Main features of rain drop size distributions observed in Benin, West Africa, with optical disdrometers

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[1] As part of the African Monsoon Multidisciplinary Analysis (AMMA) field campaign, rain Drop Size Distribution (DSD) measurements were carried out in Benin, in the Sudanese climatic zone, with optical disdrometers, over 3 rainy seasons. The observed DSDs are well modelled by a gamma distribution, with the value of the shape parameter (μ) close to 5. The average normalized intercept parameter (N_0*) is close to 10^3 mm^{-1}m^{-3}. After classification of the convective and stratiform spectra, it is shown that for a given rain rate the proportion of the bigger drops is higher in the stratiform spectra, consistent with the observed occurrences of 'N_0 jumps' within the squall lines. Specific reflectivity-rain rate (Z-R) relationships were derived for the whole data set, for the squall lines and for the convective and stratiform regions. **Citation:** Moumouni, S., M. Gosset, and E. Houngninou (2008), Main features of rain drop size distributions observed in Benin, West Africa, with optical disdrometers, *Geophys. Res. Lett.*, *35*, L23807, doi:10.1029/2008GL035755.

1. Introduction

[2] The African Monsoon Multidisciplinary Analysis (AMMA) field campaign [*Redelsperger et al.*, 2006] has provided an opportunity to analyse tropical precipitation in poorly instrumented areas. In Djougou, Northern Benin, in the Sudanese climate zone, rain gauges, radars, profilers and disdrometers were deployed to document the convective systems. The present work focuses on a particular aspect of convective systems: the rain Drop Size Distribution (DSD) observed at ground level with optical disdrometers.

[3] The DSDs observed at the ground depend on complex physical processes that progressively transform ice or water clouds particles aloft into rain below. DSD observations carried out around the world show that they vary in space and time and over a range of scales. *Sauvageot and Lacaux* [1995] analyzed DSDs at several latitudes and demonstrated the variations between the tropics and the mid latitudes, and between coastal areas and continental West African locations. Other studies have shown the dependence of the DSD parameters on the type of precipitation and the intensity of convection [*Waldvogel*, 1974; *Testud et al.*, 2001; *Tokay and Short*, 1996]. Evidence that different rain generation processes lead to distinct DSD shapes between the convective and stratiform parts of squall lines has been provided by *Maki et al.* [2001], *Uijlenhoet et al.* [2003] or *Atlas et al.* [1999]. The variability of the DSD is a major source of inaccuracy in rainfall estimation by remote sensing (active or passive) because it affects the relationship between the measured variables and the rainfall. Many authors have discussed how the Z-R relationship between radar reflectivity and rain rate depends on DSD parameters and their variability [*Testud et al.*, 2001; *Steiner et al.*, 2004; *Lee et al.*, 2004]. It has been suggested that convective and stratiform rain should be partitioned in order to use distinct Z-R relationship for each type [*Atlas et al.*,1999; *Maki et al.*, 2001; *Uijlenhoet et al.*, 2003; *Tokay and Short*, 1996]. Documenting drop size distributions in the tropics is also of interest for quantifying the impact of convective systems and for modelling applications. The parameterization of the DSD in numerical models affects key variables such as the evaporation rate which plays a crucial role in the exchange of energy between convective systems and their environment. Quantifying the proportions of convective and stratiform rain is also important because the latent heat profiles associated to these types of rain are very different [*Schumacher et al.*, 2007].

[4] The present work is based on the analysis of about 12 000 minutes of disdrometic data gathered in Benin with optical disdrometers, from 2005 to 2007. The shape of the drop size spectra and the frequency distributions of DSD parameters in this region are studied. We also analyse the differences between the spectra generated in convective and stratiform rain and finally, discuss the radar reflectivity - rainfall rate (Z-R) relationships.

2. Data Set and Methods

2.1. Data

[5] Three optical disdrometers, also referred to as Optical SpectroPluviometer (OSP hereafter), were set up near the town of Djougou (latitude 9.66°N, Longitude 1.69°) during the Enhanced Observing Period (EOP) of the AMMA Campaign [*Redelsperger et al.*, 2006]. The instruments are based on an optical principle. A near-IR rectangular single or double-beam of light is attenuated by the falling rain drops [*Salles et al.*, 1998; *Löffler-Mang and Joss*, 2000; *Delahaye et al.*, 2005]. The attenuation can be related to the size of the drop and the transit time of the drop in the beam can be related to its vertical velocity. The signal processing of the OSP allows the accurate measurement of the drop sizes over the whole spectrum including smaller drops. The quality of the measurements was confirmed by our own tests using calibrated beads. Note also that the ability of optical disdrometers to measure both sizes and fall speed helps to eliminate spurious data. In addition the instruments are equipped with a simple 'anti-splash' system to prevent big drops from breaking up when hitting the instrument.

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Table 1. Data Sets[a]

Name/Type of Disdrometer/ Horizontal Area	Location	Operating Period	Number of Validated Recorded Rain Event/ Number of Minute Spectra
Parsivel/single beam IR OSP/48.6 cm^2	Nangatchori (1.74°E, 9.65°N)	Aug–Oct/2005	10 events/1816 spectra
OSP/single beam IR/100 cm^2	Djougou (1.66°E, 9.69°N)	Jun–Sep 2006 Jun–Oct 2007	14/1772 42/4958
DBS/double beam IR/100 cm^2	Kopargo (1.56°E, 9.82°N)	Jun–Sep 2006	27/3101

[a]IR stands for Infra Red, OSP for Optical SpectroPluviometer and DBS for DualBeam optical Spectropluviometer.

The disdrometer characteristics and data sets are summarized in Table 1. The disdrometers didn't work simultaneously for the whole observing period, because of technical problems. Altogether 93 rain events and a total rain amount of 1220 mm were recorded. The quality of the dataset was verified by comparing the rain amounts recorded by the disdrometers with the nearest tipping bucket rain gauge. The correlations are between 0.85 and 0.99 for the three data sets.

[6] The raw data have been processed into one minute spectra, with the equivalent spherical drop diameters sorted into 32 diameter classes from 0.125 up to 26 mm with a variable diameter increment (0.125 up to 3 mm).

[7] A DSD spectrum $N(D)$ (dimension: $[L^{-4}]$) is defined as the raindrop concentration in a given air volume as function of the diameter . It is used to calculate several integral parameters such as the moment of order p of the DSD M_p or characteristic diameters such as the mass weighted mean diameter $D_m = M_4/M_3$. Other variables of interest for hydrological applications such as the rain rate R (mm/h) and the radar reflectivity factor Z can also be calculated.

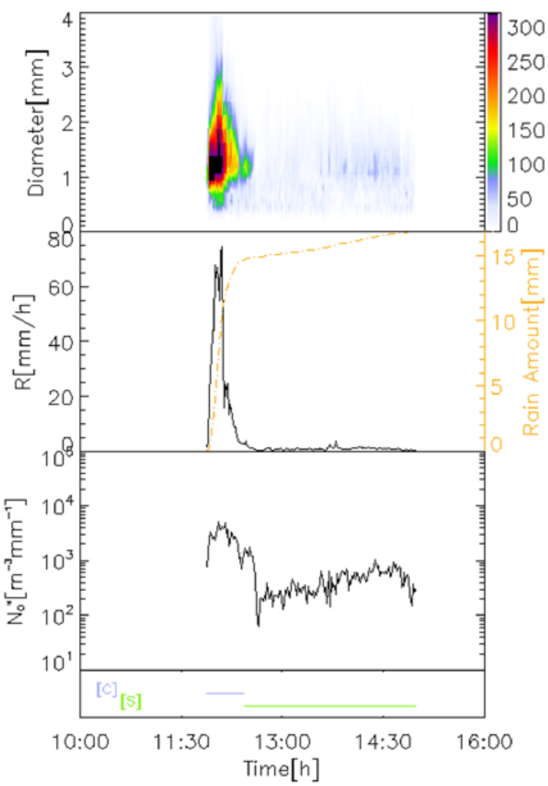

Figure 1. Illustration of the temporal evolution of the Drop size spectra within a squall line (here from the 25/07/2007). Raw spectra with the density number of drops in $m^{-3}mm^{-1}$, time evolution of the rain rate (R), time evolutions of N_0* and indication of convective (C)/stratiform (S).

2.2. Fitting a Model to the Observed Drop Size Distribution

[8] The most commonly used functional model of DSD is the exponential model which provides a good fit to the averaged DSD associated with widespread precipitation in mid latitudes. The Gamma model was introduced to better represent the convexity of observed spectra and is particularly relevant for tropical rain:

$$N(D) = N_0 D^{\mu} \exp\left[-\frac{(4+\mu)D}{D_m}\right], \quad (1)$$

with N_0 the intercept parameter expressed in $m^{-3}mm^{-1-\mu}$ for D and D_m in mm. μ is the shape parameter.

[9] It has been shown however [*Testud et al.*, 2001] that in (1) the value and units of N_0 depend on μ and it is difficult to give a physical meaning to this parameter. A normalized formulation was introduced:

$$N(D) = N_0^* \frac{\Gamma(4)(4+\mu)^{4+\mu}}{4^4\Gamma(4+\mu)} \left(\frac{D}{D_m}\right)^{\mu} \exp\left[-\frac{(4+\mu)}{D_m}D\right], \quad (2)$$

N_0* is a μ independent parameter which reduces to N_0 when μ = 0 (case of the exponential DSD). N_0* is a function of D_m and M_3, and can be readily calculated from the measured spectra:

$$N_0^* = \frac{4^4 M_3}{\Gamma(4) D_m^4}. \quad (3)$$

Several methods have been proposed to derive N_0* (or N_0), D_m and μ, from observed spectra.

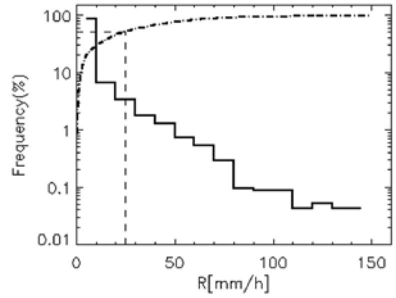

Figure 2. Frequency distribution of the rain rates in Benin (bold line) and cumulative contribution to the yearly rainfall(dot dash).

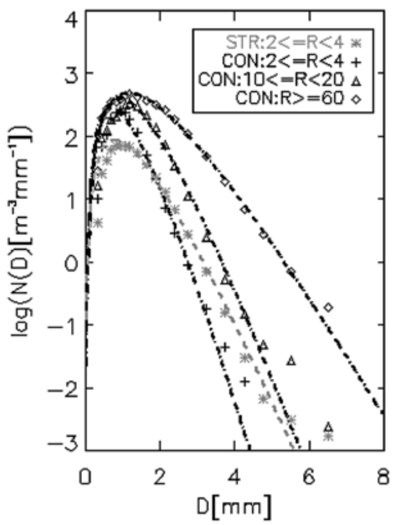

Figure 3. Average spectra calculated for several rain rate classes, as indicated. Convective (black symbols) and stratiform (gray symbols) spectra are distinguished for the lowest class. The Gamma functions fitted on each averaged spectrum are plotted.

[10] The moments method [*Tokay and Short*, 1996] retrieves the 3 parameters, for each spectrum, from 3 moments of the DSD. Others have proposed to fit a functional form to averaged DSD rather than to the individual spectra, to avoid measurement noise. *Ochou et al.* [2007] sorted their observations by class of rainfall and fitted the averaged spectra in each class. *Sempere-Torres et al.* [1994] established a normalization of the DSD as $N(D,R) = R^{\alpha}\, g(D/R^{\beta})$ and fitted the 'intrinsic function' g() to the normalized spectra. *Testud et al.* [2001] preferred a double moment parameterization (later generalized by *Lee et al.* [2004]). Testud's method has been applied to fit normalized gamma functions to our data set using M_3 and M_4. μ is obtained by a least squares fit of a gamma function over the normalized spectra or can be derived from each spectrum with the moment method. N_0 can then be calculated from N_0*, Dm and μ.

[11] The suitability of the fitting method was checked by comparing the DSD moments calculated on the observed spectra with those estimated from the model as was done by *Lee et al.* [2004].

2.3. Rain Type and Intensities

[12] In Benin most of the rainfall is provided by convective systems, about half of them being well organized squall lines. To distinguish between the spectra associated with convective and stratiform precipitation within these systems, we adopted the technique proposed by *Testud et al.* [2001] based on the variability of rain rate with time. The spectrum *k* is classified as stratiform if and only if its rain rate R_k and also the rain rate of the 2*l* neighbours (i.e. R_{k-1} to R_{k+l}) are below 10 mm h^{-1}. *l* defines the width of influence of the convective spectrum or cell. Its value is set to *l* = 10 (i.e. 10 minutes) in the present work. The classification is illustrated on a squall line in Figure 1.

[13] For the whole data set, one third of the spectra could be classified as convective and that they contribute to 75 to 80% of the recorded rainfall. Two third of the spectra were classified as stratiform and that they contribute to 25 to 20% of the recorded rainfall. Figure 2 shows the probability distribution of the rain rates in the area of Djougou and their contribution to the annual rainfall. In the region, half of the total rain amount is provided by rain rates above 25 mm/h.

3. Results

3.1. DSD Observed in Benin

[14] The mean values of N_0*, μ, D_m and N_0 for each data set are summarized in Table 2. The dispersion in the retrieved values of μ and thus N_0 is much lower for the normalization method than for the moments method. It is noteworthy that the results are consistent from year to year and between instruments. It is found that the spectra are well fitted with a gamma DSD with a parameter μ close to 5 (mean value of 5.5 with a standard deviation of 2.5, over the whole data set), confirming the deficit of small drops reported by *Sauvageot and Lacaux* [1995]. This 'convexity' of the spectra is also visible in Figure 3 where the averaged spectra for several rain rate classes are displayed. The values of N_0* are low, close to 10^3 $mm^{-1}m^{-3}$ (the mean of $\log_{10}[N_0*]$ is 3.13 and its standard deviation is 0.5, over the whole data set).

[15] We also selected 20 well organized squall lines passing over the instrument (as in Figure 1), in order to analyze the difference between the convective and stratiform parts. The results are detailed in the last 3 lines of Table 2. The values of N_0* are twice to three time higher for convective spectra than for stratiform ones. This is consistent with the sharp drop in N_0* observed in Figure 1 (and other squall line cases) at the transition between the convective peak and the stratiform trail. The averaged convective and stratiform spectra for a low rain rate class are displayed on Figure 3. *For a given rate*, the stratiform spectra contain a higher proportion of the largest drops than the convective ones. 'Large drops' stratiform spectra have previously been explained [*Tokay and Short*, 1996; *Maki et*

Table 2. Mean Value (and Standard Deviation) of the DSD Parameters for Each Data Set

	$\text{Log}_{10}(N_0*)$	D_m	μ		$\text{Log}_{10}(N_0)$	
Method	Moments M3, M4	Moments M3, M4	Moments M3, M4, M6	Fit of $F(D/D_m)$	Moment M3, M4, M6	Fit of $F(D/D_m)$
All PARSIVEL 2005	3.21 (0.5)	1.56 (0.4)	6.82 (4.9)	5.00 (2.7)	5.41 (2.3)	4.68 (1.3)
All Spectra DBS 2006	3.18 (0.6)	1.58 (0.5)	9.50 (5.5)	5.47 (2.4)	5.98 (2.4)	4.83 (1.5)
All Spectra SPO 2006	3.10 (0.4)	1.74 (0.5)	7.37 (5.2)	4.80 (2.7)	5.03 (2.0)	4.34 (1.2)
All Spectra SPO 2007	3.08 (0.4)	1.68 (0.4)	9.0 (5.7)	6.01 (2.6)	5.42 (2.1)	4.67 (1.3)
20 Squall Lines						
ALL	2.99 (0.5)	1.71 (0.4)	8.19 (5.3)	5.27 (2.4)	5.14 (2.1)	4.36 (1.3)
CONV	3.53 (0.4)	1.90 (0.5)	7.99 (5.5)	5.71 (2.5)	5.41 (2.0)	4.80 (1.2)
SRAT	2.81 (0.4)	1.65 (0.4)	8.26 (5.2)	5.12 (2.4)	5.05 (2.1)	4.21 (1.3)

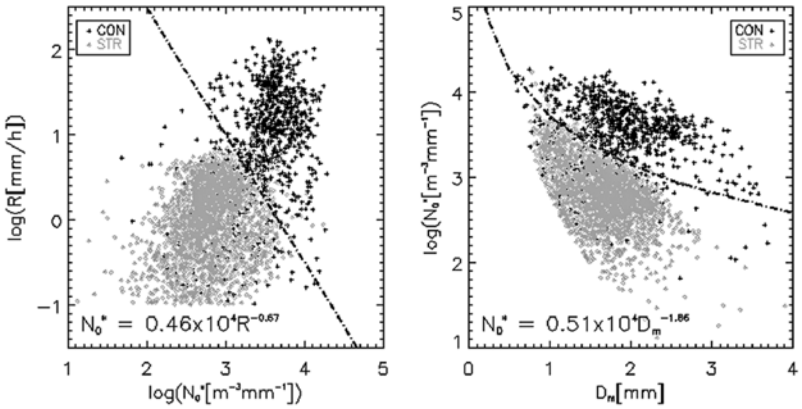

Figure 4. Scatter plots of 2 pairs of parameters: (left) (R, N_0*) and (right) (D_m, N_0*), for the 20 squall lines. Gray:stratiform spectra, Black:Convective spectra. The best fitted separation lines are shown in dash-dot.

al., 2001] by the occurrence of aggregation just above the freezing level, producing large ice particles which then melt into large drops. Spectra shifted towards large diameters could also be the result of small raindrop evaporation. The question will be further investigated within AMMA, using the tri-dimensional, dynamical and microphysical information provided by radars and profilers.

[16] The differences between the convective and stratiform regions is further analyzed in R, D_m and N_0* space, in Figure 4. As was seen by *Tokay and Short* [1996], *Maki et al.* [2001], and *Testud et al.* [2001] a clear separation is seen between the two sets of spectra. It is found that more then 82 % of the convective spectra and 92 % of the stratiform spectra fall on the right side and left side of the partition line respectively, for the 20 observed squall lines.

3.2. Z-R Relationships

[17] Drop size distribution is often analyzed in the context of weather radar applications, because the Z-R relationships depends on DSD parameters and on their variability with R. The parameters *a* and *b* of the $Z = aR^b$ relationships derived from our set and subsets are listed in Table 3. The values are consistent with those reported previously for West Africa or other continental locations (Table 4). It is noteworthy that the relationship derived for Benin when considering only the best organized squall lines, is distinct from the global relationship and is very similar to the one derived in Niamey where most of the systems *are* continental squall lines. Tables 3–4 also show that the Benin "squall line" relationship is close to the one for continental squall lines in Australia, while the one previously reported for a coastal location in Senegal is closer to the one found by *Tokay and Short* [1996] for a maritime tropical environment in the Pacific. As expected from the analytical expression of *a* and *b* and discussed in many papers, the prefactor *a* is higher in the stratiform part because of lower N_0 and this should be considered when estimating rainfall.

4. Conclusion

[18] Rain Drop Size distributions representative of the Mesoscale Convective systems found in West African Sudanese climate conditions have been analyzed. The following features stand out from this three-year data set and are consistent over the three different types of optical disdrometers used for the study.

[19] 1. A two parameter normalized gamma distribution with a shape parameter μ as high as 5 fits our observations best.

[20] 2. The classification of convective and stratiform spectra leads to two subsets which are clearly discriminated in a D_m- N_0* or N_0*-R space. The distinction of the DSD types is well observed in squall lines, with sharp changes in the normalized intercept parameter N_0* between the con-

Table 3. Coefficients of the Z-R Relationships for Our Data Set

Rain Type	a	b	R2
	Whole Data Set		
ALL	433	1.33	0.85
CONV.	343	1.38	0.85
STRAT.	468	1.39	0.67
	20 Squall Lines		
ALL	509	1.31	0.85
CONV.	289	1.43	0.84
STRAT.	562	1.44	0.66

Table 4. Z-R Relationships From Other Authors

Location	Rain Type	a	b
Ochou et al. [2007]			
Niger (Niamey)	ALL	508	1.28
Congo (Boyele)	ALL	389	1.34
Sauvageot and Lacaux [1995]			
Continental Africa (Niger, Congo)	ALL	364	1.36
'Equatorial' Africa (Ivory Coast)	ALL	369	1.28
Maki et al. [2001]			
Australia (Darwin, continental squall lines)	CONV	232	1.38
	STRAT	532	1.28
Nzeukou et al. [2004]			
Senegal (Coast)	ALL	368	1.24
	CONV	162	1.48
	STRAT	385	1.21
Tokay and Short [1996]			
Equatorial Pacific (Kapingamarangi Atoll)	ALL	315	1.20
	CONV	139	1.43
	STRAT	367	1.30

vective and stratiform regions. This occurrence of 'large drop' spectra in the stratiform region could be explained by the presence of large ice particles created by aggregation above the freezing level or it could be a sign of rainfall evaporation as it falls. Further analysis, including data available through the AMMA campaign, will allow us to investigate further the question and have a better insight into the vertical evolution of the DSDs.

[21] 3. Z-R relationships were derived from our observations. The global relationship (prefactor a = 433 and exponent b = 1.33) is consistent with those found previously for continental West Africa. When considering only the best organized squall lines, the relationships are a = 509, b = 1.31 for the whole data set, a = 289, b = 1.43 for the convective, a = 562, b = 1.44 for the stratiform part. These are similar to those for continental squall lines in Niger or in Australia. These relatively high values of the prefactor a are consistent with the low values of N_0* (3000 $mm^{-1}m^{-3}$ for convective spectra, 1000 $mm^{-1}m^{-3}$ for the stratiform) that were observed.

[22] **Acknowledgments.** Based on a French initiative, AMMA was built by an international scientific group and is currently funded by a large number of agencies, especially from France, UK, US and Africa. It has been the beneficiary of a major financial contribution from the European Community's Sixth Framework Research Programme. Detailed information on scientific coordination and funding is available on the AMMA International web site http://www.amma-international.org.

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