# Raindrop Size Distribution Over Northeastern Coast of Brazil

**Ricardo Sarmento Tenório, Byung-Hyuk Kwon and Marcia Cristina da Silva Moraes,** *Member, KIMICS*

***Abstract***—Precipitation measurement with ground-based radar needs an information of the raindrop size distribution (RSD) characteristics. A 10-month dataset was collected in tropical Atlantic coastal zone of northeastern Brazil where the weather radar was installed. The number of drop was mainly recorded in 300 – 500 drop $mm^{-3}$, of which the maximum was registered around 1.1 mm drop diameter.

***Keywords***—raindrop size distribution, rainfall rate, liquid water content, drop kinetic energy, radar reflectivity factor

## I. INTRODUCTION

The granularity of raindrops within a rain volume has been the focus of recent research projects such as the ones dealing with numerical simulation of pollutants scavenging and radar microwave electromagnetic energy dispersion by rainfall, represented by radar reflectivity factor. The raindrop size distribution (RSD) characteristics depend on the microphysical, dynamical and kinetic processes that interact to produce rain. They are the basis for the definition and computation of the major part of parameters involved in microwave propagation within clouds and rain. That is why many researchers, (e.g., Mashall and Palmer, 1948; Feingold and Levin, 1986; Zawadzki and Antonio, 1988; Willis and Tattelman, 1989; Sauvageot and Lacaux,1995; Sauvageot et al., 1999; Tenório et al., 1995, 1996, 2003; Smith and Kliche, 2005, Lee and Zawadzky, 2005) made efforts to understanding and modeling the raindrops size distribution. In general, RSD is given by a function N(D) that depends on the drop diameter (D) for a certain air volume. Functions with 2 or 3 parameters are employed for the statistics of such distributions. In this work, an exponential and a lognormal distributions were used to fit the RSD.

## II. EXPERIMENTAL SITE AND SAMPLING DATA.

The study was performed in the Campus A.C.Simões, Universidade Federal de Alagoas (UFAL), in Maceió (9°3′17.24″S, 35°46′54.84″W), located over a large flat area 80 m above sea level, known as tabuleiro costeiro (coastal plateau). The Campus is 13 km away from the coast line.

The experimental area is one of the rainiest in Northeastern Brazil (NEB), whose climate is influenced by warm Atlantic Ocean current (The Brazil Current) strongly. The wet season is from April to July with rainfall amounting to 60% of the year total. The dry season is from September to December, with only 10% of the year rain total. The large-scale rain producing mechanisms are frontal systems and high tropospheric cyclonic vortices. Wavy disturbances or perturbations in the southeasterly trade winds field are the mesoscale mechanisms responsible for the major portion of the mean year rain total. Small convective cells constitute the micro scale mechanisms (Molion and Bernardo, 2002).

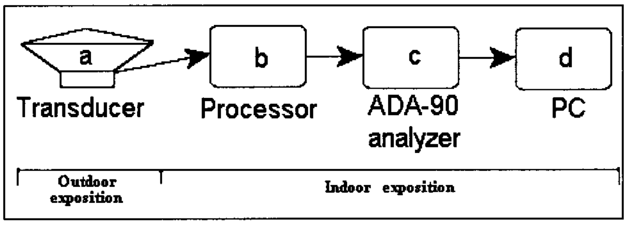

Fig. 1 Block diagram representation of the instrumental design for classifying raindrops.

Table1. Number of RSD sampled.

| Month/year | DTGs (per minute) |
|---|---|
| DEC/2001 | 250 |
| JAN/2002 | 1149 |
| FEB/2002 | 831 |
| MAR/2002 | 1185 |
| APR/2002 | 631 |
| MAI/2002 | 2423 |
| JUN/2002 | 1311 |
| JUL/2002 | 884 |
| AUG/2002 | 993 |
| SEP/2002 | 709 |
| Σ | 10,366 |

The disdrometer RD-69 (Figure 1(a) and 1(b)), made by DISDROMET LTD, has a sampling area of 50 $cm^2$ and it is sensitive to raindrop diameter ranging from 0.3 mm to 5.3 mm. The disdrometer measures the raindrop size and distribution by converting the impact of the raindrop into electrical pulses, whose amplitude is proportional to the drop size. The RD-69 is connected to an ADA-90 analyzer (Figure 1(c)) and this to a PC (Figure 1(d)). The part exposed to rain (Figure 1(a)) was

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installed on the roof and the reaming within the building of the Department of Meteorology (UFAL).

Data were collected during 10 month period (December 2001 to September 2002), that is, transition months prior to (December to March) and during the wet season (April to July). A total of 10,366 RSD (Table 1), integrated every minute, were recorded, which correspond to 172.76 h of rain sampling.

## III. METHODOLOGY

The software Disdrodata, developed by the instrument makers, is composed of two parts. In the main menu, the user selects the sampling options and some ancillary functions of rate of drops per minute and per diameter. The second part is the data recording and evaluation, where the RSD parameters are calculated. In this study, only the first part of the software was used, since the RSD were calculated using the software MATLAB, that requires feeding in a previously prepared rectangular numerical matrix. In the MATLAB, the number of drops with a diameter per unit of volume, corresponding to the class i, is calculated with the equation (1).

$$N(D_i)=\frac{n_i}{FtV(D_i)\Delta D_i} \qquad (1)$$

$D_i$ and $\Delta D_i$ are the raindrop mean diameter of class i and its class interval, respectively; F is the disdrometer sampling surface; t is the integration time interval, equal to 1 minute in this case; $V(D_i)$ is the fall speed of a drop with diameter $D_i$ and $N_i$ is the number of drop with diameter $D_i$. The rainfall rate (R), liquid water content (W), the drop kinetic energy (EK) and the radar reflectivity factor were calculated with the following equations

$$R=\frac{\pi}{6}\frac{3.6}{10^3}\frac{1}{Ft}\sum_{i=1}^{20}\left(n_i D_i^3\right) \qquad (2)$$

$$W=\frac{\pi}{6}\frac{1}{Ft}\sum_{i=1}^{20}\left(\frac{n_i}{V(D_i)}D_i^3\right) \qquad (3)$$

$$Z=\frac{1}{Ft}\sum_{i=1}^{20}\left(\frac{n_i}{V(D_i)}D_i^6\right) \qquad (4)$$

Two distributions, one with 2 and the other with 3 parameters, were used to representing the distribution of the drop number as function of diameter D. For the 2 parameter distribution it was used an exponential function (Marshall and Palmer, 1948) of the type

$$N(D)=N_0\exp(-\lambda D) \qquad (5)$$

where N(D) is the drop distribution as function of the diameter (D), $N_0$ is the number of drops, $\lambda$ is the distribution slope.

For the 3 parameter distribution, it was used a lognormal function (Sauvageot and Lacaux, 1995) of the type

$$N(D)=\frac{Nt}{(2\pi)^{0.5}(Ln\sigma)D}\exp\left[-\frac{Ln^2\left(D/D_g\right)}{2Ln^2\sigma}\right] \qquad (6)$$

where $N_t$ is the drop total number, $D_g$ is the mean diameter, $\sigma$ is the standard deviation and Ln in the natural logarithm function.

The data were stratified according to 8 rainfall rate classes for each month and for the total number of samples. The stratification is required since all RSD parameters are dependent on the rainfall rate (Sauvageot and Lacaux, 1995), Table 2 shows the classes of R selected.

Table 2 Stratification classes according to the rainfall rate.

| Sample name | rainfall rate classes (mm $h^{-1}$) |
|---|---|
| R1 | $R < 2$ |
| R2 | $2 \le R < 4$ |
| R3 | $4 \le R < 6$ |
| R4 | $6 \le R < 10$ |
| R5 | $10 \le R < 20$ |
| R6 | $20 \le R < 40$ |
| R7 | $40 \le R < 60$ |
| R8 | $R \ge 60$ |

## IV. RESULTS

The raindrop number, N(D), as function of the diameter (D) is shown in Figure 2 for the 8 classes listed in Table 2. There is a clear deficit of small droplets due to limitation of the disdrometer, remarked already, for example, by Ulbrich (1983), Feingold and Levin (1986), Sauvageot and Lacaux (1995), in tropical regions and more recently by Seifert (2005) revising the relation between the slope and shape parameters of the raindrop size distribution parameterized by a gamma distribution. The diameter of the first 3 classes did not exceed 5 mm and the maximum number of drop was always smaller than or equal to 2 mm of diameter. The number of drops equal to or larger than 5.3 mm was not recorded due to the upper limit of the instrument.

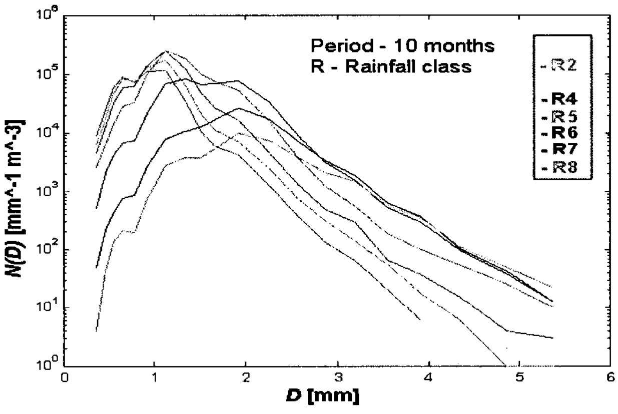


Fig. 2 Distribution of the number of raindrops N(D) as function of diameter D by classes and for the whole sampling.

### *A. SHAPE OF THE RAINDROP NUMBER DISTRIBUTION*

The shape of the RSD was analyzed by comparing the monthly rainfall rates of the same class. During the whole sampling period, the rainfall rate classes were similar in shape (Figure 3) but differ in drop quantity. Nzeukou et al. (2002), however, observed an almost perfect similarity when compared 4 years of data. So, this discrepancy may be due to the short sampling period (10 months). Another possible explanation is that the comparison was made between rainfall events of different seasons.

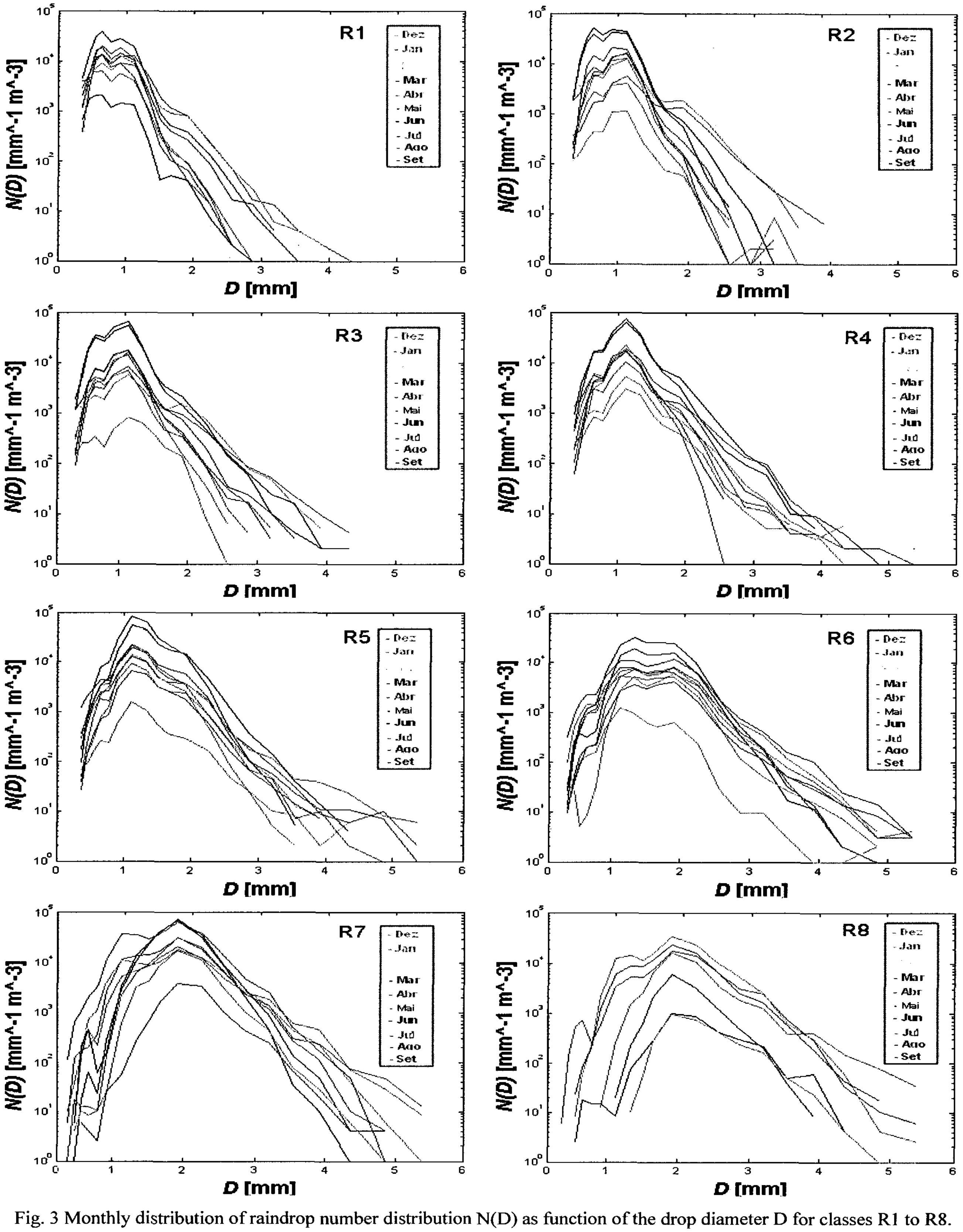


Fig. 3 Monthly distribution of raindrop number distribution N(D) as function of the drop diameter D for classes R1 to R8.

Table 3 Parameters of RSD exponential and log normal distributions for the whole sample.

| *Sample name* | *rainfall rate classes* | *DTGs number (1 min.)* | *R* | *W* | *Z* | *Exponential* | | *Log-normal* | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | (mm $h^{-1}$) | ($mm^{-3}/m^{-3}$) | ($mm^6m^{-3}$) | $N_0$ ($mm^{-1}$ $m^{-3}$) | λ ($mm^{-1}$) | $N_t$ ($m^{-3}$) | σ | $D_g$ (mm) |
| R1 | *R*<2 | 5726 | 0.02 | 0.0228 | 2.73 | 78.64 | 2.84 | 125.5 | 1.46 | 1.56 |
| R2 | 2≤*R*<4 | 1140 | 2.04 | 2.83 | 315.1 | 296 | 2.57 | 476.5 | 1.32 | 1.47 |
| R3 | 4≤*R*<6 | 1018 | 4.309 | 6.669 | 901.75 | 360.68 | 2.43 | 636.9 | 1.55 | 1.65 |
| R4 | 6≤*R*<10 | 1066 | 7.07 | 12.27 | 2222.69 | 300.71 | 2.17 | 745.3 | 1.55 | 1.65 |
| R5 | 10≤*R*<20 | 1017 | 12.59 | 25.05 | 6600.05 | 188.9 | 1.72 | 860.6 | 1.55 | 1.65 |
| R6 | 20≤*R*<40 | 480 | 25.84 | 48.75 | 10463.48 | 105.35 | 1.2 | 945.4 | 1.55 | 1.65 |
| R7 | 40≤*R*<60 | 115 | 42.53 | 101.74 | 47044.2 | 37.64 | 0.57 | 975.29 | 1.55 | 1.65 |
| R8 | 60≤*R* | 36 | 66.46 | 171.05 | 117618.8 | 20.23 | 0.14 | 1186.6 | 1.55 | 1.65 |

### *B. EXPONENTIAL AND LOGNORMAL DISTRIBUTIONS*

The results of the calculation of rainfall rate(R), liquid water content (W), the radar reflectivity factor (Z), the parameters of the exponential distribution ($N_0$, λ) and of the lognormal distribution ($N_t$, $D_g$ and σ) were shown in Table 3 For the exponential distribution, $N_0$ is proportional to the rainfall rate up to rainfall rate Class R5 tending to decrease to a minimum in Class R8 thereafter. The maximum drop numbers were found to be between Classes R3 and R4. For the whole sample (10 months), the maximum and minimum $N_0$ were 360.68 $mm^{-1}$ $m^{-3}$ and 20.23 $mm^{-1}$ $m^{-3}$, respectively.

The slope of the exponential distribution (λ) decreased with increasing R. This behavior was found by Willis and Tattelman (1989) also Srivastava (1972, 1978) hypothesized that the effect of coalescence, with increasing of large drops number and reduction of smaller ones, causes λ to decrease. In Table 3, it is seen that there was a considerable λ decrease at $R \geq 40$ mm $h^{-1}$. Willis and Tattelman (1989) found similar results for R ≥25-40 mm $h^{-1}$. The values of λ varied within the range of 0.14 mm $h^{-1}$ (R8) to 2.84 mm $h^{-1}$ (R1) for the whole sampling record.

In Table 3, it is also apparent that, in general, $N_t$ increases with R, being smaller values in Class R1, with large number of small raindrops, and larger values in Class R8. The minimum value was 125.5 $m^{-3}$ and the maximum 1186.6 $m^{-3}$. The values of σ were independent of the rainfall rate classes, almost constant and equal to 1.55 for the whole sampling period. On the other hand, $D_g$ increased with R, with maximum values in Class 8 and minima in R1 to R3.

### *C. EXPONENTIAL AND LOGNORMAL FUNCTIONS PARAMETERS FITTING*

In Figures 4 and 5, the fitting of the exponential and lognormal parameters as function of rainfall rate R were shown. The corresponding fitting equations were shown in Table 4. For $N_0$ against R, the correlation coefficients were negative –0.39 for the month of January and –0.71 for the whole sample. These values are in agreement with the ones found by Nzeukou et al. (2002). The relationship was inverse for λ and R also. The equation found was $\lambda(R) = 2.01\ R^{-0.26}$ with a correlation coefficient of 0.96, apparently similar to other authors. For a tropical region, Sauvageot and Lacaux (1995) found $\lambda(R) = 3.2\ R^{-0.09}$ with a correlation coefficient of 0.92 and Marshall and Palmer (1948) presented a classical fitting namely $\lambda(R) = 4.1\ R^{-0.21}$.

For the lognormal fitting, it was obtained $N_t = 391.1R^{0.27}$ with correlation coefficients varying from 0.41 to 0.91. For tropical regions, Sauvageot and Lacaux (1995) found $N_t = 670\ R^{0.74}$ with a correlation coefficient

Table 4. Monthly coefficients of the exponential and lognormal distributions.

| *Month* | *Exponential Parameters* | | | | | | *Log-normal Parameters* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $N_0$ | | | λ | | | $N_t$ | | | σ | | | $D_g$ | | |
| | a | b | r | a | b | r | a | b | r | a | b | r | a | b | r |
| DEC | 128.0 | 0.07 | 0.40 | 2.01 | -0.14 | -0.71 | 329 | 0.30 | 0.98 | 0.95 | 0.07 | 0.80 | 1.23 | 0.05 | 0.78 |
| JAN | 80.64 | -0.02 | -0.39 | 2.24 | -0.32 | -0.79 | 162 | 0.51 | 0.82 | 1.25 | 0.04 | 0.41 | 1.47 | 0.02 | 0.43 |
| FEB | 127.4 | -0.03 | -0.51 | 2.13 | -0.23 | -0.87 | 218 | 0.41 | 0.91 | 1.12 | 0.05 | 0.76 | 1.35 | 0.05 | 0.92 |
| MAR | 148.6 | 0.03 | -0.55 | 1.96 | -0.16 | -0.97 | 381 | 0.27 | 0.89 | 1.18 | 0.04 | 0.61 | 1.38 | 0.03 | 0.84 |
| APR | 297.5 | -0.37 | -0.71 | 4.34 | -0.51 | -0.9 | 220 | 0.45 | 0.56 | 0.80 | 0.16 | 0.75 | 1.08 | 0.11 | 0.82 |
| MAI | 147.4 | -0.07 | -0.59 | 1.75 | -0.13 | -0.86 | 541 | 0.17 | 0.58 | 1.13 | 0.03 | 0.56 | 1.43 | 0.03 | 0.93 |
| JUN | 147.4 | -0.09 | 0.38 | 2.14 | -0.23 | 0.85 | 344 | 0.31 | 0.79 | 1.03 | 0.04 | 0.40 | 1.31 | 0.05 | 0.89 |
| JUL | 65.79 | -0.08 | -0.57 | 1.67 | -0.35 | -0.91 | 363 | 0.27 | 0.49 | 1.00 | 0.01 | 0.61 | 1.21 | 0.05 | 0.87 |
| AUG | 125.7 | -0.15 | 0.43 | 2.51 | -0.36 | -0.72 | 315 | 0.25 | 0.41 | 0.75 | 0.16 | 0.59 | 1.05 | 0.14 | 0.94 |
| SEP | 103.7 | -0.23 | -0.67 | 1.84 | -0.29 | -0.87 | 384 | 0.24 | 0.59 | 0.89 | 0.09 | 0.41 | 1.18 | 0.06 | 0.88 |
| Σ | 144.4 | -0.11 | -0.71 | 2.01 | -0.26 | -0.96 | 391 | 0.27 | 0.43 | 1.47 | 0.01 | 0.82 | 1.58 | 0.009 | 0.95 |

0.97 similar to Nzeukou et al. (2002).

The $\sigma$ - R, relationship computed gave $\sigma = 1.47 R^{0.01}$ and showed a wide variability of the correlation coefficient among the months. Using the whole data set, $\sigma$ was 0.82 (Table 4), with the lowest value in June. The relationship for $D_g$ was $D_g = 1.58 R^{0.009}$ with correlation coefficient equal to 0.95.

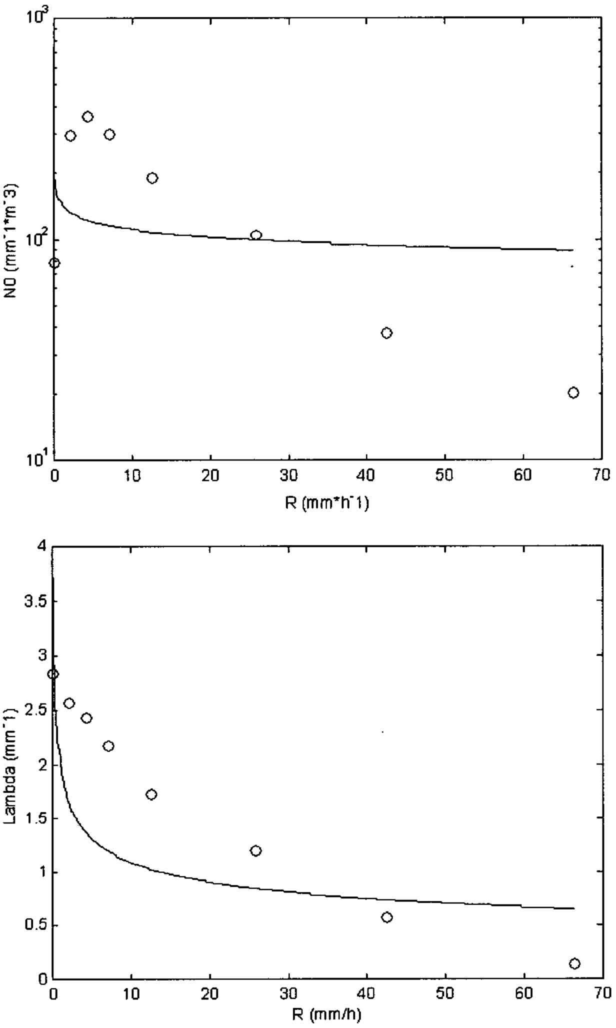


Fig. 4 Fitting curves for the exponential distribution against rainfall rate (R).

### *D. DROPLETS CONCENTRATION*

Some examples of raindrops distribution per disdrometer channels were depicted in Figures 6 and 7. During the first half of the sampling period, the maximum raindrop number was 400 drop $m^{-3}$ occurring always in Ch 7, which corresponds to mean diameter of 1.1 mm. The frequency of occurrence was higher in March and April when compared to January and February. In general, the droplets number varied from 1 to 200 drop $m^{-3}$, with a mean diameter between 0.3 to 2.8 mm corresponding to Ch 1 to Ch15.

Figure 7 shows the droplet number distribution for June and September. From May to September, the maximum droplet number recorded was in the range of 400 to 500 drop $m^{-3}$. Ch7 and Ch8, corresponding to diameters 1.1 and 1.3 mm, were the channels that recorded maximum drop numbers, not exceeding 200 drop $m^{-3}$ though. It is noted that, for this study, cloud type and basis, terminal raindrop velocity and physical mechanisms that originate the cloud/rain were taken in consideration. It is acknowledged, though, that these factors influence the raindrops number distribution as well as their diameters.

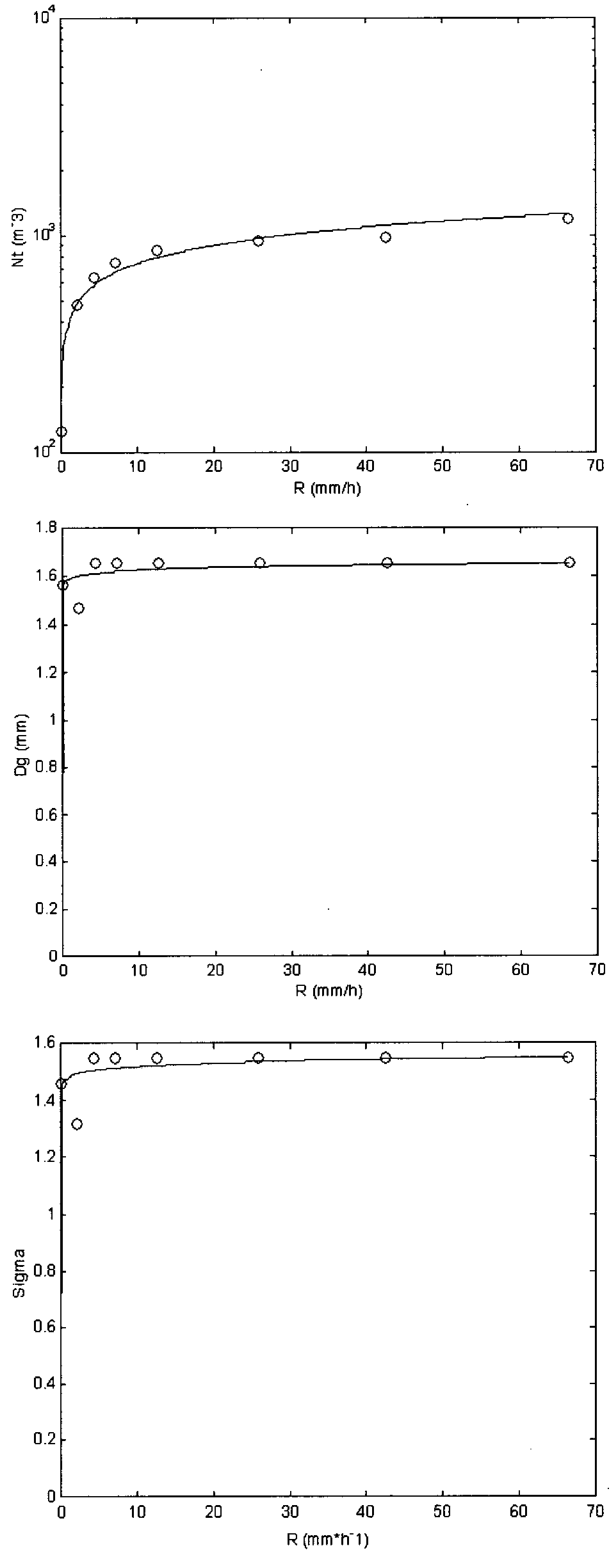
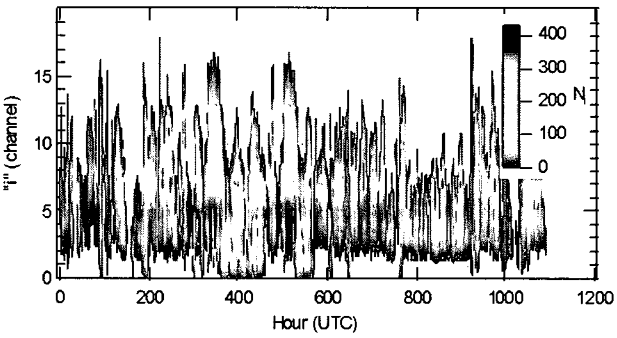


Fig. 5 Fitting curves for the lognormal distribution against rainfall rate (R).



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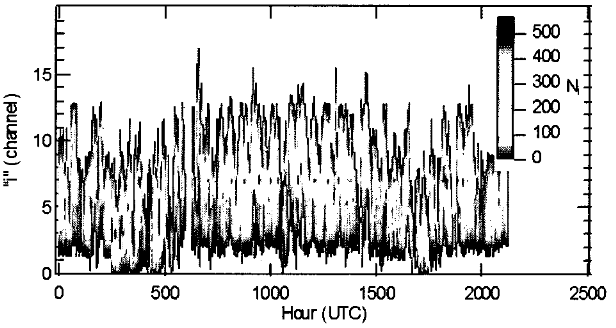
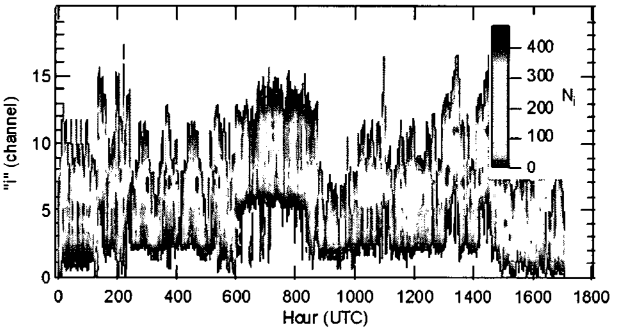


April/2002.

Fig. 6 Distribution of drops per channel during March and April 2002.



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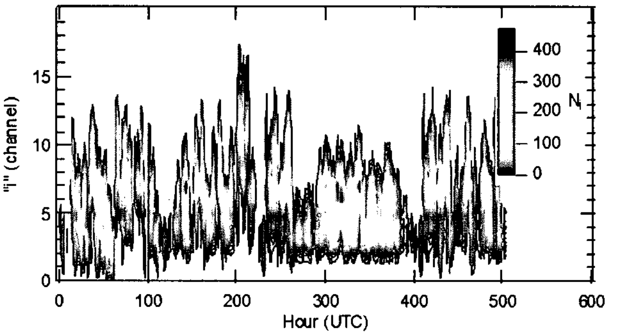

September/2002.

Fig. 7 Distribution of drops per channel during June and September 2002.

## V. CONCLUSIONS

The results showed clearly that most of the parameters of the analytical functions representing RSD depend on the rainfall rate, except for $\sigma$ and $D_g$, that remained practically constant with the rainfall rate classes. The shapes of the RSD were similar to those found in the literature but the observed raindrop numbers were not. A possible explanation for this may be the short period of this study, which encompassed only 10 months, or perhaps the physical nature of the rainfall and its interseasonal variability. The results of the correlation between parameters of exponential and lognormal distributions were in good agreement with the ones found in similar studies. In general, the recorded number of drop ranged from 300 to 500 drop $m^{-3}$, with maximum values registered in Channel 7 of the disdrometer, which corresponds to 1.1 mm drop diameter.

## REFERENCES

[1] Feingold, G., and Z. Levin, 1986: The lognormal fit to raindrop spectra from frontal convective clouds in Israel, *J. Climate Appl. Meteor.*, **25**, 1346-1363.

[2] Joss, J., and A. Waldvoge, 1969: Raindrop size distribution and sampling size errors, *J. Atmos. Sci.*, **26**, 566-569.

[3] Joss, J., and A. Waldvoge, 1967: Ein Spektrograph für Niederschlagstropfen mit Automatischer Auswertung, *Pure Appl. Geophys.*, **68**, 240-246.

[4] Lee G. and I. Zawadzky, 2005: Variability of Drop Size Distributions: Noise and Noise Filtering in Disdrometric Data, *J. Appl. Meteor.*, **44**, 634-652.

[5] Marshall, J. S., and W. Palmer, 1948: The distribution of raindrops with size, *Journal of Meteorology*, **5**, 165-166.

[6] Molion, L. C. B and S. O. Bernardo, 2002: Uma revisão da dinâmica das chuvas no Nordeste do Brasil (A review of the dynamics of rainfall over Northeastern Brazil), *Braz. J. of Meteor.* **17**(1): 1-10.

[7] Nzeukou, A., H. Sauvageot, A. D. Ochou and C. M. F. Kebe, 2002: Raindrop size distribution and radar parameters at Cape Verde, *J. Appl. Meteor.*, **43**, 90-105.

[8] Sauvageot, H., and J. P. Lacaux, 1995: The shape of averaged drop size distributions, *J. Atmos. Sci.*, **52**, 1070-1083.

[9] Sauvageot, H., R. S. Tenório and F. Mesnard, 1999: The size distribution of rain cells in West Africa and France, *J. Atmos. Sci*, **56**, 57-70.

[10] Seifert, A., 2005: On the Shape–Slope Relation of Drop Size Distributions in Convective Rain, *J. Appl. Meteor.*, **44**, 1146-1151.

[11] Smith, P. L and D. V. Kliche, 2005: The Bias in Moment Estimators for Parameters of Drop Size Distribution Functions: Sampling from Exponential Distributions, *J. Appl. Meteor.*, **14**, 1195-1205.

[12] Srivastava, R. C., 1972: A simple model of particle coalescence and breakup, *J. Atmos. Sci.*, **39**, 1317-1322.

[13] Srivastava, R. C., 1978: Parameterization of raindrop size distribution, *J. Atmos. Sci.*, **44**, 3127-3133.

[14] Tenório, R. S., H. Sauvageot, S. R. Buarque, 1995: Statistical Study of Rain Cell Size Distribution Using Radar Data During Squall Lines Episodes In West Africa, *In. III INTER. SYMP. OF HYDROLOGICAL APPL. OF WEA. RADARS*, **1**, 518-526.

[15] Tenório, R. S., 1996: Etude statistique de la distribution de taille des cellules de pluie: implications pour l'estimation des champs de précipitation par radar, PhD thesis - *Université de Toulouse III* (Paul Sabatier), 188 pp.

[16] Tenório, R. S., M. C. S. Moraes, D. A. Quintão and B. H. Kwon, 2003: Estimation of the Z-R relation through the Disdrometer for the coastal region in the northeast of Brazil, *J. of Kor. Earth Sci. Soc.*, **24(1)**, 30-35.

[17] Ulbrich, C. W., 1983: Natural variations in the analytical form of the raindrop size distribution, *J. Climate Appl. Meteor.*, **22**, 1764-1775.

[18] Willis, P. T. and P. Tattelman, 1989: Drop-size distribution associated with intense rainfall, *J. Appl. Meteor.*, **28**, 3-15.

[19] Zawadzki, I. and M. de A., Antonio, 1988: Equilibrium raindrop size distributions in tropical rain, *J. Atmos. Sci.*, 45, 3452-3459.

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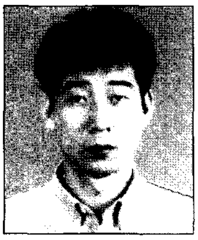

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