DOI: https://doi.org/10.24297/jap.v19i.9102

Drop Size Distribution and Lightning Manifestations in AMMA-CATH Area

Adéchinan A. Joseph[1], Moumouni Sounmaïla[1], Guédjé K. François[2] and Houngninou B. Etienne[2]

[1]Laboratoire de Physique de l'Atmosphère, Université Nationale des Sciences Technologie Ingénierie et Mathématique, Bénin

[2]Laboratoire de Physique de l'Atmosphère, Université d'Abomey-Calavi, Bénin

Abstract

This paper analyses for the first time in tropical area, the relationship between lightning and DSD (Drop Size Distribution) parameters on rainy events that occurred during the monsoon period. The Lightning data used are collected by the LINET (Lightning Detection Network) while the DSD data were recorded by a distrometer. The correlation was computed within five circles of radius varying between *10* to *50 km* with a step of *10 km*. These consecutive areas are centered on the position of the disdrometer. By taking into account only the convective spectra and remove out of the data the cases where there is rain without any lightning and vice versa, all data was computed with a time scale of one minute during each of the rainy events .The results showed that the exponential and polynomial laws fit better our data than the power and linear laws. The highest correlation coefficients are obtained within a radius of about 20 km around the distrometer location. The correlation between the parameter N_o^* and n is the most stable with a correlation coefficient equal to *0.55*.

Keywords: Lightning; Drop Size Distribution; AMMA-CATCH; Benin.

1. Introduction

Most hydrological simulation models use rainfall data. A good description of precipitation in time and space is therefore essential to improve hydrological modeling and design [1]. The estimation of rainfall data is mainly done today using rain gauges and weather radars. These two tools have strengths and weaknesses. The advantage of rain gauges is their ability to provide rainfall data in a precise location with acceptable accuracy and reliability. When the observation area becomes large, it is often necessary to use not only many rain gauges but also interpolate methods with consequence of a loss of spatial resolution [2]. To avoid this problem, radars are identified as the best possible alternative. But these also have their limits. Indeed, it makes an indirect measurement of the rain. It correctly accounts for the spatial distribution of rain but sometimes with some errors. Fortunately, the methods of correcting the sources of error exist and well documented. Z-R relationship is used to deduce the rain rate from the radar reflexivity when rainfall data is recorded with radar. But one of the difficulties of the Z-R relationship is its great spatiotemporal variability, from one rainfall to another and within the same rainy system [3]. Potential limit also include the inability to obtain correct information in mountainous areas where topography makes them difficult to use [6]. Although the problem of spatial resolution seems to be solved for regions well covered by radars, it will however be necessary to find another alternative method for measuring rain remotely in other locations radar coverage is poor. Since lightning and precipitation are both two typical phenomena that frequently co-exist in thunderstorms, lightning information is proposed as a possible measure of rain rate [4-6]. According to several authors, lightning data could be considered as additional information that can be used for input to distributed parameter hydrologic models.

In the recent decades, the link between lightning and rainfall has been extensively explored worldwide, for various temporal and spatial scales and under different climatic conditions. The important results obtained indicate overall that there is a strong relationship between both lightning activities and convective rainfall [5-7]. So, several authors have suggested that lightning could be used to estimate rain rate in areas where radar coverage is lacking. Indeed, lightning can be either cloud-to-ground (CG), or intra-cloud (IC) but most of these studies focus on CG lightning activities. This tendency may be due to the fact that it is the effects of this category of discharge that are more noticeable to humans. The most used approaches in the literature to analyze both rainfall and lightning activity can be grouped into two categories. On the one hand, we have authors who use a rain yield defined as the convective rain mass (or volume) per CG or total (IC+CG) lightning count detected over the common area [8-10]. This ratio often calculated for long temporal and spatial domains varies greatly depending on geographic region and convective environment. For example, [11] use a monthly timescale and a spatial resolution of 100 km^2 over the Iberian Peninsula during the warm season. They obtained mean values ranging from 1.2 10^8 for the semiarid region to 2.1 10^8 kg/fl for the humid region. Using the same spatiotemporal scales, [12] have computed a rain yield in North of Benin from data recorded during the monsoon period. Results found in this area pointed out that the rain yield values ranging between 1.5 10^7 and 49 10^7 kg/fl with an average of 7.2 10^8 kg/fl. Furthermore, [13] investigated in Florida, the relationships between CG lightning and surface rainfall in nine thunderstorms, and found a linear relationship between the precipitation volume and the number of CG flashes with a mean ratio around 1.9 10^4 m^3/CG flash. These authors also summarized much of the research results that used the rain yield to quantify the link between lightning and rain. These authors were able to classify in two different tables, some authors who used rain gauges to measure rain and those who used radar. Analysis of this review shows that the majority of their works are carried out in United States and the rain yield is around 10^4 m^3/fl. On the other hand, we have a case-by-case approach used in individual storms. Here, the relationship sought depends on several factors such as convective regime, oceanic and continental storms, thunderstorm type, local climatology, type of lightning flashes considered, etc.. [14]. For example, [15] have shown that when the datasets from more than one storm is use, the quality of the correlation between lightning and rain decreases.

In spite the Drop Size Distribution parameters (DSD) are identified as being an indicator for a complete description of rain, very few studies are found in the literature on the relationship between lightning and DSD. [16] suggest through these studies that, if lightning has any relationship to the convective activity of a storm, then understanding how N_o and Λ relate to lightning may provide some insight into a method for using lightning to sense remotely. More recently, [17] investigated the relationship between lightning and DSD parameters in US area. These authors have sought to correlate DSD parameters to a single characteristic of lightning. The DSD parameters used are: the rain rate per range of diameters R, the DSD intercept parameter N_o, the slope of the distribution in a semi-log frame Λ. These authors found that the lightning strokes density calculates per hour and per square mile is well-correlated with the DSD parameters considered when the power law fit is use.

The availability and the quality of data recorded during the international African Monsoon Multidisciplinary Analysis (AMMA) campaign in 2006 offering today opportunity to make a study like that carried out in US [17]. Through this work, we investigate for the first time, the relationship between lightning and the DSD parameters using the case-to-case approach in tropical West Africa area known for its climate strong variability. Our analysis focuses here on two important rainy events that occurred during the monsoon period in Benin. There are several aspects of rain and lightning that are important, but have not been discussed here. The paper is organized as follow. In Section 2 we present the study area as well as the dataset and we describe the methodology adopted. We dedicated the Section 3 to the main results obtained and their analyzes. Finally, we devoted the last section to a conclusion.

2. Materials and Methods

2.1 Study area

This study is carried out in AMMA-CATCH network. This region centered on Djougou town in the North-West of Benin republic is characterized by a Sudanian climate and is geographically bounded by latitudes 9° N to 10.4° N and longitudes 1.5° E to 3° N (Figure 1a). The rainy season covers the period from March to October with the maximum precipitation in August [18]. As can be seen in figure 1b, this area is subject to significant inter-annual rainfall variability. The annual average over the period 1970-2006 is around 1171 mm (figure 1b). According to [18], the average values of relative humidity and air temperature in this area are respectively ~ 80% and ~ 30 °C.

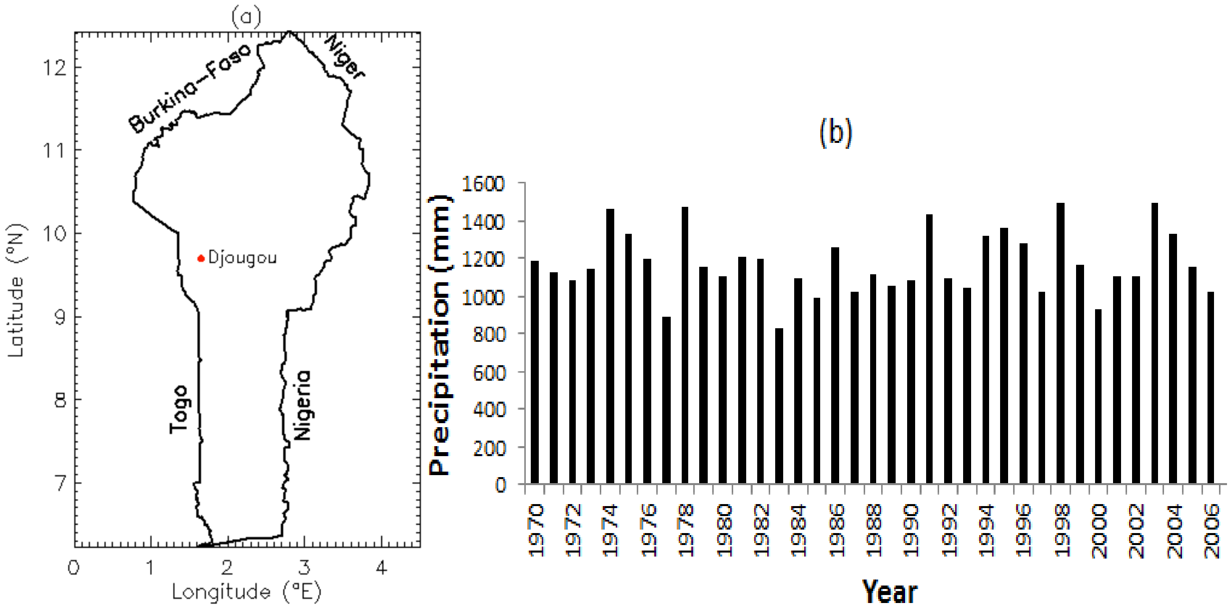

Figure 1. (a) Benin map showing the location of the distrometer used to collect the DSD; (b) Annual accumulated precipitation over the period from 1970 to 2006.

2.2 Data

The lightning data used in our study were collected by the LINET network. It consists of six receiving stations distributed over our interest area. The average distance between these stations is about 12 km and the mean station level is 429 m above sea level. The geographic coordinates of these stations is given in table 1. The LINET system measures magnetic VLF/LF emissions from lightning and use time-of-arrival technique to discriminate the detected flashes. This lightning detection system reports some parameters of lightning such as time of occurrence of the lightning flashes (UTC in year, month, day, hour, minute and second), location (latitude and longitude in degrees), polarity (positive or negative) and signal strength (kA). Beyond these parameters, this network also provides the height (km) which represents the altitude at which the discharge is intercepted above mean station level. This height is equal to zero only for cloud-to-ground lightning .The data were collected during six months from June 2006 through November 2006. This period is very important because the peak of the West African monsoon often occurs in July or August, and this corresponds to the principal maxima in lightning activity observed in many countries in North and West Africa [12]. More details of the operating mode of this system are given by many researchers [2, 7, 11-13, 18-20].

Table 1: Location of the receiving stations of the LINET network deployed in the study area.

Station location	Longitude (degree)	Latitude (degree)	Altitude (km)
Bassila	1.6704	09.0055	0.433
Bembereke	2.6733	10.2359	0.442
Boukombe	1.1038	10.1794	0.266
Djougou	1.6528	09.6798	0.471
Parakou	2.6123	09.3577	0.432
Natitingou	2.6123	09.3577	0.432

Three disdrometers were deployed in northern Benin during the AMMA campaign. These instruments did not work simultaneously. In this study, we used data from disdrometers which operated almost in the same period as the LINET network. This is the single infrared beam OSP type disdrometer with a horizontal section of 100 cm^2. This instrument is located not far (11 km) from the receiving LINET station installed in Djougou. It recorded from June to September 2006, drop sizes in twenty-two bins ranging in size from 0.3–5.5 mm. Table 2 presents the bin widths as well as the center values for each bin. During a given rain event, it is associated to each raindrop detected by this instrument, its time of entry into the beam, its size, its terminal velocity as well as a measurement quality factor. From these minute's data and using the following formula, the discrete form of the DSD was computed

$$N_i(D_i) = \frac{h_i(D_i)}{AT v_i w_i} \quad (1)$$

where $h_i(D_i)$ where is the histogram of drops having diameter D_i , v_i is the terminal velocity of a drop having a diameter , is the bin width, A is the area of the disdrometer collection surface (50 cm), T and is the duration of data collection in seconds. Since the large falling drops are very unstable due to the friction of the air, the diameter of the drops on land does not exceed 6 mm (reference). Thus, we limited ourselves in this study, as [19], to the equivalent diameter class centered on 6.5 mm.

According to [20], the distribution of raindrop sizes is defined as being the number of drops per unit volume, for each drop size. This parameter $N(D)$ is related to the rain rate via the integral

$$R = \frac{\pi}{6}\int_0^\infty N(D)D^3 v(D)dD \quad (2)$$

where v represents the terminal velocity of the drop and D is the equivalent diameter of a spherical drop having the same volume as the raindrop. In this expression, if $N(D)$is known, then R will be easy to obtain. The DSD parameters used in this work are not measured directly by the disdrometer. They are obtained from some mathematical expressions. Indeed, three models are often used in the literature to describe the particle size distribution. One of them is exponential function introduced by Marshall and Palmer (1948) [25]. This model is written in the form:

$$N(D) = N_o e^{-\Lambda D} \quad (3)$$

where $N_o(m^{-3}mm^{-1})$ and $\Lambda(mm^{-1})$ are the two parameters of the model and represent respectively the ordinate originally and the slope of the distribution. The rain rate can therefore be seen as a function of the variables N_o and Λ. These variables can be obtained from the moment of order n of the exponential model given by:

$$M_n = N_0 \frac{\Gamma(n+1)}{\Lambda^{(n+1)}} \quad (4)$$

In this expression, Γ represents the gamma function Since is difficult to give a physical meaning to the parameter N_0, the function N(D) has been normalized by the double-moment normalization formalism. In this formalism, the normalization parameters N_O^* (intersection parameter) and D_m (mean volume diameter) are given by:

$$N_0^* = \frac{4M_3^5}{\Gamma(4)M_4^4} \quad (5)$$

$$D_m = \frac{M_4}{M_3} \quad (6)$$

When we replace in these expressions the moments of order 3 and 4 calculated from Eq.(4), we obtain the relations between the normalization parameters and those of the exponential model.

It is important to note that all the data collected by both the disdrometer and the LINET are of very good quality and have already been used in several works [5, 24-28].

Table 2: Center value and bin width for each of the twenty-two drop bins recorded.

Bin	Diameter (mm)		Velocity (m/s)	
	center	bin width	center	interval
1	0,062	0,125	0.05	0.1
2	0,187	0,125	0.15	0.1
3	0,312	0,125	0.25	0.1

4	0,437	0,125	0.35	0.1
5	0,562	0,125	0.45	0.1
6	0,687	0,125	0.55	0.1
7	0,812	0,125	0.65	0.1
8	0,937	0,125	0.75	0.1
9	1,062	0,125	0.85	0.1
10	1,187	0,125	0.95	0.1
11	1,375	0,25	1.10	0.2
12	1,625	0,25	1.30	0.2
13	1,875	0,25	1.50	0.2
14	2,125	0,25	1.70	0.2
15	2,375	0,25	1.90	0.2
16	2,750	0,5	2.20	0.4
17	3.250	0,5	2.60	0.4
18	3.750	0,5	3.00	0.4
19	4.250	0,5	3.40	0.4
20	4.750	0,5	3.80	0.4
21	5.500	1	4.40	0.8
22	6.500	1	5.20	0.8

2.3 Method

In this work, our analyzes mainly focused on two rainy events of the squall line type (characterized by a convective part followed by a very remarkable stratiform part) both occur during monsoon period. Useful spectra were selected and classified using the method of [25]. According to this technique, if we consider the hyetogram of a rainy event as a series R_i where i represents the index of the spectra and Ri the corresponding intensity, a spectrum k is classified as stratiform when its intensity R_k and that of its twenty adjacent spectra are all less than 10 mm/h; otherwise, this spectrum k is classified as convective. Likewise, when the spectrum k is classified as convective, so are its adjacent spectra. Table 3 gives information on the number of spectra as well as the corresponding rainfall accumulation when this technique is applied.

The DSD parameters considered are R, ∧ and N_0^*. We have focused our attention on these parameters since it was shown that if there is a possible relationship between lightning and the convective activity of a storm, then understanding how N_0 and ∧ relate to lightning could contribute in the appropriate choice of the method of using lightning to estimate rainfall [26]. The methodology that we used to correlate lightning and the DSD parameters is similar to that proposed by [26]. The correlation is computed within ten boxes. The box sizes that were considered were ranging from 10 through 50 Km on a side with regular steps of 10 km. All these boxes are centered on the disdrometer location. The DSD data are the same for all the boxes but the number of strokes and the corresponding average intensity change from one to another. But, as the area delimited around the disdrometer location increases, the probability to detect strokes increases and the strokes density n had a greater chance of being nonzero when the box sizes were larger. Before computed the coefficient correlation, we remove out to our data the periods of precipitation with no stroke. We have also taken into account both the convective spectra and the stratiform ones. The number of strokes that occurs within each box for each minute was then compared to the DSD parameters. The data was computed taking into account both the type

(IC or CG) and the polarity (positive or negative) of strokes that occurs within each square box. Several laws have been fitted to the point cloud in the plane. The one that fits best is the exponential law of form. By doing so, the rain intensity R could be predicted in various ways from the available lightning information. One of them is to directly correlate R to strokes density using an appropriate law. Another possibility would be to calculate the variables Λ and N_o^* for a given value of the flash density, then computed R using the Eqs 2 and 3.

We have represented in figure 2 the evolution of these parameters during one of the rainy events considered in this study. As can be seen on this graph, all these parameters have the same dynamics. During this event, the maximum value of all the DSD parameters is recorded at the same time (around 3 p.m). By observing the shape of the rain rate curve, we notice that this rain event has the structure of a squall line since the contribution of the stratiform part to the cumulative precipitation recorded during this event is very low. It appears in this figure a time lag between the time when the maximum value of the lightning parameters is obtained and the moment when the maximum value of the DSD parameters study is recorded. This observation is valid whatever the type (IC or CG) of lightning considered.

Table 3: Some characteristics of the rain event study.

Event date	Useful spectrum		Convective spectrum		Stratiform spectrum	
	Number	cumulative rain (mm)	Number	cumulative rain (mm)	Number	cumulative rain (mm)
28/07/2006	136	16.82	43	15.21	93	1.61
10/08/2006	73	22.82	73	22.82	0	0
Total	209	39.64	116	38.03	93	1.61

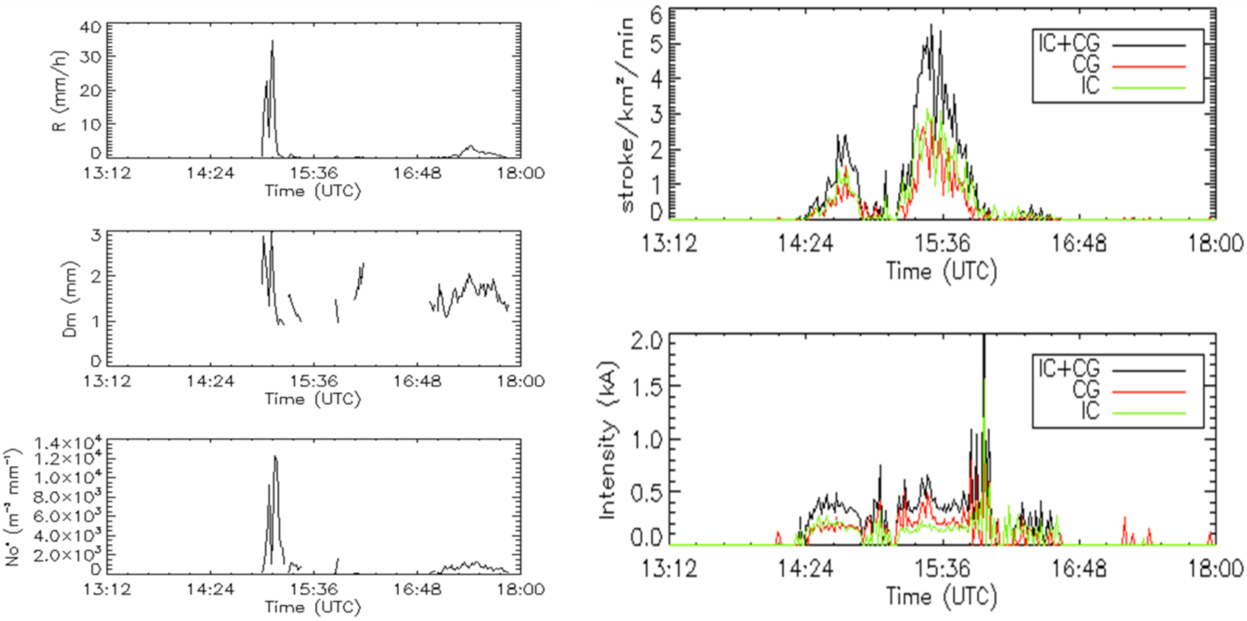

Figure 2: Time series for whole parameters recorded within a radius of 20 km around the disdrometer location during one of the events studied. From top to bottom and in left, we have: the rain rate, the drop mean diameter and their concentration. From top to bottom and in right, we have: the lightning stroke density and corresponding peak current.

3. Results and Discussion

Several laws (linear, exponential, power and polynomial) are used to fit our data. These functions fit the data reasonably well. After applied different criterions indicate in precedent section, it appears that the exponential and polynomial function fit better all of our data than the other laws. For this, in the rest of this document, only these cases where these laws are applied will be presented. Therefore, we represent in the figure 3, the proportion of correlation coefficient for each stroke parameter and for different radius ranging from 10 km to 50 km around the disdrometer location. As can be seen in this figure, the highest values of the correlation coefficient are mostly obtained when the lightning date are collected within a radius equal to 20 km around the disdrometer location. This tendency is the same whatever the type or the polarity of the stroke lightning considered.

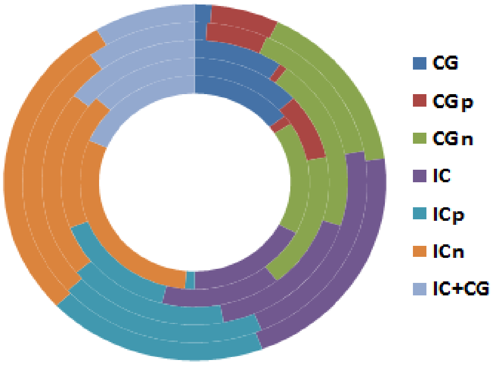

Figure 3: Proportion that represe ype for different radius ranging from 10 km to 50 km around the

3.1 Correlation between mean diameter and stroke density/intensity

Figure 3 presents scatter plot of both stroke density and inverse mean diameter for the two events study for a radius of 20km around the disdrometer location. The exponential model use to fit these data is in the following form: $\Lambda = {}^{4}/_{D_m} = ae^{bn}$ where D_m represents the mean volume diameter, n the lightning stroke density, and a and b are both the constants. For this radius, the correlation coefficient range from 0.20 to 0.26 and the highest value (0.26) is obtained with negative discharge. It appears a slight increase of the parameter Λ when the number of lightning stroke that occurs within a radius of 20 km around the position of the disdrometer increases. Although the function fits the data reasonably well, however, there is significantly more scatter than observed by [26].

We have also evaluated through figure 5 the link between the parameter Λ relating to the mean volume diameter and the strokes intensities detected in the areas defined around the disdrometer. Here we noticed that it is the polynomial function that best fits our data. As the degree of the polynomial increases, the correlation coefficient also increases. By considering a polynomial of degree 2 of the form: $\Lambda = an^2 + bn + c$, we note that the values obtained vary between 0.15 and 0.29. The maximum values are mainly obtained with negative discharges

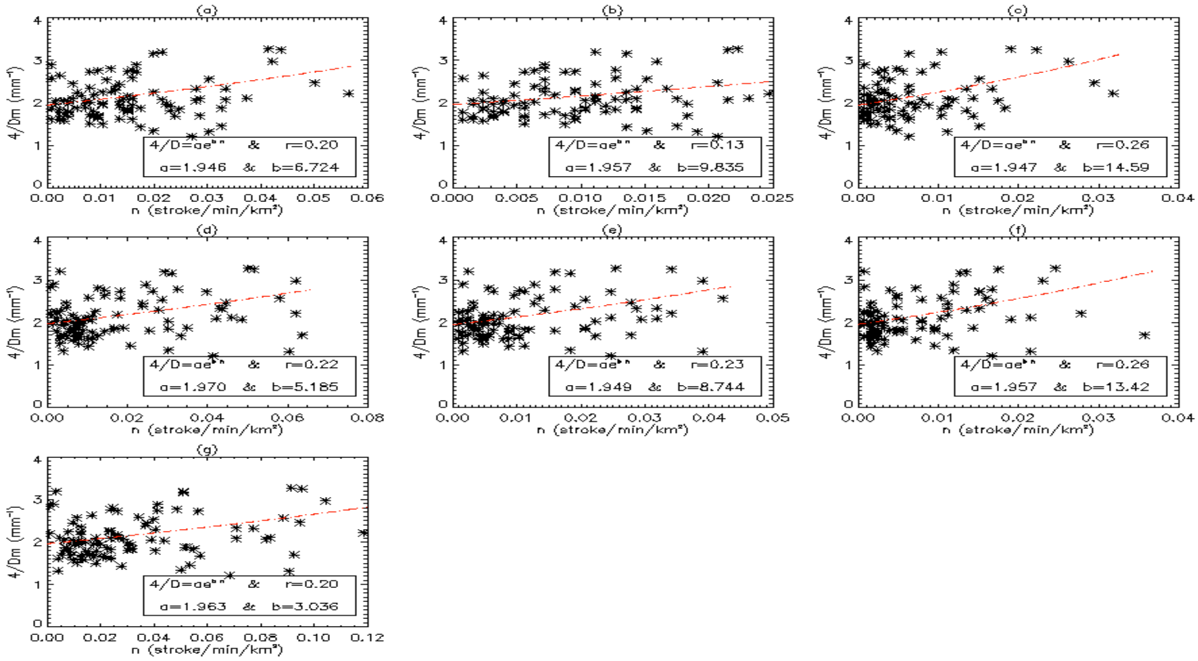

Figure 4: Λ vs stroke density computed within a radius equal to 20 km around the disdrometer for: (a) CG, (b) CG posistif, (c) CG negatif, (d) IC, (e) IC posistif, (f) IC negative and (g) IC +CG.

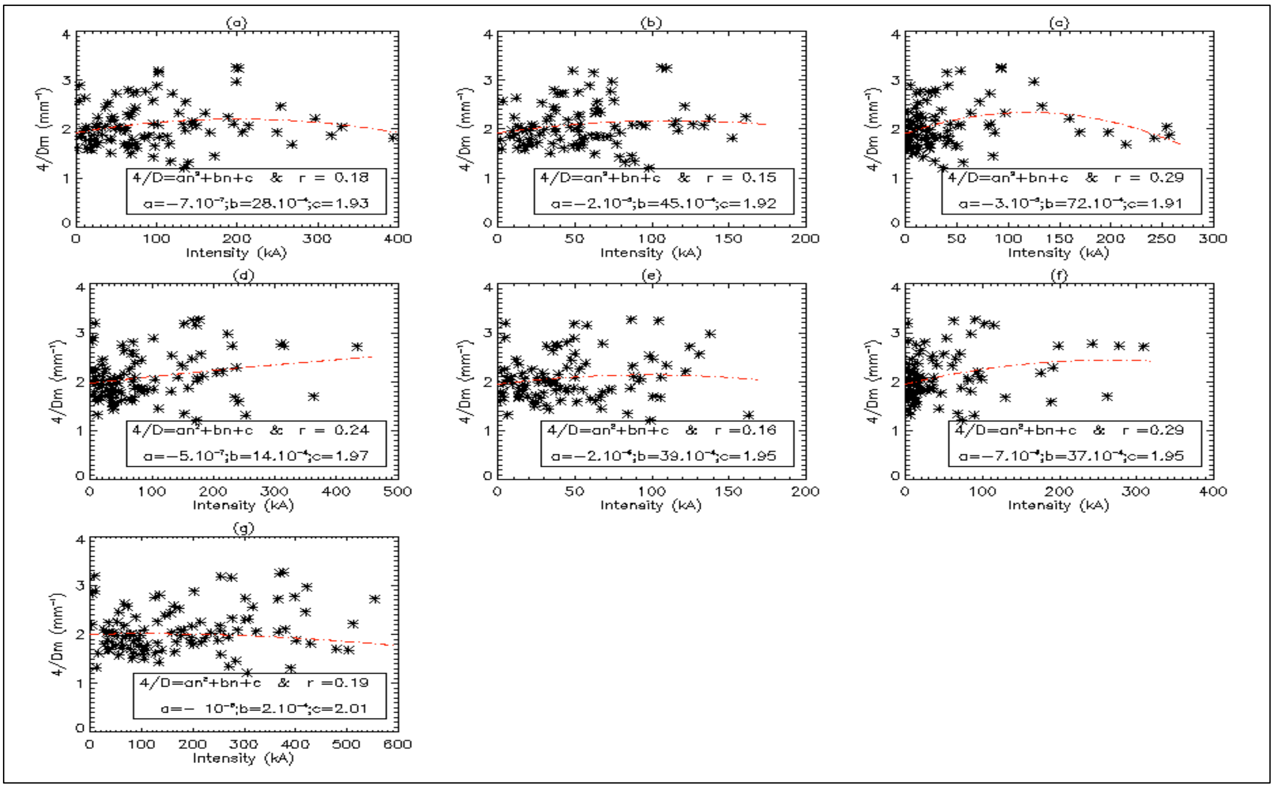

Figure 5: Λ vs stroke intensity computed within a radius equal to 20 km around the disdrometer for: (a) CG, (b) CG posistif, (c) CG negatif, (d) IC, (e) IC posistif, (f) IC negatif and (g) IC +CG.

3.2 Correlation between number of drop size and stroke density/intensity

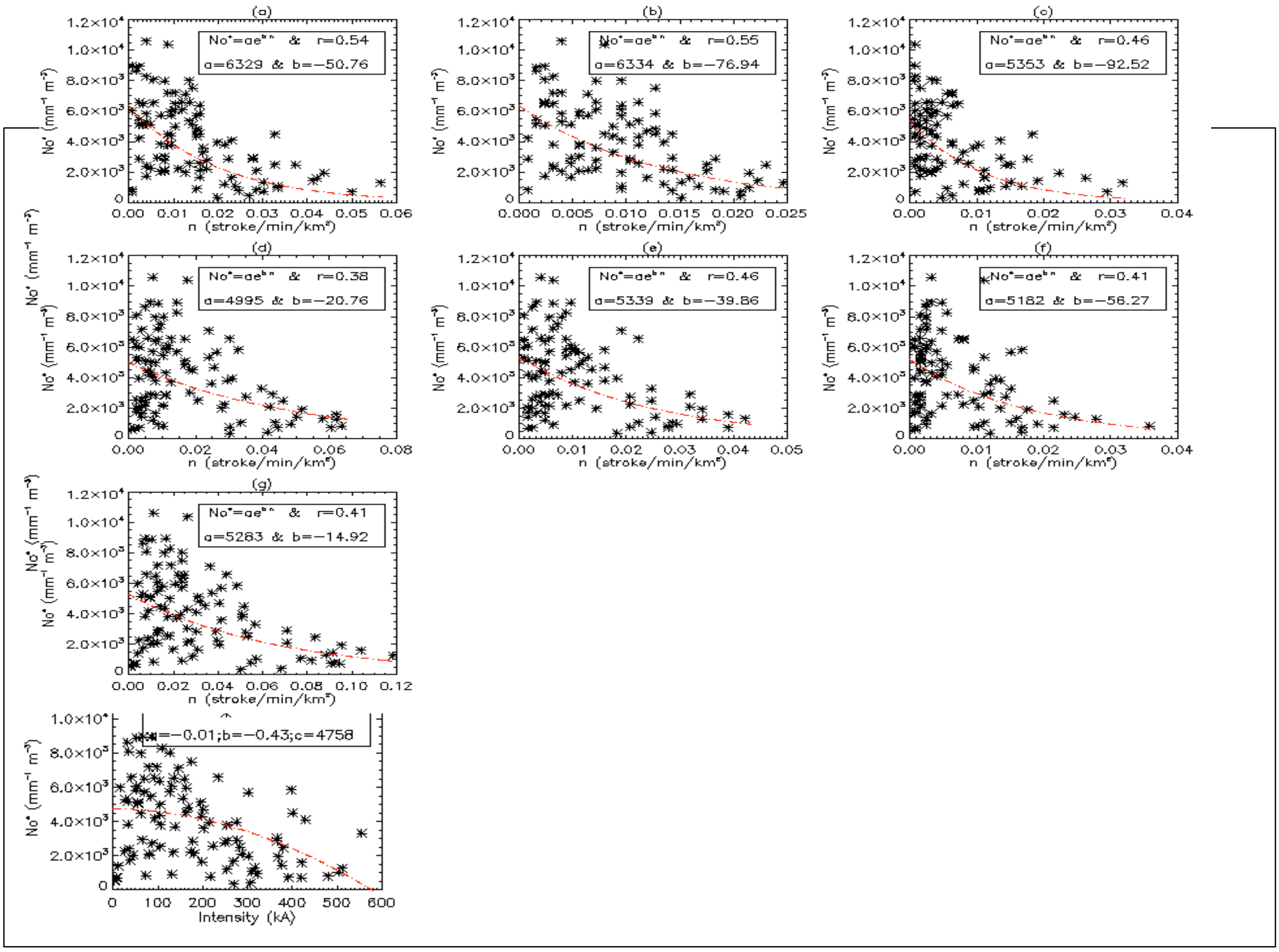

Figure 6: N_o^* vs stroke density computed within a radius equal to 20 km around the disdrometer for: (a) CG, (b) CG posistif, (c) CG negatif, (d) IC, (e) IC posistif, (f) IC negatif and (g) IC +CG.

Figure 7: N_o^* vs stroke intensity computed within a radius equal to 20 km around the disdrometer for: (a) CG, (b) CG posistif, (c) CG negatif, (d) IC, (e) IC posistif, (f) IC negative and (g) IC+CG.

Figure 6 presents scatter plot of both the parameter N_o^* and stroke density within a radius of 20 km around the disdrometer. The exponential model use to fit is in the following form: $N_o^* = ae^{b\,n}$ where N_o^* is related to the number of raindrops, n the stroke density computed each minute during these rainy events study, and a and b are both the constants. Here, for this radius, the correlation coefficient range from 0.38 to 0.55 and the highest value (0.55) of this coefficient is obtained with positive discharge. As can be seen in this figure, as the stroke density n computed around the disdrometer increases, the parameter N_o^*decreases.

As was the case with the parameter Λ, we noticed that it is the polynomial function which best fits the data (see figure 7). The values of the correlation coefficients obtained here are better than those preceding, whatever the type and the polarity considered. These values vary between 0.20 and 0.54 with the greatest obtained cloud-to-ground stoke lightning. The function used is of degree 2 and is in the following form: $N_o^* = an^2 + bn + c$. It is important to point out that as the degree of polynomial increases, the fit becomes better.

3.3 Correlation between rain rate and stroke density/intensity

Figure 8 presents scatter plot of both stroke density and the rain rate computed during these two events study for a radius of 20km around the disdrometer location. The exponential model use to fit is in the following form: $R = ae^{b\,n}$. The correlation coefficients range from 0.41 to 0.51 and the highest value is obtained with negative discharge. In this case, for the same radius like above, the highest values of the correlation coefficient are also obtained with cloud-to-ground strokes.

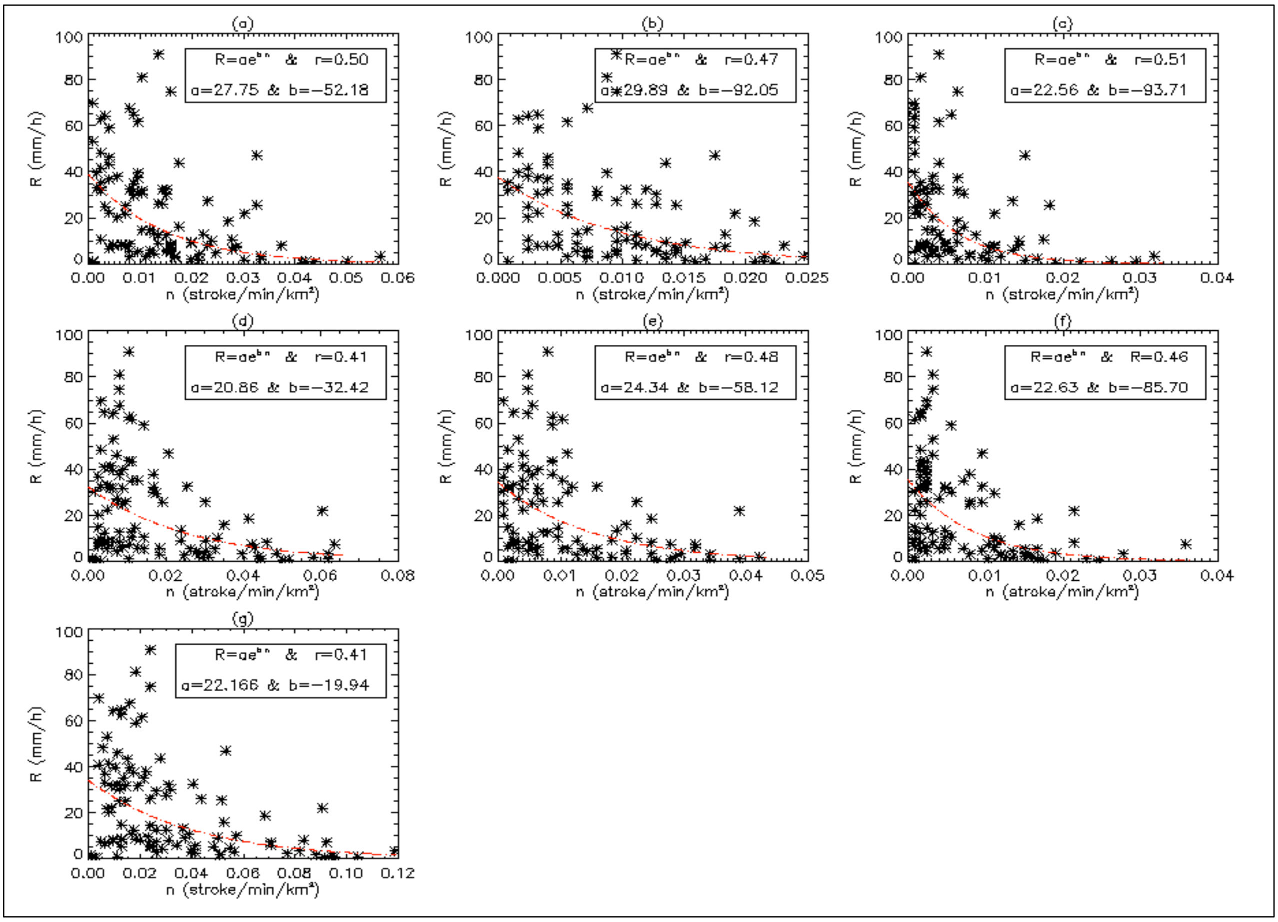

Figure 8: Rain rate vs stroke density computed within a radius equal to 20 km around the disdrometer for: (a) CG, (b) CG posistif, (c) CG negatif, (d) IC, (e) IC posistif, (f) IC negative and (g) IC+CG.

We have used again the polynomial function to fit our data concerning the correlation between rain rate and strokes intensity (see figure 9). This function is in the following form: $R = an^2 + bn + c$. It clearly appears a decrease in the values obtained compared to the previous case. These values varying between 0.28 and 0.43. The highest values are obtained with cloud-to-ground stroke.

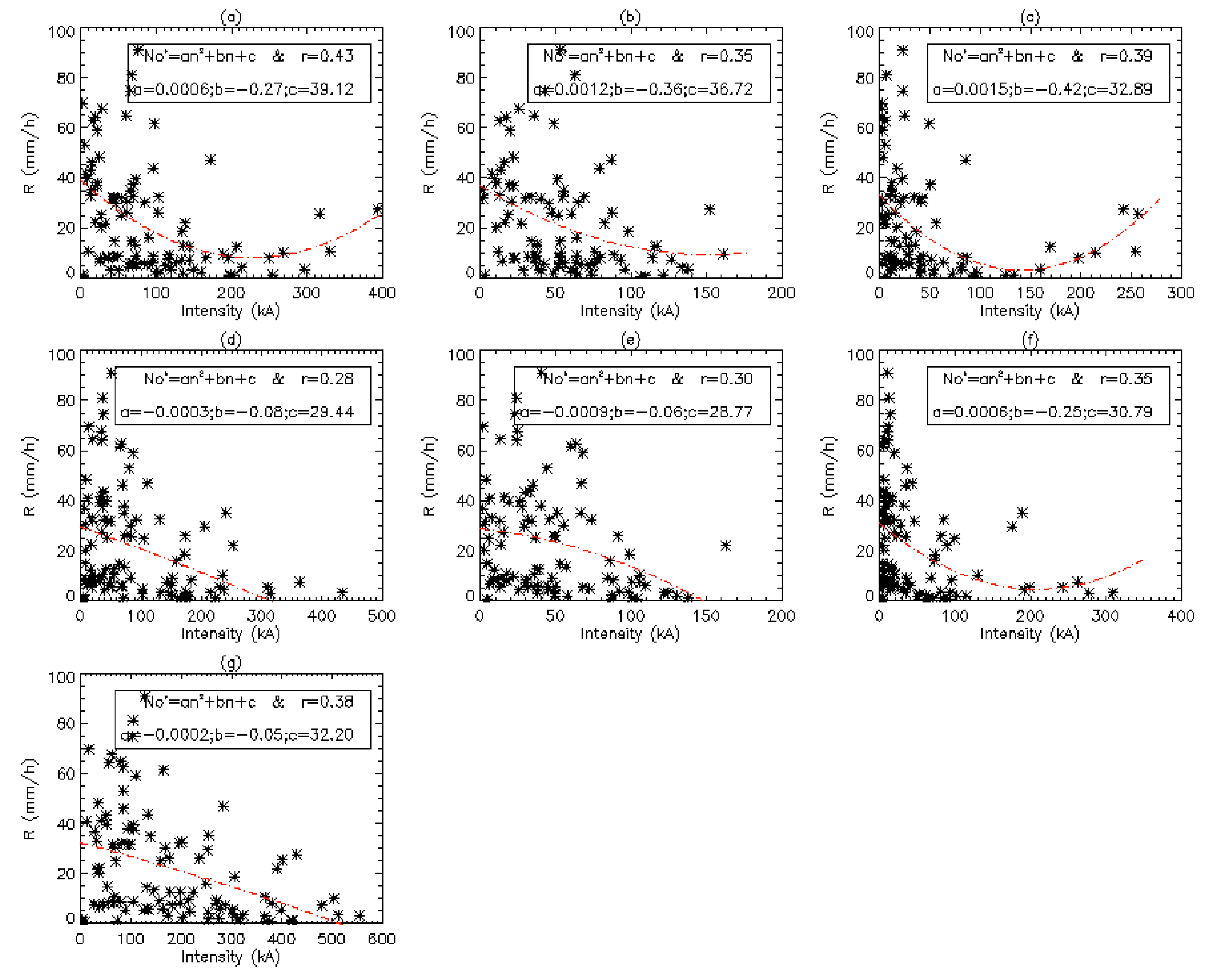

Figure 9: Rain rate vs stroke intensity computed within a radius equal to 20 km around the disdrometer for: (a) CG, (b) CG posistif, (c) CG negatif, (d) IC, (e) IC posistif, (f) IC negative and (g) IC+CG.

Even if the values of the correlation coefficients obtained are within the range of those found in the United States by [26] it is important to note that our conclusions diverge. Indeed, at the end of their investigation, these authors noted that the correlation of the parameter relate to the mean volume diameter to stroke density was particularly stable. One of the reasons that may justify this non-coverage of the results may be due to the characteristics of the rainy events that we have chosen in our study. The events that we have brought our reflections have the structure of a squall line type therefore have a very precise form. To this possibility we can also add the time scale chosen to calculate the density of the strokes lightning. In their study, they computed this density per hour while in our study we worked on a one-minute scale. This scale is finer and seems to us to be better suited to fully understand the variations to which the parameters we are studying are subject during rainy events which can sometimes last for less than an hour.

4. Conclusion

The analysis performed in this work aims to explore for the first time the correlation between drop size distribution and lightning characteristics in AMMA-CATCH area in Benin republic. We focused our analyzes on two rainy events having the structure of a squall line and occurring during the monsoon period of 2006. The corresponding data were collected both by the lightning detection network LINET and by a disdrometer located in djougou. The lightning strokes density (n) as well as their average intensity recorded within a circle of radius R centered on the position of the disdrometer were compared with three DSD parameters (R, Λ and N_o^*) computed using only the convective spectra identify by Testud's method. We have eliminated from our data the cases where there is rain without any lightning and vice versa. We have taken into account all type (IC or CG) and lightning polarity (positive or negative). All data was computed with a time scale of one minute during each of the rainy events. The method adopted is purely statistical. So, the time series obtained after applying the different criteria are fitting by an exponential regression model. The main results obtained show that the exponential and polynomial laws fit better our data than the power and linear laws. The maximum correlation coefficients are obtained in 20 km around the disdrometer position. The correlation coefficient decreases as the area of the area delimited around the position of the disdrometer increases except for radius equal to 10 km and 20 km. The number of raindrops is the DSD parameter that best correlates with the lightning strokes density. The correlation between the parameter N_o^* and n is the most stable. The correlation coefficients obtained vary between 0.1 and 0.55 depending on the parameter and the radius chosen. The highest values are recorded with cloud-to-ground lightning.

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Conflicts of Interest

The authors declare that they have no conflict of interest.

Funding Statement

The authors declare that they have no funding for this work.

Acknowledgments

The authors would like to thank the African Monsoon Multidisciplinary Analysis (AMMA) project campaign for providing lightning data. We also express their great appreciation to the editor and the anonymous referees for their valuable suggestions.