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ANALYSIS OF THE CLOUD DROPLET SIZE DISTRIBUTIONS OBTAINED DURING THE EMfiN!-ESN EXPERIMENT

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1. INTRODUCTION

It is well known that clouds play an important role in the climate and weather forecasts. At any instant, about half of the planet is cloud covered, making them very important in several atmospheric processes, like precipitation and radiant transfer, where they reflect incident solar radiation and absorb terrestrial infrared radiation, interfering directly in the earth energy budget.

Although this importance, its representation in the numerical models still depends on several parameterizations. The main reason for that is the high computational demand for the complete numerical microphysical description, causing the preference of the bulk parameterizations over the full bin microphysics. The main problem of the bulk microphysics resides on the fact that it uses empirical functions to represent the hydrometeor distribution functions, making the choice of them and its intrinsic parameters a key to successfully describe all the processes, like precipitation for example.

In this work, the cloud droplet size distributions (CDSD) obtained during the EMfiN!-ESN experiment are analyzed concerning its representation by the empirical functions of the bulk microphysical parameterizations and its small scale variability. The observed CDSD were divided in three categories: continental, urban and maritime, regarding their different regime of formation.

Four different empirical functions are adopted in this work: exponential (Marshal-Palmer), gamma, lognormal and Weibull. It is shown that the exponential function was unsuitable for most of the observed spectra, the gamma and lognormal ones were very similar, better than exponential one, and the Weibull provides the best fit. This result is in very good agreement to what was observed by Costa et al. (2000) for the same region and cloud types.

To assess the small scale variability of the CDSD, it is utilized the technique proposed by Rodi (1978) and Austin et al. (1985), that adopts the normalized variability coefficients. It is shown that all the observed CDSD presents a great variability concerning the shape and the total number concentration, what reveals the complexity of the in-clouds processes, giving an indication of turbulence and/or entrainment. All this variability imposes important limitations to bulk microphysical modeling as it requires even more sophisticated parameterizations that are allowed to vary in time and space.

2. THE EMfiN!-ESN EXPERIMENT

In order to obtain microphysical data for the tropical clouds and to assess the feasibility of cloud seeding, the EMfiN!-ESN experiment was held in Ceará state, located in the Northeast Brazil, a semi-arid region, during the 2002 rainy season, which comprehends the months of February to May.

The instrumentation used in this field campaign consisted of an instrument aircraft, meteorological radar and a radio-sounding station. The instrumented aircraft was an EMB110 Bandeirante, an non pressurized twin turboprop equipped with a GPS, temperature, pressure and liquid water content sensors, a cloud condensation nuclei counter and three spectrometer probes (FSSP-100, OAP-200X and OAP-200Y). The complete description of the aircraft could be found at de Almeida et al. (1992). In this work, the focus will be on the DMS FSSP-100 data, which consists of 10 Hz CDSD measurements. The probe was calibrated to categorize the spectrum in 15 diameter classes, ranging from 2 to 47 µm. Corrections for dead-time and coincidence were used (Baumgardner et al. 1985; Brenguier 1989; Brenguier and Amodei 1989).

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There were 6 flights in the total, all of them collecting microphysical data. The set of at least 5 s of continuous FSSP total concentration greater than 20 cm^{-3} will henceforth be referenced as a cloud. The obtained clouds were classified in three categories, according to their different regime of formation: continental, maritime and urban. The latter class is related to flights over Fortaleza city, the capital of the state, where anthropogenic effects are expected. The flight notation adopted here is YYYYMMDD-N, where YY represent the year, MM the month, DD the day and N the data file index. The number of clouds collected in each flight during the campaign is shown in Table 1.

Flight \ Class	Continental	Maritime	Urban
20020402-1	8	–	–
20020404-1	18	–	3
20020405-1	15	–	15
20020408-1	16	15	–
20020409-1	36	–	3
20020409-2	–	5	–
Total	93	20	21

Table 1. Total number of sampled clouds during each flight in the EMfiN!-ESN campaign, classified according their different regime of formation.

3. FITTING THE CLOUD SPECTRA

It is well known that bulk parameterizations that represent the microphysical processes in cloud models demands less computational effort than the complete numerical description of them. The success in simulating the microphysical processes using bulk schemes is, in general, case and model dependant.

The bulk microphysics uses empirical functions to represent the hydrometeor distribution functions. The choice of them and its intrinsic parameters represent a key to successfully describe all the processes, like precipitation for example.

There are several empirical functions in the literature that could represent the CDSD (Costa et al. 2000; Liu and Hallett 1998; Liu et al. 1995). Four different empirical functions are adopted in this work: exponential or Marshal-Palmer, gamma, lognormal and Weibull, as they are the most common distributions found in the numerical models.

The mathematical expression for the exponential distribution as a function of the diameter is

$$N(D) = (N_t / D_0)\exp(-D/D_0) \qquad (1)$$

where

$$D_0 = (q_l / \pi\rho_w N_t) \qquad (2)$$

represents the scale parameter, N_t the total number concentration, q_l the liquid water content and ρ_w the density of water.

The expression for the Gamma distribution is

$$N(D) = \left[N_t \left(1/\Gamma(\nu)\right)(D/D_0)^{\nu-1} \right] (1/D_0)\exp(-D/D_0) \qquad (3)$$

where

$$D_0 = \left\{6\left[\Gamma(\nu)/\Gamma(\nu+3)\right]\right\}^{1/3} \left\{\left[q_l/(\pi\rho_w N_t)\right]\right\}^{1/3} \qquad (4)$$

represents the scale diameter and the ν the shape parameter.

The Lognormal is represented by the following expression

$$N(D) = \left(N_t / \sqrt{2\pi}(\ln\sigma)\right)(1/D) \exp\left\{-1/2\left[\ln(D/D_0)/\ln\sigma\right]^2\right\} \qquad (5)$$

where

$$D_0 = \left\{\left[6 q_l \exp\left(-4.5(\ln\sigma)^2\right)\right]/(\pi\rho_w N_t)\right\}^{1/3} \qquad (6)$$

is the scale diameter and σ is the width parameter.

The Weibull expression is represented by

$$N(D) = N_t \mu (D/D_0)^{\mu-1}(1/D_0) \exp\left[-(D/D_0)^{\mu}\right] \qquad (7)$$

where

$$D_0 = \left\{\left[6/\left(\Gamma(1+3/\mu)\right)\right]\right\}^{1/3} \left[q_l/(\pi\rho_w N_t)\right]^{1/3} \qquad (8)$$

is the scale diameter and μ is the shape parameter.

It is beyond the scope of this work comparing the statistical properties of the observed spectra and the empirical functions. Instead, a direct and numerical comparison is made between them, with the criteria for considering an acceptable or good fitting is the one for which the root mean square difference between the fitted and the observed values of the CDSD is equal or less than 2% of the total number concentration, as suggested by Costa et al. (2000).

The observed CDSD were calculated for a time interval of 1 s, which corresponds to 80 m of flight distance inside the cloud.

Table 2 shows the number of good, or acceptable, and bad fittings for each category of sampled clouds. These results shown that the Gamma, Lognormal and Weibull distributions were able to represent the most of the sampled CDSD. Conversely, the exponential function represented only a small fraction of the CDSD, showing that it is not a good choice for bulk microphysics.

Function\Class	Fit	Cont.	Marit.	Urban
Exponential	Good	229	95	7
	Bad	1943	373	359
Gamma	Good	2119	453	353
	Bad	53	15	13
Lognormal	Good	2128	454	354
	Bad	44	14	12
Weibull	Good	2101	446	353
	Bad	71	22	13

Table 2. Number of good and bad fittings for each empirical functions, for each category of sampled clouds.

Table 3 shows how many times each empirical function provided the best fitting for each category of sampled clouds. Here, the adopted criteria for considering the best fitting is the one for which the root mean square difference between the fitted and the observed values of the CDSD is the lower one, observing the criteria of 2% from the total number concentration, as described above, represented by the "None of Above" line.

Function\Class	Continental	Maritime	Urban
Exponential	0	0	0
Gamma	735	118	169
Lognormal	582	203	85
Weibull	811	133	100
None of Above	44	14	12

Table 3. Number of times that each distribution function provided the best fitting. The criteria adopted was the lowest value of the root mean squared difference between the fitted and the observed values of the CDSD, that did not exceeded the 2% criteria.

It can be seen from Table 3 that the Gamma distribution provided the best fittings for most of the spectra in the urban regime of formation. The Lognormal was able to represent better the CDSD from clouds of the maritime category and the Weibull, the continental one.

These results above show that the choice of the empirical function to describe the observed CDSD in bulk microphysics is case dependant. The exception is the exponential one, which did not represent well the observed spectra.

Concerning the shape and scale parameters for each distribution, significant variations of them were observed. Table 4 shows the mean shape parameter (and standard deviation) for all empirical functions and sampled clouds. The exponential function was discarded because its bad fitting characteristic.

Function	Cont.	Marit.	Urban
Gamma	14.4 ± 9.1	9.4 ± 7.3	14.9 ± 7.9
Lognormal	1.3 ± 0.3	1.4 ± 0.4	1.3 ± 0.4
Weibull	4.0 ± 1.9	3.1 ± 1.5	4.0 ± 1.7

Table 4. Mean shape parameter (and standard deviation) for all empirical functions and sampled clouds.

These results show that the variability of the lognormal was the modest one, which agreed with the results obtained by Costa et al. (2000). However, they pointed out that this result could lead to an error when one assumes distributions with shape parameter fixed in cloud models. They have shown that the best results with prescribed values were obtained with the Weibull functions.

4. THE VARIABILITY COEFFICIENTS

The variability coefficient was first proposed by Rodi (1978) to assess the small scale variability inside clouds. It is defined by

$$C_N = \frac{\sigma_N}{\bar{N}} \tag{9}$$

Where N is the total number concentration, σ_N its standard deviation and $\bar{N}$ represents its time average. The time averages in this work are performed over an interval of 5 s inside the clouds.

Austin et al. (1985) showed that this definition could be applied not only to the total number concentration, but for any arbitrary measurement. They also proposed a new coefficient, the normalized variability coefficient, defined by

$$R_N = \frac{C_N}{C_N(\text{stable})} = \frac{\sigma_N}{\sqrt{\bar{N}}} \tag{10}$$

where *stable* means a Poisson distribution, which was the one expected when the variability inside clouds where due only to random fluctuations, like equipment noise.

The definitions above could also be applied to the variability on the CDSD shape. The variability coefficient for the shape, C_S, could be defined by

$$C_S = \frac{1}{\overline{N}} \sum_{i=1}^{15} \overline{f}_i C_{f_i} \qquad (11)$$

where $\overline{f_i}$ is the time average of the *i*-th FSSP channel, and $C_{f_i} = \sigma_{f_i} / \overline{f_i}$ is the variability coefficient for that channel.

The normalized variability coefficient for the CDSD shape could be defined as

$$R_S = \frac{1}{\overline{N}} \sum_{i=1}^{15} \overline{f}_i R_{f_i} \qquad (12)$$

where $R_{f_i} = \sigma_{f_i} / \sqrt{\overline{f_i}}$ is the normalized variability coefficient for the *i*-th FSSP channel.

With the coefficients defined, one must define a critical value to identify regions inside clouds where the variability is significant. Austin et al. (1985) utilized a critical value of 1.0. If $R_N > 1.0$ then the region was considered variable regarding the total number concentration. de Oliveira (1998) adopted a critical value of 1.3 for the shape and concentration variability coefficients. This work will adopt this latter critical value to define the regions.

Once the critical value is defined, one could establish 4 regions inside the clouds:

- Type 1: values of $R_N < 1.3$ and $R_S < 1.3$, representing an uniform region, either regarding total number concentration and the spectrum shape.
- Type 2: values of $R_N > 1.3$ and $R_S < 1.3$, representing variable region for the concentration and uniform for the spectrum shape.
- Type 3: values of $R_N < 1.3$ and $R_S > 1.3$, representing an uniform region for the concentration and variable for the spectrum shape.
- Type 4: values of $R_N > 1.3$ and $R_S > 1.3$, representing a variable region, either regarding total number concentration and the spectrum shape.

Region\Class	Cont.	Marit.	Urban
Type 1	22%	18%	16%
Type 2	13%	22%	10%
Type 3	5%	3%	1%
Type 4	60%	57%	73%

Table 5. Percentages of occurrence for each type of region inside the clouds during the EMfiN!-ESN campaign.

Table 5 shows the percentage of occurrence for each region on the observed CDSD, divided by sampled cloud categories.

It can be observed that most of the regions inside clouds are of type 4, representing regions with variability in the concentration and in the shape. It could be an indicative of processes like entrainment and turbulent mixing, as suggested by dos Santos et al. (2002).

5. CONCLUSIONS

In this work, CDSD obtained during the EMfiN!-ESN experiment were analyzed concerning its representation by the empirical functions of the bulk microphysical parameterizations and its small scale variability.

Significant differences were observed among clouds formed over different regions and different regimes.

It was shown that the Gamma, Lognormal and Weibull distributions were able to represent the most of the sampled CDSD. Conversely, the exponential function represented only a small fraction of the CDSD, showing that it is not a good choice for bulk microphysics. The choice of the empirical function to describe the observed CDSD in bulk microphysics was shown to be case dependant. These results are in very good agreement to what was observed by Costa et al. (2000) for the same region and cloud types.

To assess the small scale variability of the CDSD, it is utilized the technique that adopts the normalized variability coefficients. It was observed that most of the regions inside clouds are of type 4, representing regions with variability in the concentration and in the shape, that could be an indicative of processes like entrainment and turbulent, revealing the complexity of the in-clouds processes.

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