over West Africa presented in this study is based on two slightly different approaches of IWC retrieval from simultaneous analysis of in situ cloud particle imagery and radar reflectivity measured at 95GHz with the cloud Doppler radar RASTA.

2. Method used to retrieve the mass-diameter relationship.

The reflectivity at 95 GHz is usually calculated, assuming the mass of the ice particles. Thus, our purpose is to estimate the mass-diameter relationship which produces the smallest deviations (equation 2) between the measured radar reflectivity (Z\text{MEAS}) and the equivalent reflectivity (Z\text{EQ}) calculated from the mass-diameter power law (equation 1). The diameter D stands either for the equivalent or the maximum diameter. In the present study the maximum error (cf. equation 2) has been set to 5%.

\[ m(D) = a D^\beta \]  
\[ \text{error (\%)} = 100 \left( \frac{Z_{\text{MEAS}} - Z_{\text{EQ}}}{Z_{\text{EQ}}} \right) \]

The equivalent reflectivity at 95 GHz can be calculated as shown in the equation 3, where Ki and Kw are the dielectric constants for ice and water. The PSD is represented with n(D) and the Mie scattering effect is described by the function f(D). However, this formula is difficult to implement, since the Mie scattering effect cannot be described by a simple equation. Therefore, to calculate properly the equivalent reflectivity we use an algorithm, where the Mie theory is applied on a sphere with a homogenous mixture of ice and air. The mixture is related to the mass-diameter law by the fact that the ice fraction is proportional to the mass of the ice in the particle divided by its mass if the particle would only consist of ice.

\[ Z_{\text{95GHz}} = \left( \frac{K_i}{K_w} \right)^2 \sum_D n(D) m(D)^2 f(D) \]
In this study we consider that the diameter-area law is equal to \( S_D = \gamma \cdot D_{\text{max}}^\sigma \) (eqn. 5).

The diameter-area law could be explained as the expected area (or mean area) for a given maximum length \( D_{\text{max}} \). An example of a diameter-area law is given in figure 1 and has been calculated using all particle images in a time interval of 10 seconds for one arbitrary flight of the MT1 campaign. We can see that the relationship between the mean area and the maximum length is well fitted with a power law. The diameter-area law shown in this figure has been calculated for 2D images recorded by the PIP probe in the size interval 1000µm and 6400µm. The calculated mean areas are represented by triangular symbols and the line corresponds to the fitted power law. The line above and below the data points represents one standard deviation.

Figure 1. Example of relationship for crystal mean area as a function of the maximum length for an ice crystal population of more than 200 analyzed crystals within a time period of 10 seconds. The particles have been recorded by the PIP probe.

3. Results.

In this first part of the results, we show findings obtained when fixing \( \beta \) equal to 2.1. In figure 2, the calculated coefficient \( \alpha \) of the power law is plotted as a function of the reflectivity measured by RASTA. The temperature measured in the corresponding cloud volume is color coding the data points. We can see that there is some temperature dependency in this figure. Low values of \( \alpha \) are particularly found for low temperatures, which is of course the result of having chosen a constant exponent \( \beta \) independently of the temperature and related to the clouds microphysics.

A reason to study area-diameter relationships from particle imagery is also to compare the in situ findings to the terminal velocity of the hydrometeors deduced from the reflectivity measured by the radar RASTA. Since area-diameter relationship is varying during a flight and since the area-diameter law of the particles is strongly influenced by the specific ice microphysics, different relationships between the \( \sigma \) exponent of the mass-diameter law and the \( \beta \) exponent from the area-diameter law have been tested. Figures 3 and 4 present the results obtained with the dataset from the MT1 campaign. The mass-diameter laws are calculated for the flights 15, 17, 18, 19, 20 with a time integration of 10 seconds. The PSD used have been built as a function of the equivalent diameter \( D_{\text{eq}} \) and the area-diameter law has been calculated using the 2D images monitored with the PIP probe. In figure 3 we can see the relationship between the condensed water content (equation 6; \( C_{\text{W}} \)) and the measured reflectivity \( (Z_{95GHz}) \). The data points are color coded with measured temperature. The resulting relationship is a power low which is influenced by the temperature (equation 7). For a given reflectivity, \( C_{\text{W}} \) increases with decreasing temperature. We can also conclude that a given \( C_{\text{W}} \) produces lowest reflectivities for lowest temperatures.

The subsequent relation in equation 8 resumes what is presented in figure 4. \( \alpha \) is written as a power law of \( \beta \) and with \( C_m \) and \( A_m \) both depending upon temperature. Overall, \( \beta \) increases (for given \( \alpha \)) with increasing temperature \( T \), whereas \( \alpha \) increases with decreasing \( T \) (for given \( \beta \)).

Finally figure 5 shows the impact on \( C_{\text{W}} \) retrievals when applying 6 different mass-diameter relationships. The figure is a zoom of 15 minutes of calculations for one exemplary flight (flight number 19). It shows results obtained with 4 different relationships between \( \sigma \) (from the area-diameter law) and \( \beta \) (from the mass-diameter law) calculated for PSD expressed in
terms of the maximum length Dmax and the area-diameter law calculated from the PIP probe (maximal length between 1000µm to 6400µm). To these four curves are added two curves. In one of these two curves CWC is calculated for PSDs expressed in terms of the equivalent diameter Deq with data from the PIP probe, whereas in the other curve CWC is calculated for Dmax, however for CIP data (maximal length between 500µm to 1600µm) derived area-diameter relationships.

The results of these 6 curves are rather similar and somewhat independent of the relationship between \( \sigma \) and \( \beta \), independent of the probe used for the area-diameter relationship and thus, the range of the particles used to calculate that relationship, and independently of the parameters (Dmax or Deq) of 2D images used to classified the particles to build up the PSD.

4. Conclusion.
To resume figures 3, 4, 5, we can state that the mass-diameter relationship is significantly influenced by the temperature. CWC calculated from the RASTA radar reflectivities using the Mie theory and applying different relationships for the mass-diameter relation, the results are approximately the same, if all (mD) relations have been constraint by the radar reflectivities. In fact, for any given value of \( \beta \), \( \alpha \) can be calculated to fit to the function given in equation 8. It is important to give the variations of the area-diameter law to the mass-diameter law. It seems that the area-diameter law is influenced by the temperature and some further parameters. More studies have to be performed in order to understand how the area-diameter law varies in clouds, and what are the most significant physical parameters controlling the calculation of the area-diameter law.

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References


