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ON THE CHARACTERISTICS OF THE RAINFALL EVENTS IN THE SAHEL WITH A VIEW TO THE ANALYSIS OF CLIMATIC VARIABILITY

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ABSTRACT

The lack of appropriate data has long been a major obstacle to the study of the Sahelian rainfall at the event scale. In this paper, use is made of the EPSAT-Niger recording rain-gauge data to characterize the convective rain events of the central Sahel. Although some considerations lead to the identification of two main types of mesoscale convective systems, it is shown here that the most relevant stratification in terms of statistical analysis of the event rainfall distribution is between the events of the margins and those of the core of the rainy season. In fact, the average storm rain-depth appears to be non-stationary in time, with storm rain-depths slightly higher in the core of the rainy season than on the margins. Separation between the core and the margins thus allows the fitting of an exponential model to the observed storm rain-depth distributions of each period (core and margins), although a better fit would certainly be obtained if a proper modelling of the time non-stationarity was carried out. It is then shown that there is little, if any, correlation between the mean storm rain-depth of a given year and the overall abundance of the corresponding rainy season. This is a validation of previous works, which reached the same conclusion using daily rainfall data only. One major result of this work is that the statistics characterizing the rain events in the Sahel display little fluctuations, either in space or from year-to-year, as compared with those observed for the total seasonal rainfall. Each year and at each station the average storm rainfall remains close to 12 mm during the margins of the rainy season and close to 15 mm in the core. During the same period, the average seasonal rainfall over the study area ranged from 400 to 660 mm and for any given year the ratio between the maximum and the minimum point seasonal rainfall was of the order of 2. It is therefore concluded that the main source of rainfall variability in the Sahel is linked to the variability in the number of events rather than in the magnitude of these events. © 1998 Royal Meteorological Society.

KEY WORDS: Sahel; mesoscale convective systems; storm rainfall; rain events; exponential distribution; interannual variability

1. INTRODUCTION

Tropical rainfall is mostly of convective origin, associated with the Hadley circulation. The ascending branch of the Hadley cell, where deep convection develops, is known as the Inter Tropical Convergence Zone (ITCZ). Over West Africa the rainfall regime is determined by the two north–south movements of the ITCZ. When moving away from the Equator, the duration of these events tends to decrease while the average inter-event duration increases. In the semi-arid areas that border the deserts associated with the tropical divergence zones, the rainfall regime consists of a succession of easily separable storms occurring during a single rainy season and corresponding to the circulation of the convective systems embedded in a westward circulation. The abundance of rainfall in the rainy season is thus determined by the number of storms, on the one hand, and by the average storm rainfall on the other hand. The seasonal rainfall largely varies from one year to another and the semi-arid regions of Africa, whether north or south of the Equator, are notorious for their droughts, which are a permanent threat to the local people.

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Whereas quite a few papers have been devoted in the past decade to the possible causes of the prolonged drought that has struck the Sahel for 25 years now (Bryson, 1973; Winstanley 1973; Charney, 1975; Kraus, 1977; Lamb, 1978a,b; Nicholson, 1981; Folland *et al*., 1986; Janicot, 1992; Janicot and Fontaine, 1993), the rainfall patterns associated with this drought have not yet been totally described and modelled. A recent study by Le Barbé and Lebel (1997) has shown that in the central Sahel most of the precipitation reduction for the period 1970–1989, with reference to the period 1950–1969, is explained by a decrease in the number of rain events, whereas the average storm rainfall did not vary much.

Such conclusions are of paramount importance for the hydrology and the agriculture of the region. Fewer events of unchanged magnitude, distributed over a rainy season of roughly unchanged length could imply a more drastic reduction of the water available for the vegetation than would an unchanged number of rainfall events of lower magnitude. One major difficulty in studying the characteristics of the storm rainfall comes from the lack of appropriate data. In the Sahel, the meteorological and hydrological networks comprised very few recording rain-gauges until recently and where such gauges were available, recordings are often of poor quality (large proportion of missing data). Therefore, only data may be used to characterize the storm rainfall. As a rain event may be not encompassed within the limits of a single day, or, in rare instances, more than one event may occur in 1 day, the daily rainfall cannot be directly equated with storm rainfall.

The ongoing ESPSAT–Niger experiment, which has taken place in the region of Niamey from 1990 onwards, offers a first opportunity to remedy this situation thanks to the operation of several dozen digitized recording rain-gauges spread over a 16000 km^2 area (Lebel *et al*., 1992). Using the data collected from 1990 to 1995 the intent of this paper is to provide some insights into the characteristics (mean and variability) of the Sahelian storm rainfall. Two variability modes will be investigated: the interannual and the intraseasonal modes. At both scales, it will be examined whether the frequency distribution of the storm rain-depths is stationary in time and space and whether it cofluctuates or not with the seasonal rainfall.

2. THE EPSAT-NIGER DATA SET

In the region of Niamey, where the EPSAT-Niger network is located, the average length of the rainy season is about 5 months (from May through to September). About 99% of the annual rain total falls during this period. The peak of the rainy season is August, but local dry spells of up to 10 days are

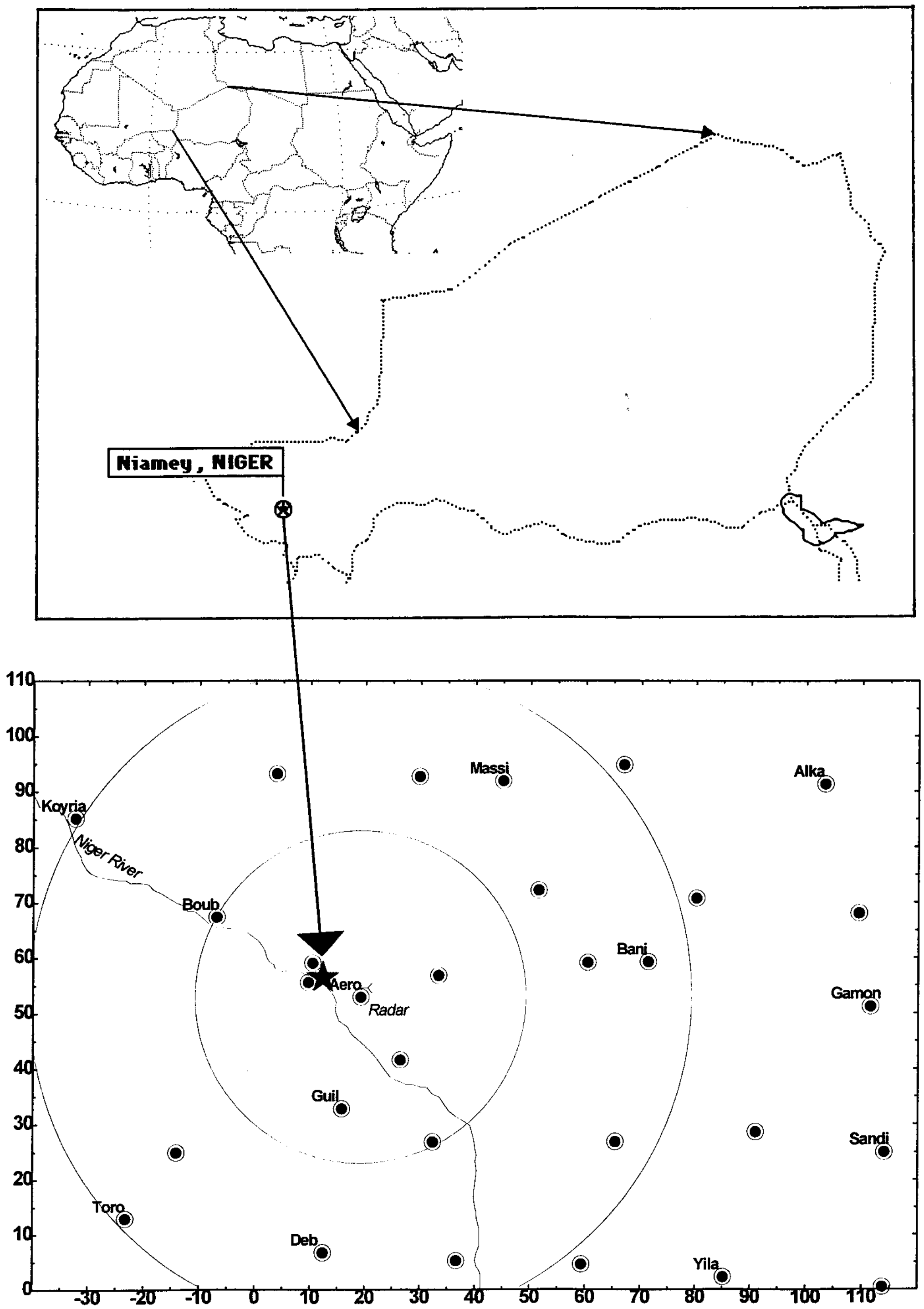

Figure 1. The study area and the long-term monitoring EPSAT-Niger rain-gauge network (30 stations). Coordinates are in kilometres, the origin (0, 0) being located at 13°N and 2°E. The stations used in Figures 3 and 7 are indicated (abbreviated names). The circles indicate the 30 and 60 km ranges from the radar

Table I. Storm rainfall statistics for the 30 stations of the long-term observing EPSAT-Niger network: rainfall in millimetres: latitude and longitude in degrees and decimal minutes. The stations are listed by decreasing latitude order. Conditional means that zero rainfall are excluded from the computation of the average

Number	Name	Latitude	Longitude	1990–1993 (170 rain events)		1994 (53 rain events)	
				Number of non-zero rainfall events	Mean conditional storm rainfall	Number of non-zero rainfall events	Mean conditional storm rainfall
1	Korborbe Fand.	13 51.16	2 37.18	113	13.57	32	17.78
2	Gorou Goussa	13 50.30	2 02.13	118	14.01	31	11.78
3	Massi Koubou	13 50.10	2 24.46	123	12.78	36	13.03
4	Gardama Kou	13 50.06	2 16.55	117	12.64	29	15.20
5	Alkama	13 49.31	2 57.46	117	13.51	33	17.78
6	Koyria	13 46.00	1 42.00	124	11.80	27	14.43
7	Beri koira	13 38.99	2 28.61	131	15.17	41	10.47
8	Darey	13 38.20	2 44.53	123	13.70	42	11.59
9	Kaligorou	13 36.74	3 00.78	122	13.70	36	17.24
10	Boubon	13 36.40	1 56.15	130	13.86	33	13.47
11	Banizoumbou	13 31.97	2 39.62	126	13.20	46	13.88
12	Fandou Beri	13 31.91	2 33.52	124	13.87	42	13.81
13	Niamey ORST.	13 31.87	2 05.80	133	13.06	39	13.89
14	Berkiawal	13 30.68	2 18.51	134	12.77	39	11.55
15	Niamey IRI	13 30.00	2 05.35	129	13.78	38	15.36
16	Niamey Aero.	13 28.79	2 10.39	132	12.90	40	14.15
17	Gamonzon	13 27.67	3 01.90	130	14.69	34	15.42
18	Kollo	13 22.45	2 14.66	136	12.68	39	14.62
19	Guilahel	13 17.69	2 08.75	133	15.92	40	16.83
20	Harikanassou	13 15.46	2 50.47	132	13.92	38	14.21
21	Houre Sud	13 14.51	2 36.30	130	14.09	43	14.88
22	IH Mil	13 14.48	2 17.94	136	14.25	43	14.09
23	Sandideye	13 13.52	3 03.23	116	14.49	38	13.39
24	Bololadie	13 13.48	1 52.20	130	12.71	42	12.61
25	Torodi	13 07.00	1 47.10	130	15.30	36	17.21
26	Debere Gati	13 03.66	2 06.86	122	12.71	40	17.16
27	Kare	13 02.87	2 20.31	122	13.78	43	17.65
28	Tanaberi	13 02.50	2 32.88	129	14.77	42	12.57
29	Yillade	13 01.27	2 47.13	123	13.03	40	16.04
30	Koure Kobade	13 00.28	3 03.00	113	14.32	38	15.40
Average					13.7		14.6

Table II. Main statistics characterizing the Sahelian rainfall events observed over the period 1990–1993 by the EPSAT-Niger set-up. MCCs (mesoscale convective complexes) and MCSOs (other mesoscale convective systems) have been identified based on a classification adapted from Amani *et al*. (1996)

Sample	No. events		Areal mean storm rainfall (mm)		Average percentage of zero rainfall		Average duration (minutes)		Average speed (MCCs only)
	MCC	MCSO	MCC	MCSO	MCC	MCSO	MCC	MCSO	
(a) At the event scale[a]									
1990	18	20	15.6	4.4	6.9	41.2	126	65	
1991	27	18	14.0	5.6	7.2	39.6	158	62	
1992	23	26	15.8	4.1	8.3	49.7	159	62	
1993	18	20	16.7	5.0	7.0	47.3	169	59	
1990–1993	86	84	15.4	4.7	7.4	45.0	157	64	54 km h^{-1}
	170		10.1		26				

Sample	No. events			Total seasonal rainfall (mm)	Share of the seasonal rainfall (%)			
	MCC	MCSO	Total		MCC	MCSO	All MCS	Isolated rain
(b) At the seasonal scale								
1990	18	20	38	396	71	22	93	7
1991	27	18	45	523	72	20	92	8
1992	23	26	49	513	71	21	92	8
1993	18	20	38	459	66	22	88	12

[a] The areal mean storm rainfall is for the entire EPSAT-Niger study area, including the areas of zero rainfall

station over the period 1990–1993 and 53 in 1994) and the series of non-zero values, the number of which changes from one station to another. The statistics of the non-zero series are given for each station in Table I.

3. GENERAL CHARACTERISTICS OF THE SAHELIAN RAINFALL EVENTS

3.1. Definition of the rainfall events

A rain event is defined with respect to the network observations as follows: at least 30% of the rain-gauges in operation must record rainfall over the event period; at least one station must record more than 1.0 mm of rainfall; the rainfall must not stop over the entire network for longer than half an hour (otherwise the event is considered to have ended at the time when it stopped at the station(s) having recorded the last rainfall). Obviously this definition is contingent upon the area of the study zone as well as the network density. Nevertheless, the EPSAT-Niger network appeared to be dense enough so as to give a good estimation of the rainy areas. The number of rain events, or storms, determined from the entire network (107 gauges) over the period 1990–1993 was 172. When considering only the 30 stations of the long-term monitoring network, the number of storms totalled 170. The long-term network used in this study thus appears to be dense enough for detecting the major rain events affecting the area. Note that in a comparative study of the rainfall events so detected by the EPSAT-Niger network and of the mesoscale convective systems (MCSs) identified from the analysis of Metosat infrared data, Laurent *et al.* (1997) have shown that there was a 90% agreement between the EPSAT-Niger set of events and the Meteosat set of MCSs. In the following we will thus admit that the EPSAT-Niger rain events are assimilable to the MCSs overpassing the area during the rainy season. These rain events account for about 90% of the total seasonal rainfall (Lebel *et al.*, 1997).

In West Africa, MCSs have commonly been classified according to their extension and dynamics (see e.g. Barnes and Sieckman, 1984; Desbois *et al.*, 1988; Laing and Fritsch, 1993; Polcher, 1995). Amani *et al.* (1996) have proposed an objective procedure to stratify the sample of EPSAT-Niger events into three categories. An equivalence can be made between the mesoscale convective complexes (MCCs) of Laing and Fritsch (1993) and the two first groups of a ground-based classification adapted from Amani *et al.* (1996) by adding F_0 as a classification parameter (F_0 is the probability of zero rainfall at the event scale). The third group of the ground based classification is made of the less organized MCSs, to which we will refer in the following as other mesoscale convective systems (MCSOs). The statistics of the MCCs and MCSOs subsamples are given in Table II. Although there is a similar number of events in each group, the MCCs produce a little more than 70% of the seasonal rainfall. The MCCs storms are long-lived and produce more rainfall than the MCSOs due to a smaller proportion of non-zero rainfall within the storm area and to a higher average intensity (Table II).

3.2. Spatial variability and stationarity

At the regional and interannual scales, the Sahelian rainfall is characterized by a climatological north-to-south gradient of about 1 mm km^{-1} (Lebel *et al.*, 1992), that is a difference of more than 100 mm between the south and the north of our study area. At smaller scales, the preliminary works of Lebel *et al.* (1995) and Lebel *et al.* (1997) have shown that the seasonal rainfall displays a large year-to-year variability and, for a given year, an equally large station to station random variability, as illustrated in Figure 2. Every year the ratio between the maximum and the minimum point seasonal rainfall recorded by the EPSAT-Niger network was of the order of 2 (for instance in 1991: average rainfall $A = 523$ mm; minimum $m = 340.9$ mm; maximum $M = 745.3$ mm; $M/m = 2.2$; $(M - m)/A = 0.77$). There is also a strong variability, when considering individual rainfall events, inherent in the convective nature of the Sahelian rainfall. One could thus expect to find some trace of these features in the storm rainfall statistics, either as a systematic trend linked to the interannual north-to-south gradient, or as a random variability that could explain that which is found at the seasonal scale. To study this, the averages of the storm rainfall computed at each station are compared.

The storm rainfall is computed for each station, on a yearly basis and over the reference period 1990–1993. In the following, only the conditional averages of the non-zero rainfall series are considered, that is:

$$\bar{r}_i = \frac{1}{K_i} \sum_{k=1}^{K_i} r_{ik}, \tag{1}$$

where r_{ik} is the storm rainfall for station i and event k and K_i is the number of non-zero storm rainfall at a station i over the period considered. A variance analysis is then carried out to test the hypothesis that all the above-defined station averages are equal. This is done by computing the ratio of the among-station variance to the sum of the within-station and the among-station variances. Given I populations (stations), the means of which are estimated from samples of size K_i, the variable

$$F_{\text{obs}} = \frac{\dfrac{1}{I-1} \displaystyle\sum_{i=1}^{I} k_i (\bar{r}_i - \bar{r})^2}{\dfrac{1}{K-I} \displaystyle\sum_{i=1}^{I} \sum_{k=1}^{k_i} (r_{ik} - \bar{r}_i)^2} \tag{2}$$

in F-Snedecor distributed with $v_1 = I$ and $v_2 = K - I$ degrees of freedom, where

$$K = \sum_{i=1}^{I} K_i \tag{3}$$

and,

$$\bar{r} = \frac{1}{K} \sum_{i=1}^{I} K_i \bar{r}_i \tag{4}$$

Theoretically, the populations should be normally distributed and their variances equal. Nevertheless, according to Haan (1977), as soon as the sample sizes, K_i, are larger than 30 (which is the case here), this requirement is of secondary importance. The results of the test are given in Table III. The computed values of F are much smaller than either the $F_{0.05}$ and $F_{0.1}$ values, whatever the period considered. This indicates that assuming the mean storm rainfall as being first order stationary from year-to-year and for all stations is a reasonable hypothesis. The average mean storm rainfall (conditional upon the rainfall being non-zero) computed globally over the period 1990–1993 is 13.7 mm. We thus come to the first conclusion that the deterministic latitudinal trend characterizing the interannual averages and the random

Table III. Results of the F-test computed to compare the equality of the mean storm rainfalls of the 30 stations

Sample		Degrees of freedom	F computed	F theoretical 10%	F theoretical 5%
1990–1993	$I = 30$ $K = 3778$	$v_1 = 29$ $v_2 = 3748$	0.57	1.35	1.47
1990	$I = 30$ $K = 856$	$v_1 = 29$ $v_2 = 826$	0.65	1.38	1.50
1991	$I = 30$ $K = 1078$	$v_1 = 29$ $v_2 = 1048$	0.98	1.37	1.49
1992	$I = 30$ $K = 1025$	$v_1 = 29$ $v_2 = 995$	0.47	1.38	1.50
1993	$I = 30$ $K = 819$	$v_1 = 29$ $v_2 = 789$	1.02	1.37	1.49

Table IV. Results of the F-test computed to compare the equality of the mean storm rainfall for each year of the period 1990–1993. The hypothesis H_0 is $m_{1990} = m_{1991} = m_{1993} = m_{1993}$. $p(=4)$ is the number of years. K_i is the number of non-zero storm rainfall over the total period 1990–1993, for the station considered. In the last line, the individual mean storm rainfall of the 30 stations are averaged to define the mean storm rainfall of a given year

Sample		Degrees of freedom	F computed	F theoretical 5%	F theoretical 1%
Banizoumbou	$I=4$ $K_i = 126$	$v_1 = 3$ $v_2 = 122$	0.46	2.69	3.96
Boubon	$I=4$ $K_i = 130$	$v_1 = 3$ $v_2 = 126$	0.59	2.69	3.95
Massi Koubou	$I=4$ $K_i = 123$	$v_1 = 3$ $v_2 = 119$	0.43	2.69	3.96
Yillade	$I=4$ $K_i = 123$	$v_1 = 3$ $v_2 = 119$	0.80	2.69	3.96
All 30 stations	$I=4$ $K_i = 3778$	$v_1 = 3$ $v_2 = 3774$	2.37	2.60	3.78

spatial fluctuations of the seasonal rainfall are not matched by similar features in the spatial distribution of the mean storm rainfall. In other words, the variability modes in space are quite different whether considering the storm rainfall for a single event, the storm rainfall average over an ensemble of realizations, or the seasonal rainfall. The storm rainfall average may be considered as climatologically stationary at the scale of the EPSAT-Niger study area.

4. INTERANNUAL VARIABILITY

4.1. Average storm rain-depth

Using the same approach as above for comparing the stations, the value of the F-test has been computed to compare the mean storm rainfalls observed each year. The test was first performed on a station by a station basis. Expression 2 then becomes:

$$F_{\text{obs}}^{(i)} = \frac{\dfrac{1}{P-1} \sum_{p=1}^{P} k_{ip} (\bar{r}_{ip} - \bar{r}_i)^2}{\dfrac{1}{K_i - P} \sum_{p=1}^{P} \sum_{k=1}^{k_{ip}} (r_{ik} - \bar{r}_{ip})^2} \tag{5}$$

where

$$K_i = \sum_{p=1}^{P} K_{ip} \tag{6}$$

and,

$$\bar{r}_i = \frac{1}{P} \sum_{p=1}^{P} K_{ip} \bar{r}_{ip} \tag{7}$$

P $(=4)$ being the number of years, and the other indices similar to those used previously. The results are given in Table IV for four stations having less than 5% of missing data and chosen as far apart as possible (see Figure 1), so as to minimize their correlation. The computed value of F is well below the theoretical values at either the 1% or 5% level. Similar results were obtained from the other stations, indicating that the mean storm rainfall did not change significantly from year-to-year at any of the stations of the EPSAT-Niger network. The test was then repeated to evaluate the time stationarity at the scale of the whole study area. Instead of being constituted by the storm rainfalls recorded at one station only, the sample of a given year is made of all the non-zero storm rainfalls recorded by all the 30 stations. The equality of the mean of the four yearly samples so constituted is then tested in a similar way as was done for each station individually. The result is given in the last line of the Table IV. Again the computed value of F is below the theoretical values at either the level of 1% or 5% by a lesser margin, however.

The analysis of variance indicates that the mean storm rainfall did not vary significantly from year-to-year during the period 1990–1993. In contrast, an F test performed on the seasonal rainfall (the yearly sample being constituted by the 30 seasonal totals recorded at each of the stations) leads to the rejection of the hypothesis of identical mean seasonal rainfalls from 1 year to another ($F_{obs} = 14.6$; $F_{0.01} = 3.98$ for $v_1 = 3$ and $v_2 = 116$ degrees of freedom).

Thus, both in space and from year-to-year, the mean storm rain-depth displays much less variability than the seasonal rainfall. As a first approximation, the storm rain-depth may thus be considered to be stationary in the mean. Its statistical distribution will now be examined.

4.2. The global storm rain-depth distribution

Several studies, including those of Hershfield and Kohler (1960) (as a direct consequence of the validity of the Gumbel extreme value procedure), Smith and Schreiber (1974) and Cowpertwait (1994), have pointed to the fact that the storm rainfall distribution might be considered as exponential under certain conditions. The work of Smith and Schreiber (1974) is especially relevant to ours, because they used data from Arizona, a semi-arid region where rainfall is essentially convective in nature.

The exponential distribution has also been widely used in conceptual models (Todorovic and Yevjevich, 1969; Eagleson, 1978), especially those rooted in the compound poisson process theory (see e.g. Rodriguez

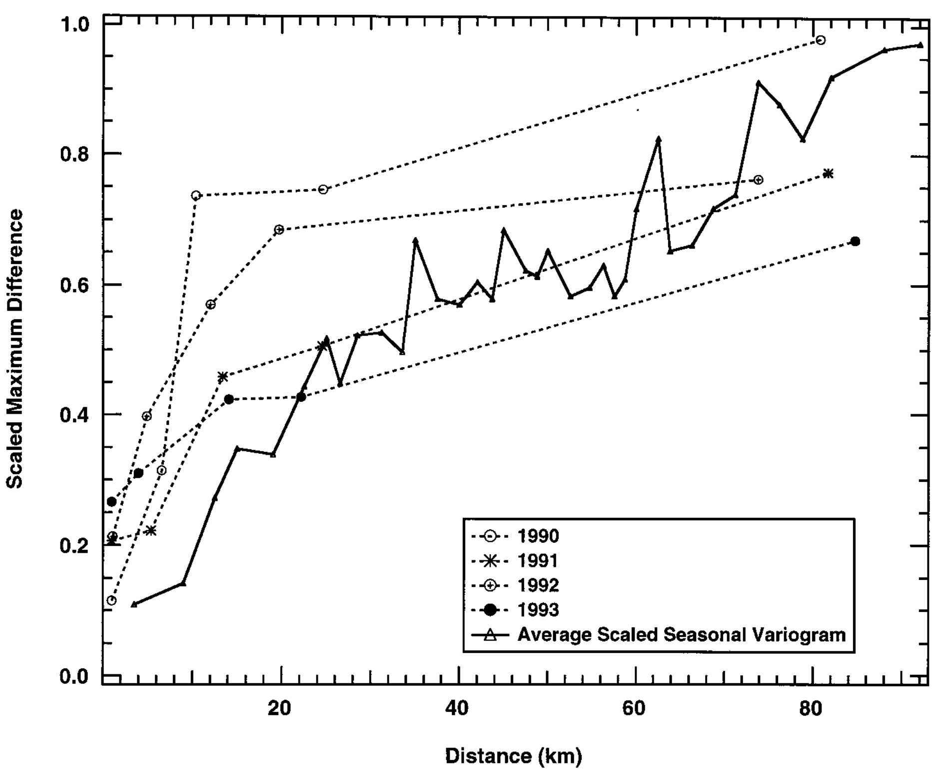

Figure 2. Space variability of the seasonal rainfall. The maximum differences between two stations recorded each year have been scaled by the average seasonal rainfall of the year over the EPSAT-Niger study area. The scaled differences are plotted along the average scaled seasonal variogram computed over the same 4 years. The steep increase of both the maximum differences and the variogram between the origin and 30 km illustrates the strong local variability of the seasonal rainfall in the Sahel

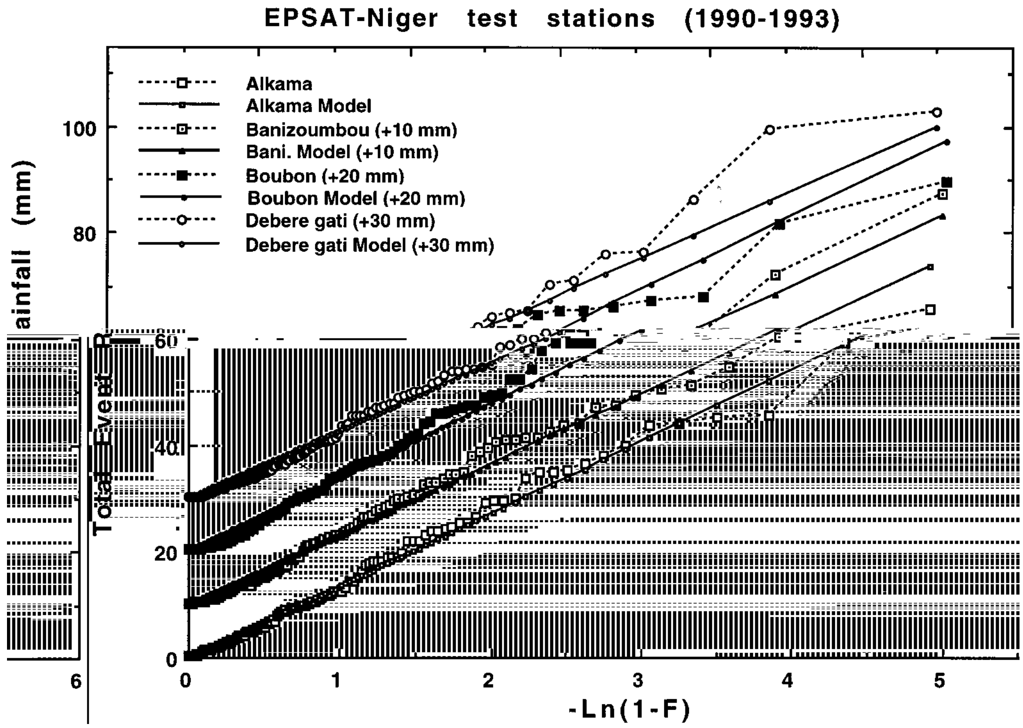

Figure 3. The global (seasonal) storm rainfall distributions for four stations. Each distribution is shifted 10 mm from the previous one along the rainfall axis for the purpose of clarity

Iturbe *et al.*, 1984; Cowpertwait, 1994) These models have not always been validated on real data but in a few instances they were (Eagleson *et al.*, 1987), with positive results.

A central requirement of this study is to find a regional model valid for all the 30 stations, because it would be senseless to end up with different types of models to extrapolate for stations belonging to the same climatic area, without any orographic effect. It will thus be tested first whether the distribution of the storm rain-depth in the Sahel may be considered as exponential. One main advantage of such a model is that it requires the estimation of only one parameter.

The exponential model of a probability density function (PDF) is:

$$f(r) = \frac{1}{s}\, e^{-r/s}, \tag{8}$$

and the corresponding cumulative distribution function (CDF) is:

$$F(r) = 1 - e^{-r/s} \tag{9}$$

Note that the non-exceedance probability of $r = 0$ is zero, which means that the exponential distribution applies to the series of non-zero rainfall only, the number of which k_i varies from one station to another, as explained above.

As shown in Figure 3 for a representative subset of four stations, the exponential distribution fits well to most of the 30 series but, in some cases, deviations may be observed in the upper part of the distribution. These deviations are alternately upward or downward. Among several alternative models tested, using the SAFARHY software (Lubès *et al.*, 1994), the only one that appeared to improve the quality of fit for some stations is the gamma-Pearson III distribution, as shown in Figure 4. However, this improvement is limited to a few cases, and is obtained through the estimation of an additional shape parameter. The value of this parameter varies from one station to another. Its average value is close to 1, indicating that the average behaviour of the 30 distributions is close to an exponential distribution. The question is thus whether this shape parameter should be allowed to vary from one station to another or to be constrained to be equal to 1 (which means that the variations of the estimated shape parameter are to be attributed to the effects associated to the sampling of the parent exponential distribution). To answer the question, a test, presented in the Appendix, has been designed. It is based on a joint analysis of the 30 fits, rather than on a case by case analysis.

The value e_i, for $i = 1$, 30, of this 'exponential test' was computed for each of the global storm rainfall distributions over the period 1990–1993. 'Global' here means that all the events are considered, irrespective of their data of occurrence within the rainy season. The parameter of the exponential distribution has been estimated by a moment method:

$$\hat{s}_i = \frac{1}{k_i} \sum_{k=1}^{k_i} r_{ik}. \tag{10}$$

The distribution of the 30 values e_i was then compared with the distribution $F_{125}(e)$ derived from the Monte Carlo simulation presented in the Appendix. It turns out that the values of the test computed on the EPSAT-Niger distributions are larger than those expected if the samples had been drawn from an exponential population, as shown in Figure 5. This leads one to question the validity of the exponential model for the global distributions. On the other hand, no alternative model seems really satisfactory in a regional perspective. The identification of a proper model of storm rain-depth distributions must be addressed by looking at the influence of the intraseasonal variability, which may affect the stationarity of the mean storm rain-depth.

5. INTRASEASONAL VARIABILITY

5.1. Study of the non-stationarity for the two types of rain events

The recent study of Le Barbé and Lebel (1997) has shown that, in the Central Sahel, the storm rainfall seems to be lower in the margins than during the core of the rainy season. If confirmed (it was reached

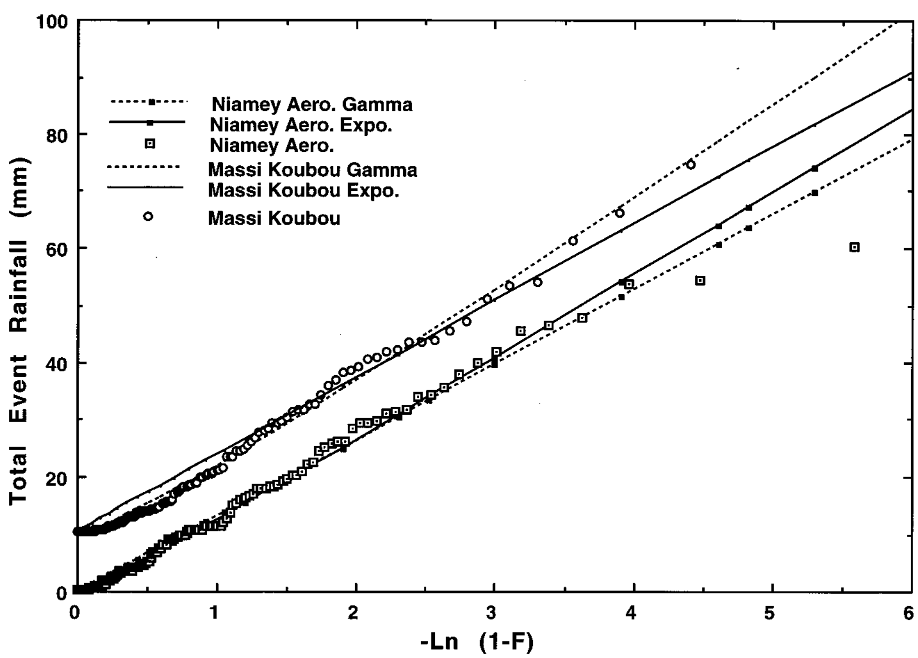

Figure 4. Comparison of the Pearson III and exponential fits to two experimental distributions: Massi Koubou (exponential test value: 0.29) and Niamey Aero (exponential test value 0.13)

Table V. Rainy events statistics by subperiod and type of events. The mean storm rainfall is at a point, conditional to non-zero

Period		April–May	June	1–15 July	16–31 July	1–15 August	16–31 August	September–October
Sample size	MCC	8	12	9	17	10	18	12
	MCSO	10	21	8	11	12	10	12
Point mean storm rainfall (mm)	MCC	15.3	14.3	11.9	15.8	24.7	17.7	14.6
	MCSO	8.5	9.9	10.6	6.5	10.1	7.2	9.2

indirectly because only one daily rainfall data were used), this result would indicate that one reason for not being able to fit a simple model to the storm rain-depth distribution is the intraseasonal variability. It can also be assumed that the different characteristics of the MCCs and of the MCSO are a factor of heterogeneity in the global sample.

One feature of the EPSAT-Niger data set is that it allows the investigation of the time evolution of the event rainfall during the rainy season separately for the MCCs and the MCSOs, an approach impossible when working on daily data as was the case for Le Barbé and Lebel (1997). Accordingly, the number of events and the mean event rainfall were calculated for each of these two categories of events and for seven different periods of the rainy season, chosen so as to obtain a sufficiently large number of events during each period (Table V). A classification procedure adapted from Amani *et al.* (1996) was used to produce the two subsamples, the first one numbering 86 MCCs and the 84 MCSOs. There is a significant fluctuation of the averages computed for each subperiod. Part of this fluctuation may be attributed to the sampling (the size of the series built for each of the seven subperiods is small) but when testing the hypothesis of equality of mean it is rejected at the level of 10%. It is thus likely that non-stationarity is present in the series of mean event rainfall that has to be taken into account. Therefore, in order to

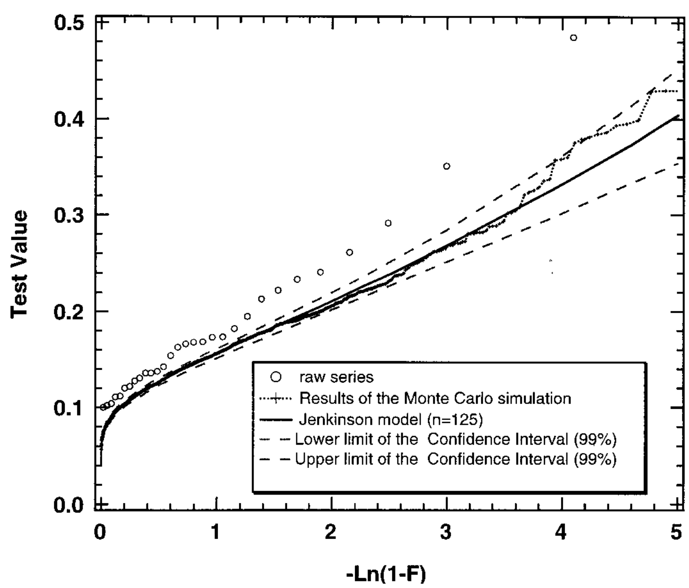

Figure 5. Comparison of the distributions of the exponential-test values, as resulting from the Monte Carlo simulation and from the fitting to the 30 seasonal storm rainfall distribution over the period 1990–1993. Also shown are the Jenkinson distribution fitted the experimental Monte Carlo distribution and the limits of the corresponding 99% confidence interval

remove some of the noise introduced in the testing of the exponential hypothesis by this non-stationarity, the 30 rainfall series have been scaled, using the following procedure:

$$r'_{ik} = \frac{r_{ik}}{\bar{r}_{l_k}(T_k)}, \tag{11}$$

where l_k denotes the subperiod in which the event k belongs and $\bar{r}_{l_k}$ is the experimental average of the mean event rainfall over this period for the type T_k (MCC or MCSO) of the event k.

The global mean of the $\{r'_{ik}\}$ series is equal to 1, but the individual stations means, $\bar{r}'_i$, fluctuate around 1, because the scaling factors are global averages and not the individual averages at each station.

5.2. Fitting the exponential distribution to the scaled stationary series

The exponential distribution has been fitted to the 30 scaled series $\{r'_i\}$. As may be seen from Figure 6, the scaling procedure considerably improves the quality of fit in several cases. In other instances, the improvement is minor or negligible. Finally, there are a few series for which the quality of fit is worse on the scaled series than on the original series. All in all, however, there is a marked improvement, as shown in Figure 7, where the respective experimental distributions of the test for the 30 unscaled and 30 scaled series are compared. Although the experimental distribution for the unscaled series is always outside the confidence interval of the theoretical distribution, the scaled series experimental distribution follows very closely the theoretical distribution, at least for the first 24 values of the test. The last six values of the exponential test are much larger than would be expected from the Monte Carlo simulations. This may come from s_l (the value of the mean event rainfall over the period l) being not correctly estimated, due to the small sample sizes, or from the representation of the non-stationarity being too crude.

Apart from the deviation observed at the end of the distribution, the results of the test tend to accredit the exponential hypothesis, or at least make it the most plausible, based on the data available in the region. Note that the model applies to partial duration series where MCCs and MCSOs have been grouped, after scaling by their own average.

5.3. Impact on the global distribution

The global distribution of the scaled series is exponential and so is the distribution of each partial series, $\{(r'_i)_l\}$ constituted for each subperiod l. These partial series are drawn from the same global population, which has a scale parameter s equal to 1. The partial unscaled series are also exponentially distributed, but their scale parameter, s_l, changes from one period to another, so that the raw global series are not distributed exponentially. We thus end up with a piecemeal representation of the global event rainfall distribution, which is not fully adequate, because there are sudden leaps in the average when going from one period to the next. A representation of the average as a continuous function of day of year would be more realistic, but again, this is difficult to obtain with the data currently available. This is why it is anticipated that the EPSAT-Niger monitoring network will be maintained in operation for several years to come.

6. ARE THE STORM RAIN-DEPTH CHARACTERISTICS CORRELATED TO RAINFALL PATTERNS AT LARGER SCALES?

In section 3 it was found that the space–time fluctuations of the global mean storm rain-depth were not correlated to the space-time variability of the seasonal rainfall, and that the climatological north-to-south gradient did not influence the magnitude of the rainfall events. We will examine in this section whether this independence still holds when the intraseasonal variability is taken into account. To increase the size of the subsamples, which is a limitation for the robustness of the statistical tests, two main subperiods are considered: the core of the rainy seasons (15 July to 31 August; mean event rainfall = 15 mm; mean MCC rainfall = 19 mm; mean MCSO rainfall = 8 mm) and the margins (before and after this period; mean

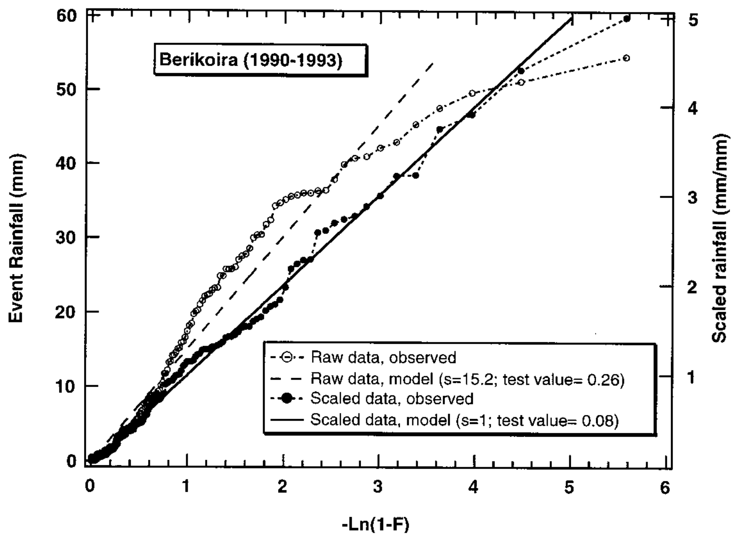

Figure 6. Comparison of the quality of fit of the exponential distribution to the series of raw data and to the series of scaled data. In the example shown, the improvement is significant (the test value is divided by a factor of three)

event rainfall = 12 mm; mean MCC rainfall = 14 mm; mean MCSO rainfall = 10 mm). By doing so, the sample sizes are all greater than 30, and greater than 40 in three cases out of four (whereas with the 14 samples of Table V, there were three samples where the size was less than 10).

6.1. Correlation with the latitudinal gradient of the seasonal rainfall

In Figure 8 the mean storm rain-depths computed for each station and each subperiod have been plotted against the latitude of the station. There is no apparent correlation between the latitude or either dependent variable. The coefficient of determination, r^2, is equal to 0.102 when considering the global

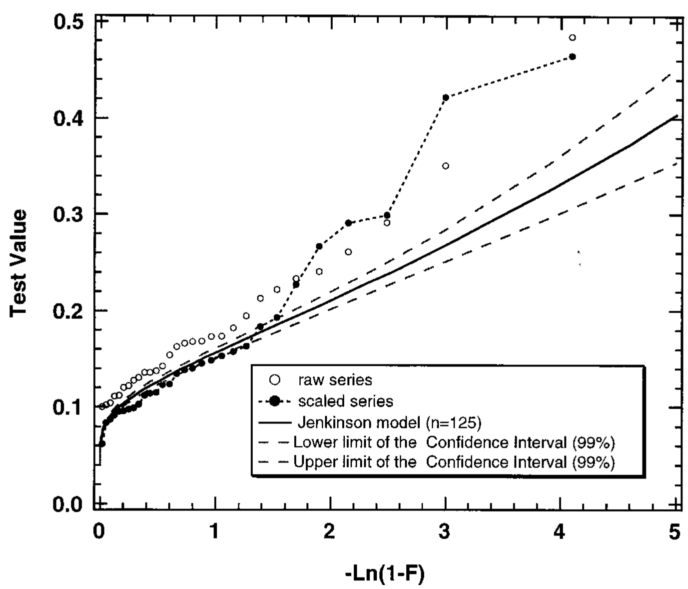

Figure 7. As Figure 5, except for the distributions of test values computed on the scaled series being compared to the distribution of test values computed on the raw series. The results of the Monte Carlo simulation is not shown for the purpose of clarity (see Figure 5)

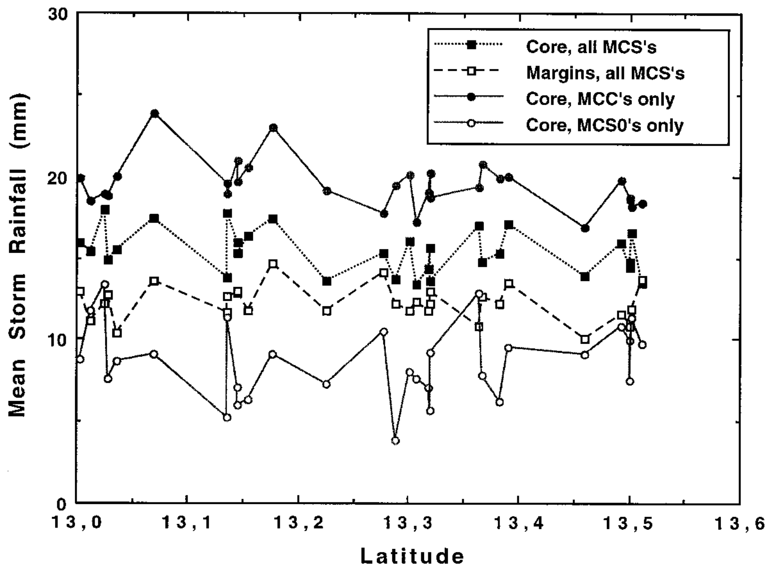

Figure 8. Fluctuations of the mean storm rainfall with respect to the latitude of the station considered (core and margins of the rainy season)

core mean storm rain-depth and equal to 0.037 when considering the global margin mean storm rain-depth. The corresponding value of the t-test is 1.52 for the core and 1.04 for the margin, both below the t_{95} value of 1.70. When considering the core MCCs only, r^2 is equal to 0.11 and equal to 0.001 when considering the core MCSOs only. In all cases the hypothesis of no correlation is thus accepted by the t test, indicating that the latitude does not explain the mean event rainfall fluctuations.

In fact, the mean event rainfall for each subgroup appears to be stationary in space. The F test of section 3 (expression 2) has been re-computed for each subsample and the results, given in Table VI, show that the observed values are below the $F_{0.1}$ value for both the core and the margin periods. This means that, within a given subperiod, all the mean storm rainfalls may be considered as being drawn from the same population, the differences from one station to the other being caused only by sampling effects.

It comes out very clearly from these tests that, whether stratified by type of events or not, the event rainfall is stationary in space, at the scale investigated herein. It does not depend on the latitude, or if it does this dependence produces very little variation as compared with: (i) the random sampling fluctuations, and (ii) the non-stationarity in time detected in section 5.

As there is a well established north-to-south gradient of the interannual mean of the seasonal rainfall, it has to be supposed that it is governed by a corresponding gradient in the number of events rather than in the magnitude of the event rainfall. This conclusion confirms for the interannual variability the relationship found by Le Barbé and Lebel (1997) for the decadal variability.

Table VI. Results of the F-test computed to compare the equality of the core and margins mean storm rainfalls averaged over the 30 stations

Sample		Degrees of freedom	F computed	F theoretical 10%	F theoretical 5%
Core	$I = 30$	$\upsilon_1 = 29$	0.53	1.35	1.47
All 4 years	$K_i = 1820$	$\upsilon_2 = 1790$			
Margins	$I = 30$	$\upsilon_1 = 29$	0.44	1.35	1.47
All 4 years	$K_i = 1928$	$\upsilon_2 = 1928$			

Table VII. Similar to Table IV, except for core (left numbers) and margins (right numbers) of the rainy season separately

Sample		Degrees of freedom	F computed	F theoretical 5%	F theoretical 1%
Banizoumbou	$I=4$ $K_i=61–65$	$v_1=3$ $v_2=57–61$	0.07–1.00	2.77–2.76	4.15–4.13
Boubon	$I=4$ $K_i=65–65$	$v_1=3$ $v_2=61–61$	0.99–0.16	2.76–2.76	4.13–4.13
Massi Koubou	$I=4$ $K_i=62–61$	$v_1=3$ $v_2=58–57$	0.65–0.50	2.77–2.77	4.14–4.15
Yillade	$I=4$ $K_i=56–67$	$v_1=3$ $v_2=52–63$	0.26–0.70	2.78–2.75	4.19–4.12
Core (all 30 stations)	$I=4$ $K_i=1820$	$v_1=3$ $v_2=1816$	7.60	2.61	3.80
Margins (all 30 stations)	$I=4$ $K_i=1958$	$v_1=3$ $v_2=1954$	4.65	2.61	3.80

6.2. Correlation with the interannual variability of the seasonal rainfall

In section 4 it was shown that the year-to-year fluctuations of the global mean storm rainfall were relatively small as compared with the year-to-year fluctuations of the seasonal rainfall, so that it could be considered as stationary at the interannual scale. This comparison is repeated here for each subperiod (margins and core) separately, using the F-test as given in expression (5). The observed value of the $F_{0.05}$ value for both the core and the margin periods, when the test is carried out on a station by station basis (Table VII). However, when the individual mean storm rainfall of the 30 stations are averaged to define the mean storm rainfall of a given year, the F value increases and becomes larger than the $F_{0.01}$ value.

To independently test the interannual stability of the mean storm rainfall, the data of 1994 have been used. The year 1994 is of particular interest in this respect because the seasonal rainfall was especially abundant as compared with the four previous years (660 mm compared with a maximum of 520 mm in 1991 and a minimum of 395 mm in 1990). The equality of the 1994 mean storm rainfall and the 1990–1993 mean storm rainfall was checked with a t-test on a station basis. As seen from Table VIII, the proportion of stations for which the t-test is negative, only once exceeds the expected proportion when the t-test hypothesis (equality of means) is satisfied: level $\lambda=1\%$, no stations rejected for all samples (expected number: between zero and one); level $\lambda=5\%$, no stations rejected for the core, one for the season and three for the margins (expected number: between one and two); level $\lambda=10\%$, two or three stations rejected (expected number: three). The t-test is rejected only for the margins at the level of 5%. Thus, most indices indicate a year-to-year stability of the mean storm rainfall, whether considered globally or after stratification between the core and the margins of the season.

Table VIII. Number of stations for which the t-test theoretical value at level λ is exceeded by the experimental value, when comparing the 1994 mean storm rainfall to the 1990–1993 mean storm rainfall

Sample	Degrees of freedom	Confidence level $\lambda=1\%$	Confidence level $\lambda=5\%$	Confidence level $\lambda=10\%$
Season	143–177	0	1	2
Core	65–82	0	0	2
Margins	76–94	0	3	3

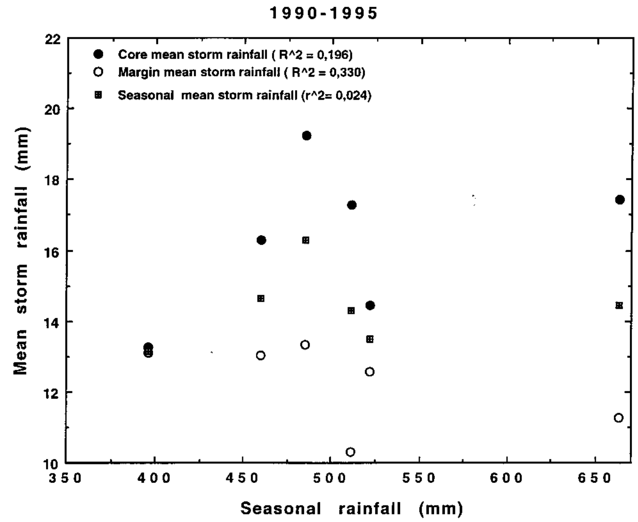

Figure 9. Mean storm rainfall versus seasonal rainfall for the period 1990–1995 (core, margins and global)

Beyond the year-to-year stationarity the question of interest is whether the mean storm rainfall varies with the total seasonal rainfall, that is: are dry (respectively wet) years associated with rainfall events of lesser (respectively larger) magnitude? In Figure 9 the seasonal core, and margin mean storm rain-depths have been plotted against the total seasonal rainfall. It turns out that the core storm rainfall is positively correlated ($r = 0.44$; $r^2 = 0.196$) with the seasonal rainfall and the margin storm rainfall is negatively correlated ($r = 0.58$; $r^2 = 0.330$) with the seasonal rainfall. However, both correlation coefficients do not pass the t-test (Table IX), that is they are not significantly different from zero. When the season is considered globally, the t-test is still more strongly negative, the correlation coefficient being almost equal to zero ($r^2 = 0.024$). Given the very small sample size, some correlations may not be totally excluded but, if it does exist, it is very weak and cannot explain either the large year-to-year fluctuations of the total seasonal rainfall, or the 25% decline of the annual rainfall of the past 25 years.

7. CONCLUSION

This paper has analysed the main characteristics of the Sahelian rainfall events, based on an experimental digitized rain-gauge data set covering 16000 km^2 over the period 1990–1995. Some statistics describing the two main groups of mesoscale convective systems (MCSs) producing 90% of the rain in this region

Table IX. Results of the t-test computed to evaluate the correlation between the seasonal rainfall and the mean rainfall (1990–1995). See also Figure 9

Sample		Degrees of freedom	t computed	t theoretical 10%	t theoretical 5%
Core	$r^2 = 0.196$ $r = 0.442$	$\upsilon = 4$	1.10	1.53	2.13
Margins	$r^2 = 0.330$ $r = 0.575$	$\upsilon = 4$	1.71	1.53	2.13

were first given. Although they represent only half the MCSs, the most organized and efficient producing systems, the mesoscale convective complexes (MCCs), account for more than 70% of the annual rainfall, a proportion very stable from year-to-year. They travel westward at an average speed of 54 km h^{-1}. The MCS storm rainfall appears as a stationary random variable over the study are. Its average point value (conditional to being non-zero) over the rainy season is about 14 mm (13.7 mm over the period 1990–1993) and its average areal value is close to 10 mm (10.1 mm over 1990–1993). The average proportion of zero rainfall is close to 26%. It was then examined whether the well-known interannual and intraseasonal variabilities of the seasonal rainfall were matched by similar variabilities of the mean storm rain-depth.

As a starting point, the point storm rain-depth was assumed to be distributed exponentially. A specific procedure has been designed to test this assumption, which appeared to be not fully verified when considering the event rainfall distributions in their entirety. However, when taking into account the non-stationarity of the mean event rainfall during the rainy season and stratifying between MCCs and MCSOs, the distributions of the resulting scaled series appear to be close to exponential, as revealed by the test derived herein. This leads to identifying the core (15 July–31 August) and the margins (May to 15 July and September–October) of the rainy season as a minimum stratification in order to study the statistical properties of the rain events, even though a finer stratification into seven sub-periods has been used here. The choice of an adequate stratification to account for the non-stationarity during the rainy season is conditioned by the quantity and quality of the data available. A representation on a day-by-day basis would be ideal, but this would require an amount of high quality data that are not currently available in the Sahel.

Whatever the averages considered (global, core, margin storm rain-depths), they display little interannual fluctuations, as compared with that of the seasonal rainfall. The seasonal rainfall over the study area ranged from a 660 mm high in 1994 to a 395 mm low in 1990, whereas the global mean storm rain-depth ranged from 14.7 mm in 1994 to 13.1 mm in 1990. Furthermore the small year-to-year fluctuations of these storm rain-depths proved to be very poorly correlated to those of the seasonal rainfall.

Thus, the variability modes of the event rainfall are not in phase with those of the seasonal rainfall. In time, the event rainfall is stationary at the interannual scale (with an overall average of around 13.7 mm), at least in the present period, but display an intraseasonal fluctuation linked to the migration of the ITCZ (with a core average of 15 mm and a margin average of 12 mm). As for the seasonal rainfall, it is characterized by a strong interannual variability. It is also characterized by a marked interdecadal variability (one manifestation of which is the current drought, started at the end of the 1960s), but the EPSAT-Niger data set did not allow the investigation of this mode for the event rainfall. In space, the seasonal rainfall is characterized by very large random fluctuations over distances between 5 and 50 km and the interannual rainfall displays a regular north-to-south gradient of 1 mm km^{-1}. None of these modes are traced in the event rainfall, which appears to be rather stationary in space over the various time-scales considered here. In other words, the mean storm rainfall is a stable parameter characterizing well the rainfall climatology of the Sahel: the main cause of the interannual variability of the Sahelian rainfall resides in the variability of the number of events rather in the variability of their magnitude.

Appendix A. TESTING THE EXPONENTIAL HYPOTHESIS

The goodness of fit of the exponential distribution for station i is measured by the distance between the theoretical CDF, $F(r)$ (expression 9), and the experimental CDF, $F^*(r)$, that is:

$$d_i = \sqrt{\frac{1}{K_i}\sum_{k=1}^{K_i}[F(r_{ik}) - F^*(r_{ik})]^2} \tag{A1}$$

When working in natural coordinates the value of $F(r) - F^*(r)$ is small when r is large, that is when both F and F^* converge towards 1. This leads to minimizing the impact on the calculation of d_i of the differences between the model and the experimental distribution for values of r which matter the most.

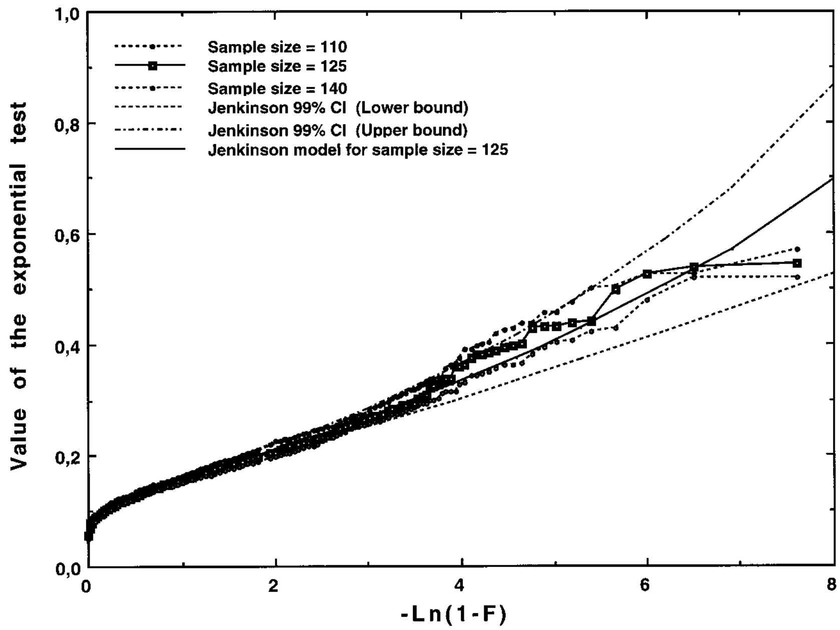

Figure A1. Distribution of the exponential test as derived from the Monte Carlo simulation for respective sample sizes $n = 110$, 125, 140. Also shown are the Jenkinson distribution fitted to the distribution for a sample size $n = 125$ and the limits of the corresponding 99% confidence interval

Working in $\log(1 - F)$ permits a linearization of $F(r)$ and gives more weight to the differences $F(r) - F^*(r)$ at large values of r. Therefore, the goodness of fit is measured by the following quantity:

$$e_i = \sqrt{\frac{1}{K_i}\sum_{k=1}^{K_i} [G(r_{ik}) - G^*(r_{ik})]^2}, \tag{A2}$$

where

$$G = -\ln(1 - F) \quad \text{and} \quad G^* = -\ln(1 - F^*) \tag{A3}$$

The statistical properties of e, when a sample of size n is drawn from an exponential parent distribution, were studied using a Monte Carlo procedure. As our samples of observed storm rainfall have a size ranging from 113 to 136, the distribution of e_n for samples of size $n = 110$, 125 and 140 were computed by generating 1000 samples drawn from an exponential population with parameter $s = 1$. Note that, because s is a scaling parameter of r, its value has no influence on the value of e_n. The distribution of e_n displays some variations with the value of n (the test values being smaller for larger sample size) but all three distributions are contained within the limits of the 99% confidence interval of the Jenkinson distribution fitted to the distribution of e_{125}. Thus, this distribution was used to represent the average distribution of e for the 30 global samples of our study and for numerically evaluating the goodness of fit of our observed storm rainfall samples. The fitting of the Jenkinson distribution to the distribution $F_{125}(e)$ is shown in Figure A1. Its expression is:

$$f(r') = \frac{1}{\vartheta - kr'} e^{(1/k)\log(1 - kr'/\vartheta)}\left(-\left[1 - \frac{kr'}{\vartheta}\right]^{1/k}\right), \tag{A4}$$

where $r' = (r - r_0)$, $r_0 = 0.0124$, $k = -0.132$, and $\vartheta = 0.04$.

The fit of a theoretical model to the empirical distribution of e_n allows for the calculation of a confidence interval to be used when assessing the validity of the exponential model. The Jenkinson distribution was also found to provide the best fit to the distribution of e_n for smaller n ($n = 50$, 60, 80) resulting from the classification.

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