Small scale spatial variability of the annual rainfall in the Sahel

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Abstract In anticipation of the HAPEX-SAHEL (Hydrologic and Atmospheric Pilot EXperiment in the Sahel) experiment, a long term rainfall monitoring program has been set up. It is based on a network of a hundred recording raingauges combined with a C band weather radar system. The raingauge implementation began in 1988, and the results of three years (1989-1991) of complete measurements are presently available. For a large spectrum of space and time scales, this data set allows one to study the variability of the Sahelian rainfall fields. From a preliminary analysis it appears first of all that the small scale spatial variability of the annual rainfall is unexpectedly large. A consequence of the smoothing out of the rainfall fields due to usual sparse sampling schemes leads to the ignoring of local rainfall extremes, and results in large errors (up to 100% over 200 km^2) in the computation of areal rainfall. The spatial distribution of the number of rainfall events appears to explain a great deal of the unexpectedly large variability of the annual rainfall at small spatial scales.

INTRODUCTION

The interannual variability of rainfall over the Sahel has long been noted. It is one of the most significant features of the Sahelian climate. The coefficient of variation of the annual rainfall distribution in Niamey is 0.26, as compared to values between 0.15 and 0.20 for rainfall series in temperate climates. Despite this, the isohyetal maps of mean annual rainfall, as established from the national raingauge networks, display a very regular pattern. Over Niger the isohyets, computed over the period 1950-1989, are oriented along a general east-west direction, with a decreasing northward gradient of about 1 mm/km (Lebel *et al.*, 1992). This pattern repeats itself over most of the Sahel, with the exception of local anomalies related to the influence of the topography (which, otherwise, is generally flat). It could be inferred from this regular spatial gradient of the mean annual rainfall, that pattern of the annual rainfall for a given year should display the same kind of repartition. This assumption has great impact on the agricultural planning and water resources management, for it supposes a northward decreasing gradient and excludes strong local variations other than those associated with the topography.

Up to now the usually low density of the national raingauge networks over western Africa has been a major impediment to a proper assessment of the annual rainfall pattern within surface areas smaller than 10 000 km^2. The EPSAT-NIGER (Estimation des Précipitations par SATellite au Niger) experiment was set up in 1988 to remedy

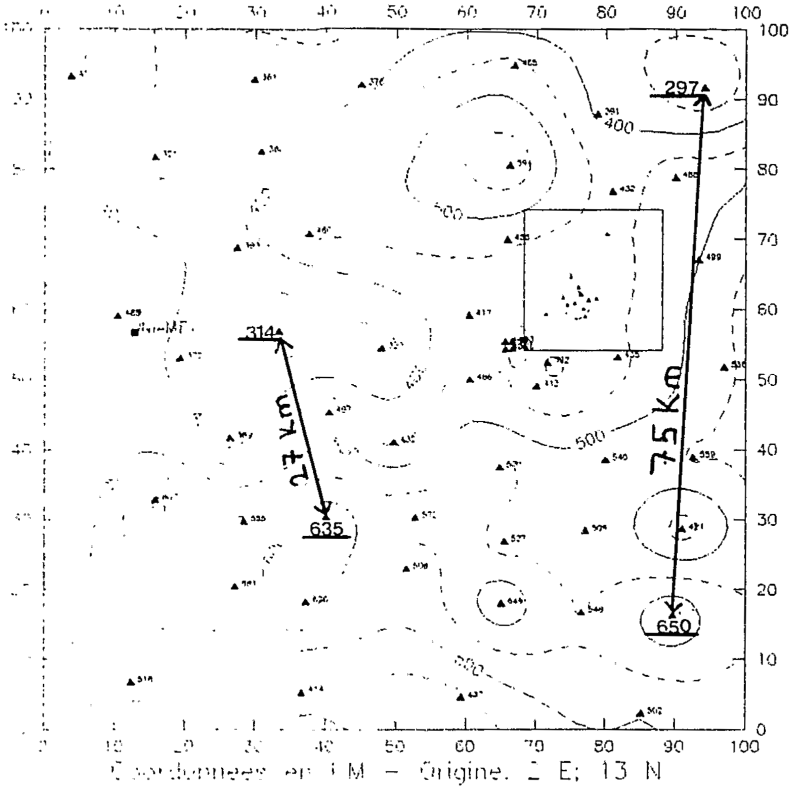

Fig. 1 Isohyetal map of the 1991 seasonal rainfall, values in mm.

to this lack of knowledge (Lebel *et al.*, 1992), and as a first step in the implementation of the HAPEX-SAHEL field experiment (Goutorbe *et al.*, 1992). The preliminary processing of the 1989 to 1991 data shows that in fact the annual Sahelian rainfall fields exhibit a strong spatial variability over distances smaller than 100 km (Fig. 1). The EPSAT-NIGER recording raingauge network (a hundred stations spread over 16 000 km^2) is 20 times more dense that the operational raingauge network in this region. The network is a regular grid with nodes spaced at approximately 12.5 km. Roughly in the middle of the network, a target mesh has been equipped with additional gauges arranged in increasing density towards the centre of the mesh, where four raingauges form a square with 1 km sides (Fig.1). This high density network has allowed the measurement of rainfall differences of 100% over distances smaller than 30 km in 1991 (from 314 mm to 635 mm), and of 60% over less than 10 km in 1990 (from 305 mm to 488 mm). This raises some questions:

(a) is there an appropriate model of the Sahelian annual rainfall distribution at the sub-regional and smaller scales (below 10 000 km^2), to be used for areal rainfall estimation, based on ground sensors only?
(b) how does this variability translate when it comes to the estimation of areal rainfall, using networks of decreasing densities between that of the EPSAT-NIGER network and that of the operational network of Niger?
(c) is it possible to relate the spatial variability of the annual rainfall to that of the rainfall events?

The research presented here was actually based on seasonal rather than annual rainfall, for only a few gauges remain in operation during the dry season. However, since the rainy season accounts on average for 90 to 95% of the annual rainfall, the main conclusions drawn from the study of the seasonal rainfall can be applied to the annual rainfall.

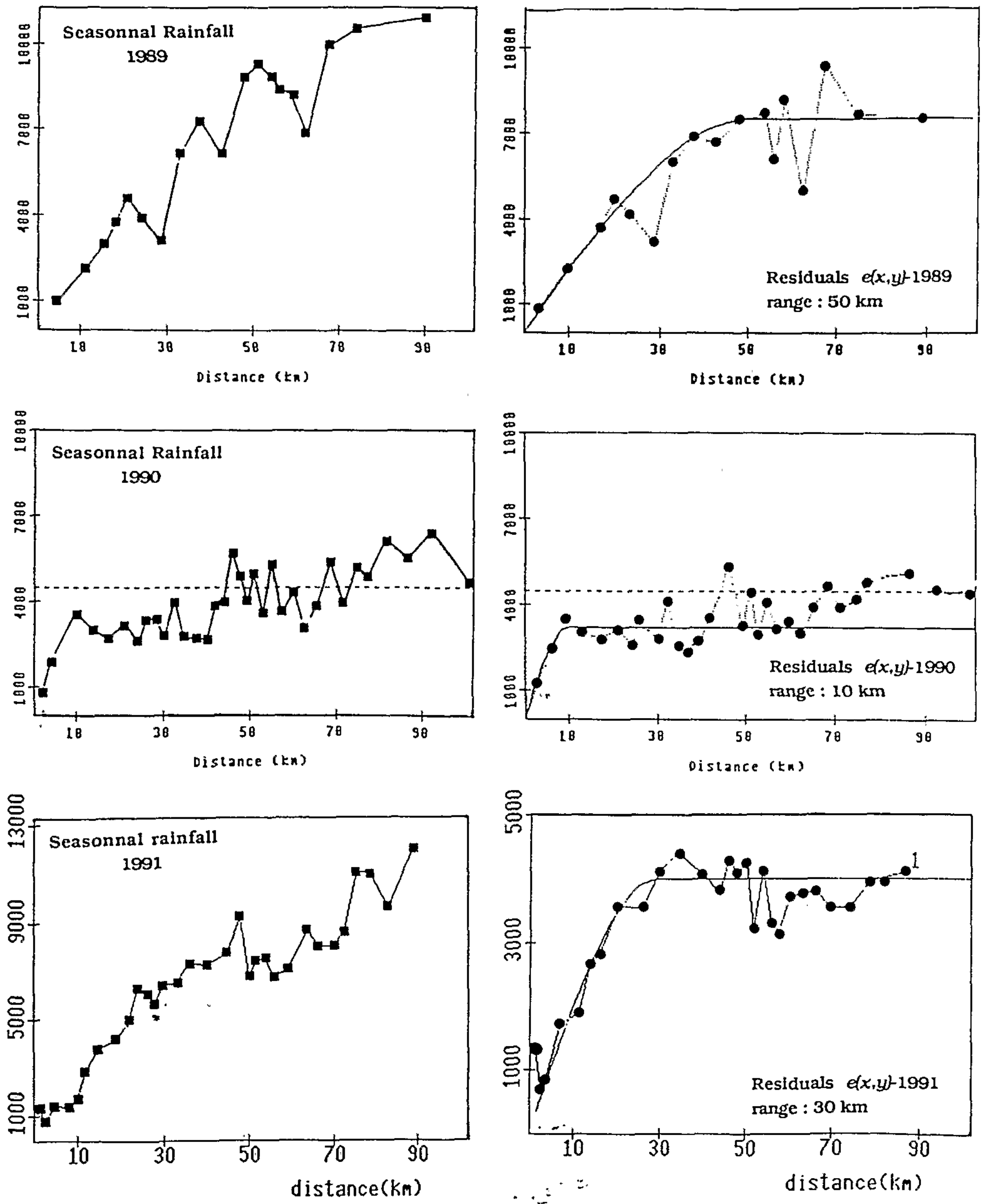

Fig. 2 Seasonal rainfall variograms of the raw data $Z(x,y)$ (left), and of the residual $e(x,y)$ to the climatological trend (right). Note that, contrary to that of $Z(x,y)$, the variogram of $e(x,y)$ reaches a well defined sill for all three years; variograms of 1989 and 1990 after Thauvin (1992).

THE SPATIAL DISTRIBUTION OF THE SAHELIAN ANNUAL RAINFALL

The small scale variability that can be seen in the map of Fig. 1 calls for the incorporation of some sort of stochastic component in the characterisation of the annual rainfall field. A first analysis of this variability was carried out through the computation of the raw variogram (Fig. 2). The variograms of 1989 and 1991 are both unbounded, which indicates a probable non-stationarity of the random process. As for the variogram of 1990, it is characterized by a plateau between 10 and 40 km, pointing to a rapid decorrelation of the rainfall field.

The existence in all three cases of a first sill at distances smaller than 50 km seems to indicate a small scale structure which is not in continuity with the large scale structure. This large scale structure is impossible to identify from the EPSAT-NIGER data, for the networks cover too limited an area. On the other hand, some sort of spatial structure is known to exist, if only as the general northward decreasing gradient. In order to get a more exact idea of the small scale structure, it is thus important to remove a possible effect of the large scale structure from the data set. This was done by subtracting the climatological trend, $M(x,y)$, from the measured rainfall $Z(x,y)$. The trend is written as: $M(x,y) = 600 - (L - 13) \times 100$, where $M(x,y)$ is in millimetres and L is the latitude in degrees (Lebel *et al.*, 1992). The residual $e(x,y)$ $(= Z(x,y) - M(x,y))$ is then analysed in the same way as the original variate $Z(x,y)$. The variogram of $e(x,y)$ is clearly bounded (Fig. 2), with a sill that is reached at a range of $e(x,y)$ varying from 10 km in 1990 to 50 in 1989. This range represents the distance of decorrelation. Note that it is smaller than the basic grid cell size of the meteorological network of Niger. A cross validation procedure developed by Thauvin (1992) allows the comparison of several classes of interpolation models. In particular, the estimates obtained from a direct kriging of $Z(x,y)$, (with both a zero and one order trend) can be compared to the estimates obtained from a kriging of the residuals $e(x,y)$. The estimate $Z_e(x,y)$ $(Z_e(x,y) = M(x,y) + e^*(x,y)$, where $e^*(x,y)$ is computed by kriging of the residuals $e(x,y))$ turns out to minimize the mean square error criterion of the cross validation procedure (see Thauvin, 1992 for the detailed results). Two main conclusions are to be drawn from the above analysis:

(a) even though the climatological trend is not very apparent on the annual rainfall maps for 1990 and 1991, its taking into account improves the results of the rainfall field interpolation;

(b) the residuals $e(x,y)$ to this trend display a strikingly low covariance at distances larger than 50 km, with no auto correlation beyond 10 km in 1990 (Fig.2).

HOMOGENEOUS VERSUS HETEROGENEOUS NETWORKS IN ESTIMATING AREAL RAINFALL

An extensive investigation of the areal rainfall estimation accuracy depending on the network density and configuration is under way. Here, only one example (Fig. 3) is given showing that, for a range of densities extending from a gauge area (Ag) of 200 km^2 to a gauge area of 1600 km^2, the heterogeneity of the raingauge network is a major cause of degradation in accuracy, whereas the decrease in density does not dramatically change the rainfall pattern.

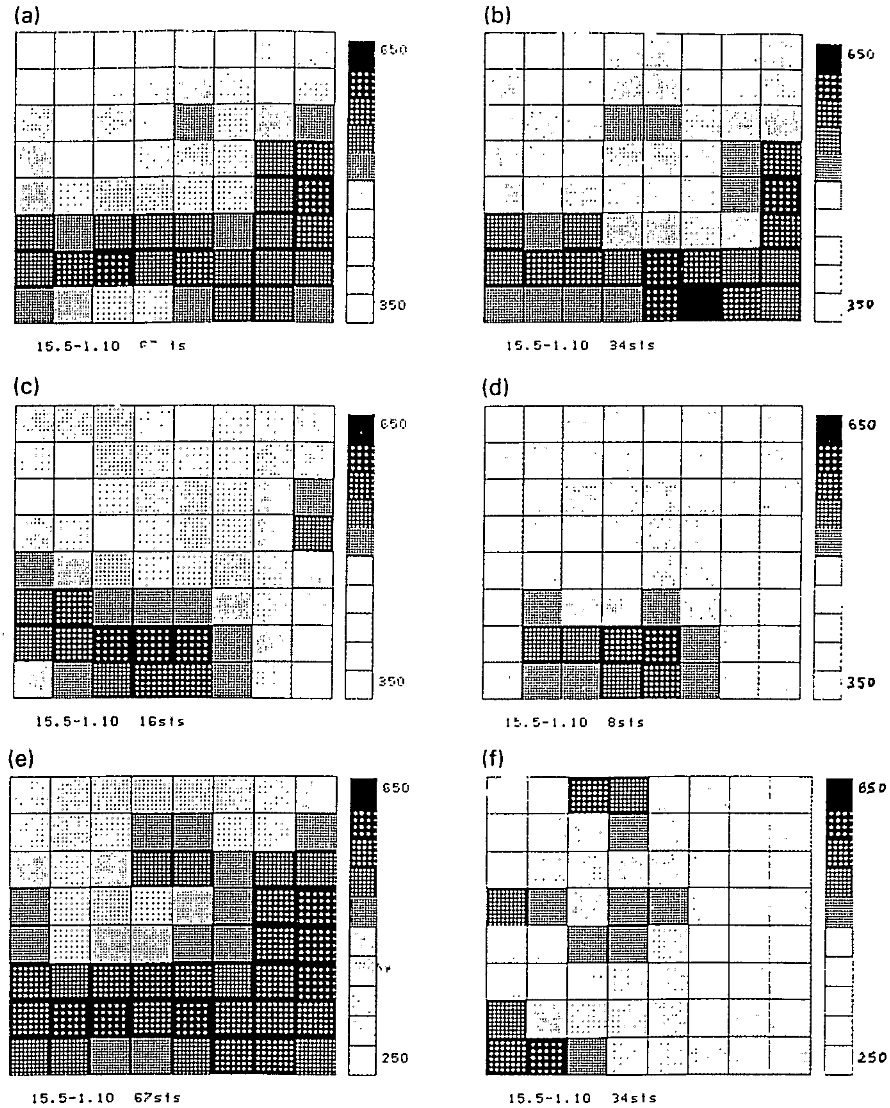

Fig. 3 Areal rainfall estimation over 15 x 13 km^2 grid cells using various networks of decreasing density; (a) 67 stations (density of one station per 200 km^2); (b) 34 stations, regular; (c) 16 stations, regular; (d) eight stations, regular; (e) same as 3(a), except for the colour scale; (f) irregular network of 34 stations. The rainfall is in mm, and the period of accumulation ranges from 15 May to 1 October 1991.

In Figs 3(a)-(d), the areal estimates over 64 grid cells of 15 x 13 km^2 in area (that is, approximately that of an HAPEX-SAHEL supersite) are compared, using four regular networks. The first has 67 stations (Ag = 200 km^2), the second 34, the third 16 and the fourth 8 stations (Ag = 1600 km^2). As the number of stations decreases, most of the contrast between the different cells is lost, especially in the northern and eastern part of the study area. The low rainfall spot in the extreme south (cells N° 3 and 4, starting from the left) is totally overlooked when the density is divided by a factor 2. While all the areal estimates remain in the range 350-650 mm differences of up to 50% are observed over a couple of meshes (610 mm with the 67 stations network against 405 for the eight stations network over one mesh of the eastern edge).

In Figs 3(e) and (f) the results from the 67 stations regular network and a 34 stations irregular network are compared. While with the regular networks the general pattern of the rainfield was kept, even when dividing the density by a factor 4, it can be seen that this is no longer the case with this irregular network. The rainfall distribution over the eastern area becomes fairly uniform with an underestimation of the areal rainfall by a factor 2, from those meshes without any raingauge. Even in the western part, where most of the stations were located, differences of more than 100% appear. Hence this type of network, however dense as compared to the operational networks in this region, leads to three major errors:
(a) the areal rainfall over the whole study area (10 000 km^2) is poorly estimated (40% underestimation in the example above);
(b) the general pattern and the local gradients are both lost;
(c) the error, for a mesh of 200 km^2 may be as high as 100%.
The effect of the homogeneity factor is thus predominant over the density factor as long as the density remains above one station per 1600 km^2: the largest estimation error with the smallest density regular network (Ag = 1600 km^2) is 15% over a 10 000 km^2 area and 50% over a 200 km^2 area, while it climbs up to respectively 40% and 100% with a denser irregular network (Ag = 400 km^2) .

RELATIONSHIP BETWEEN THE NUMBER OF EVENTS AND THE ANNUAL RAINFALL

Thauvin (1992) has shown that 60 to 65% of the seasonal rainfall was associated with events of large spatial extension, namely the Mesoscale Convective Complexes (MCCs) as defined in Hastenrath (1991). The spatial covariance of these events appears to be fairly stable from one event to another. Thauvin (1992) fitted a climatological variogram, with an equivalent range of between 50 to 60 km, to the MCCs data of 1989 and 1990. A similar structure was found by Taupin *et al.* (1992) for the large extension events of 1992. It is thus rather unexpected that having such correlation distances at the scale of individual events, the seasonal rainfall displays correlation over smaller distances (10 km in 1990, and 30 km in 1991). Usually the range of spatial correlation of cumulative rainfall increases with the duration of accumulation (see e.g. Laborde Lempereur, 1986; and Lebel *et al.*, 1987). A first reason for the larger randomness of the seasonal rainfall as compared to the MCCs rainfall may be found in the weight of ill-structured events which account for one-third of the seasonal total. For such events the main structuring factor for rainfall accumulation over several events is the spatial pattern of the number of events over the period of accumulation. The number of events recorded over the study area was 36 in 1990 and 47 in 1991 (Lebel *et al.*, 1991; Taupin *et al.*, 1992). Among them, 15 were considered as MCCs in 1990 and 30 in 1991, which may partly explain the larger correlation range of the 1991 annual rainfall, as compared to that of 1990. To support the investigation of the influence of the number of events in the structure of the seasonal rainfall, a subset of 39 stations in 1990 and 45 stations in 1991 were selected, which presented a continuous recording over the period 15 May-30 September.

The number of events, $n_i(s)$ recorded at a given station i depends on the definition of the event: minimum cumulative rainfall, s, and minimum duration with no rainfall between two events, q. The number of events proved to be relatively insensitive to q when q varies between 30 minutes and a few hours. Consequently the value of q was set equal to 30 minutes, in order to compute $n_i(s)$ for each station i and the corresponding cumulative rainfall over all these events, denoted $Z_i(s)$, s varying between 1 and 20 mm. The average over all the stations is denoted $n(s)$ ($n(s) = 1/k$ $Sn_i(s)$, $i = 1,k$; $k = 39$ in 1990, and $k = 45$ in 1991). Figure 4(a) shows that, for both seasons, $n(s)$ is logarithmically related to s, with a determination coefficient of 0.99. For any threshold, $n(s)$ is smaller in 1990 than in 1991. Taking $n_i(1)$ (the total number of events for which at least 1 mm was recorded at station i) as a scaling factor, we define $n_i^*(s) = n_i(s)/n_i(1)$ as a scaled number of events, and $n^*(s)$ as the average of $n_i^*(s)$ over all the stations. The values of $n^*(s)$ for 1990 and 1991 are then almost identical, so that a single relationship between $n^*(s)$ and s holds for the two seasons: $n^*(s) = 0.95\text{-}0.59 \log(s)$, $r^2 = 0.98$ (Fig. 4(b)). An even stronger relationship is found between $Z^*(s)$ and s, where $Z^*(s)$ is the average of $Z_i^*(s)$, $Z_i^*(s) = Z_i(s)/Z_i(1)$ ($Z_i^*(s)$ is

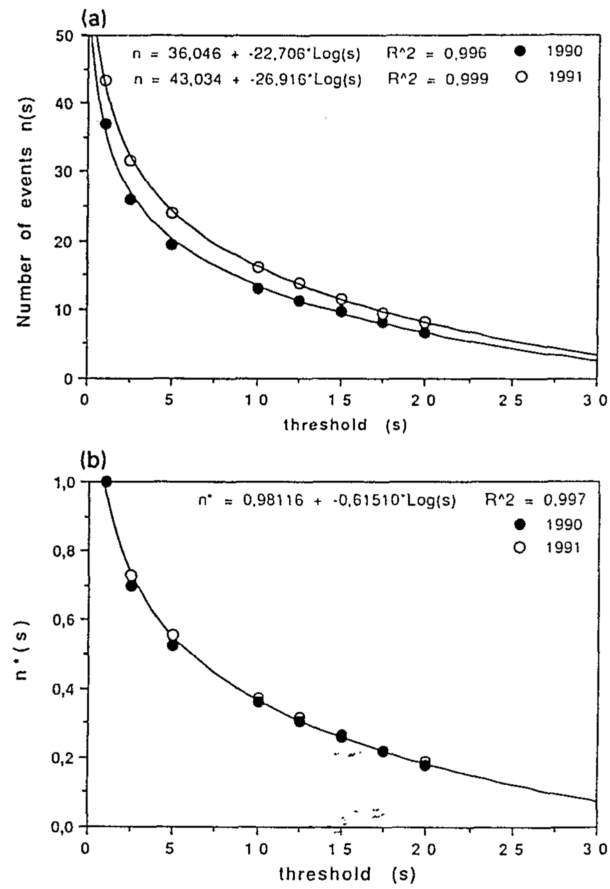

Fig. 4 Average number of events above a threshold, $n^*(s)$, as a function of the threshold (s) for 1990 and 1991; (a) absolute values; (b) ratio between the absolute values and the number of events above threshold 1 mm (a single curve fits the two data sets).

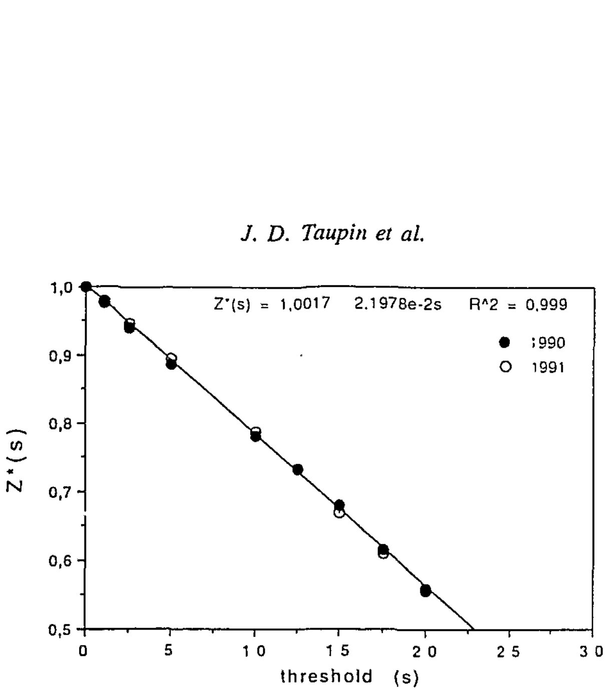

Fig. 5 Average scaled cumulative rainfall $Z^*(s)$ as a function of the threshold (s). Threshold in mm.

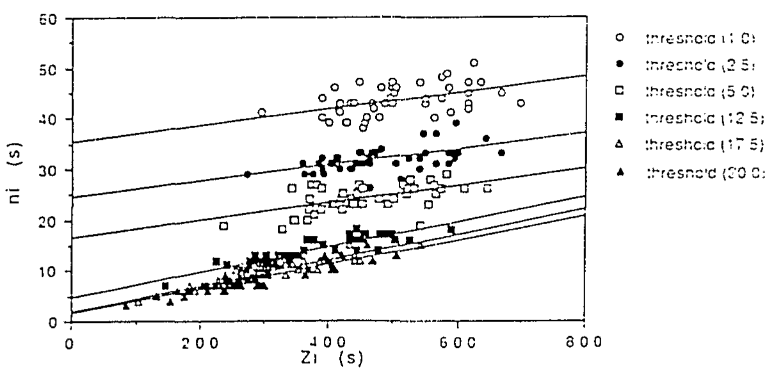

Fig. 6 Number of events $n_i(s)$ versus cumulative rainfall $Z_i(s)$ for events above the threshold (s). Rainfall in mm.

the scaled cumulative rainfall over all events above the threshold s). This relationship is linear ($Z^*(s) = 1 - 0.022\ s$) with a determination coefficient $r^2 = 0.999$ (Fig. 5). Even if this result has still to be confirmed by getting additional years of data, it seems to indicate that, at the seasonal scale, the proportion of rainfall associated to a given event magnitude is fairly stable and characteristic of the rainfall regime of the region. Looking now at the relationship between $n_i(s)$ and $Z_i(s)$ when i varies over the whole set of stations, Fig. 6 shows that the correlation between these two variates increases with s. It reaches an optimum around 15 mm ($r^2 = 0.88$ in 1991 for $s = 15$ mm, and $r^2 = 0.81$ in 1991, for $s = 12.5$ mm). Knowing that the events larger than 10 mm account for 80% of the seasonal rainfall and the events larger than 12.5 mm for 73% it is obvious that the spatial distribution of the number of events above the thresholds 10-15 mm largely explains the spatial distribution of the annual rainfall itself, as may also be seen from a comparison of the isohyetal maps of Figs 1 and 7. It will thus be a major direction of investigation to study the conditional spatial distribution of the threshold rainy events and to relate it to the variations in the general circulation pattern.

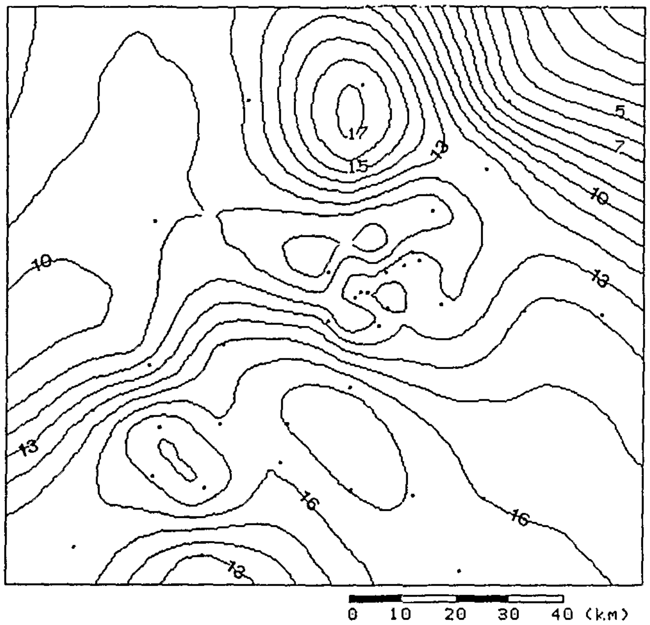

Fig. 7 Contour map of the number of events above the 12.5 mm threshold .

CONCLUSION

The EPSAT-NIGER raingauge network, which constitutes the backbone of the HAPEX-SAHEL long-term rainfall monitoring set up, made it possible to investigate the small scale spatial variability of the seasonal rainfall in the Sahel. Significant differences in this variability, as represented by the variogram of the residuals to the climatological trend, were observed between 1989, 1990 and 1991: in 1990 the variogram reaches a sill at a range of 10 km, as compared to 50 km in 1989, and 30 km in 1991. A proper assessment of the spatial distribution of the seasonal/annual rainfall over relevant Sahelian hydrological units (1 to 100 km^2), or meteorological satellite pixels (1 to 15 km^2) thus demands far denser networks than those currently operational in Western Africa.

Differences of up to 50% on the estimation of areal rainfall over 200 km^2 areas were found when using a 200 km^2 gauge area network on the one hand and a 1600 km^2 gauge area network on the other hand, both being regular networks. With an irregular network of intermediate density (400 km^2), the maximum error over 200 km^2 was found equal to 100%. Having in mind that a typical validation procedure for METEOSAT rainfall estimation is carried out over an area of 3 x 3 pixels (approximately 200 km^2), the above results underline the difficulty of obtaining appropriate ground truth for the validation of algorithms that will be increasingly used in the near future for regional water balance modelling. In this respect however the most reliable information that can be retrieved from the geostationary satellites, such as METEOSAT, is the number of rainfall events, rather than the amount of rainfall. From the preliminary work presented here it appears that the number of events above a threshold ranging from 10 to 15 mm is well correlated to the seasonal rainfall. Thus using the satellite data to monitor the occurrence of these events, and the ground networks to calibrate the relationship between the number of events and the cumulative rainfall could lead to a significant improvement of the rainfall estimation algorithms in the Sahel.

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