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IV: EPSAT-NIGER STUDY OF RAINFALL OVER THE SAHEL AT SMALL TIME STEPS USING A DENSE NETWORK OF RECORDING RAINGAUGES

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ABSTRACT

The high density, static memory raingauge network of the EPSAT-NIGER experiment was designed with the aim of: (1) studying the rainfall spatial variability in the Sahel, as may be seen from ground networks of varying density, and (2) providing reference values for the calibration of a C band radar system. A first subset of 37 raingauges was installed in 1988 and the remaining 43 in 1989, thus providing a network of 80 stations, spread over a 100 × 100 km square area. The data analysis is based on the indentification of the structural function for each rainfall event. This permits classification of the events into three main categories with respect to their spatial organization. Furthermore the differences between the shower body and the trail are important and it is shown that the analysis of the spatial organization at the event scale may not be applicable to the calibration of high temporal resolution radar data. Estimation of the areal rainfall over two reference areas is also carried out.

KEY WORDS Rainfall estimation Dense network Static memory recording raingauge Sahel

INTRODUCTION

The study area

The high density, static memory raingauge network of the EPSAT-NIGER experiment presented in Hoepffner *et al* (1989) was designed with the aim of studying in detail the Sahelian precipitation and of determining the best way to measure it. This network covers an area east to Niamey, measuring one degree in longitude (108 km) and one degree in latitude (111 km). The basic pattern is a regular grid, with a $12 \times 12\ \text{km}^2$ mesh (see Figure 2 in Hoepffner *et al*, 1989). A Target Area, made of sixteen gauges, was also set up. This Target Area is roughly a $10 \times 10\ \text{km}^2$ square. The centre of the Target Area is $1 \times 1\ \text{km}^2$, instrumented with four raingauges. A first subset of 37 raingauges was installed in 1988, an additional 18 by mid August 1989 and the remaining 25 by mid September, thus providing a network of 78 raingauges spread over the $108 \times 111\ \text{km}^2$ study area. While the partial network available in 1988 allowed only for a general decription of the spatial pattern of the rainfall over the study area, the 1989 network has the required density to carry out studies at smaller scales. Unfortunately, given the schedule of this publication, it was impossible to process in time the data acquired after mid August 1989. The results presented herein are thus only a first overview of the enhancement of tropical rain systems knowledge at various time scales that can be expected from such a network.

Climatic conditions in 1988–1989

The Sahelian precipitation regime is characterized by the succession of one dry season (October–May) and one rainy season (June–September), the maximum monthly rainfall occurring generally in August. The yearly average rainfall for the period 1905–1975 is 585 mm (Brunet-Moret *et al.*, 1986). With 558 mm of

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rainfall recorded at the station of Niamey in 1988 and over 600 mm in 1989, the total rainfall of the past two years was good as compared to that of the nine previous years. As a matter of fact, from 1979 to 1987 the yearly total was over 500 mm only once in 1975, and four times in the order or below the dry ten year rainfall which is 424 mm. The years 1988 and 1989 may thus be considered 'normal', after a long period of dry years, at least from the yearly total viewpoint.

Geostatistical techniques to analyse rainfall spatial distribution

Given the point nature of raingauge data, any attempt at mapping them or at computing areal values requires interpolations. Finding the best methods to perform such interpolations has long been identified as a major research field in hydrology. Our purpose here is not to elaborate on this topic but, since contour mapping and areal rainfall computation will be largely used in this paper to illustrate our results, some indications regarding the methods selected will be helpful.

Following the work of Creutin and Obled (1982), several studies (e.g. Tabios III and Salas, 1985; Lebel *et al.*, 1987) have shown that optimal linear interpolation techniques perform generally better than their counterparts which do not make use of the statistical structure of values observed in a 2D space. These results hold for medium density networks, since when the density is too low the statistical structure cannot be studied, and when it is high (with respect to the spatial variability) a local arithmetic mean is accurate enough. Based on these conclusions, kriging will be used here to interpolate the point data, mainly because it allows the spatial structure function to be identified separately for each realization of the random process. Kriging, a method developed by G. Matheron, belongs to the BLUE (Best Linear Unbiased Estimators) family of interpolation techniques, using the variogram as the structure function describing the data correlation in the 2D space. An experimental variogram is computed from the experimental data, and a theoretical model is fitted which is then used to fill the variance–covariance matrix of the interpolation system (for more details see e.g. Delfiner and Delhomme, 1973). Two models of variogram will be used below:

The linear model:

$$\gamma(h) = \gamma_o + bh \qquad (\theta > 0).$$

The spherical model:

$$\gamma(h) = \gamma_o + (\alpha - \gamma_o)\cdot[3/2\, h/a - 1/2(h/a)^3]$$

$$\text{for } 0 < h < a$$

$$\gamma(h) = \alpha \qquad (h > a).$$

where γ, γ_0, and α are in mm^2 (for rainfall measured in mm), and h and a are distances in metric units.

In the latter model, a is the range, that is the distance beyond which no correlation exists any longer between two points. For $h < 2/3a$, the spherical model is almost identical to a linear model with $b = 3\alpha/2a$. Since the identification of the parameter a largely depends on the observations available at large distances (as compared to the decorrelation distance of the phenomenon), it is frequent that either model may be used with similar results as long as the interpolation is performed over relatively short distances. This point will be illustrated below when studying the spatial distribution of rainfall cumulated over a whole precipitation event.

PRELIMINARY STUDIES IN 1988

Pattern of monthly rainfall fields

The seventeen stations of the conventional raingauge network of the meteorological service of Niger are located within (11 stations) or in the vicinity (six stations) of the EPSAT-NIGER study area. This allowed for the drawing of the isohyetal map of the total rainfall, as shown in Figure 1. The rainfall is seen as a well

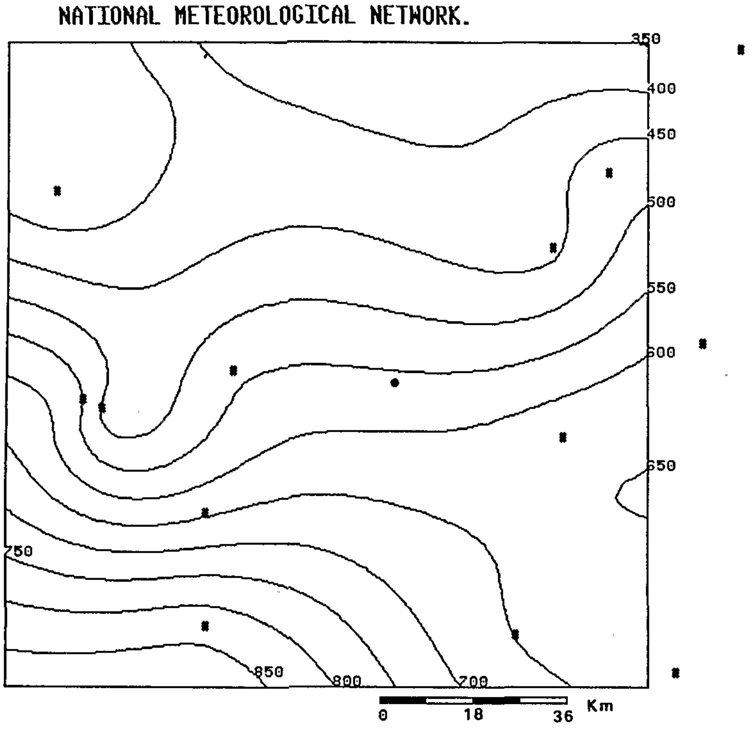
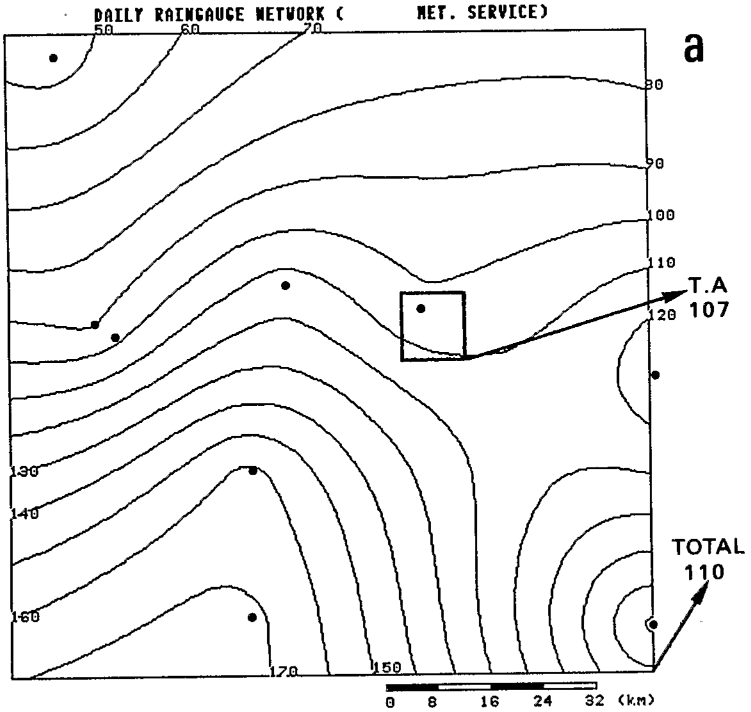


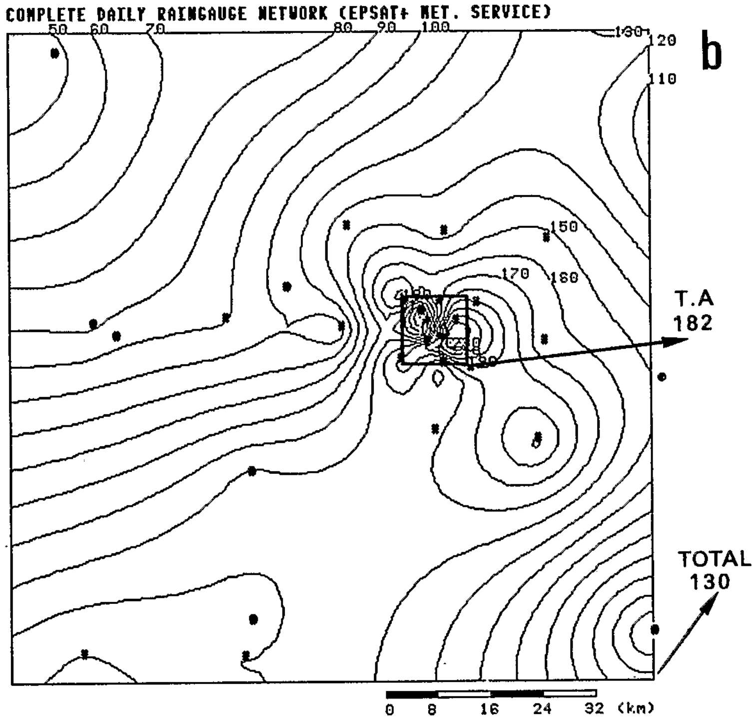
Figure 1. 1988 yearly rainfall (mm). Daily raingauge network of the Niger meterological service (11 stations within the study area and six stations in the vicinity; all seventeen stations used for the contour mapping)

organized process displaying a decreasing gradient from the south northward. The EPSAT-NIGER-raingauges could not be used to get more information about the 1988 yearly rainfall since they had been progressively installed all along the rainy season. It is nevertheless possible to compare the monthly rainfall isohyetal maps obtained from the conventional raingauge network and from the complete network (conventional gauges and EPSAT gauges). In September 1988 for instance, 25 EPSAT-NIGER stations have been fully operating, thus providing a complete network of 42 raingauges, which may be used concurrently with the meteorological network to draw contour maps of the September monthly rainfall (Figure 2). The contour mapping was performed over a 100*100 km^2, a zone slightly smaller than the basic study area, and using a linear variogram.

The map of Figure 2a (meteorological network) is rather smooth with the noticeable exception of an irregularity created by the station of Birni N'Gaoure which recorded 66 mm only while the values at all the nearest stations are over 120 mm.

In Figure 2b is shown the contour map obtained from the complete network of 42 stations (met. + EPSAT stations). The pattern is dramatically different, globally as well as in detail. Indeed such a chaotic structure as the one observed over the Target Area, is expected for storm or daily rainfall contour maps, but in no way for monthly rainfall during the rainy season. As a matter of fact, eighteen different rainfall events were recorded during September 1988, among which twelve were well organized storms (more than half of the stations recording rainfall lasting more than two hours). The accumulation of such a large number of storms is generally believed to result in a strong smoothing, which is not the case here. This means that, in these regions, the maps drawn using networks with a distance between stations greater than twenty kilometres give a very simplified picture of the monthly rainfall spatial distribution. It may of course be objected that the very dense central network creates a singularity biasing the perception of the rainfall field. Yet the local perturbations are not created by the network: they are observed (twelve stations of the Target Area were operating at that time). This suggests that similar unobserved 'singularities' may exist elsewhere, and prevent


DAILY RAINGAUGE NETWORK (MET. SERVICE)


COMPLETE DAILY RAINGAUGE NETWORK (EPSAT+ MET. SERVICE)

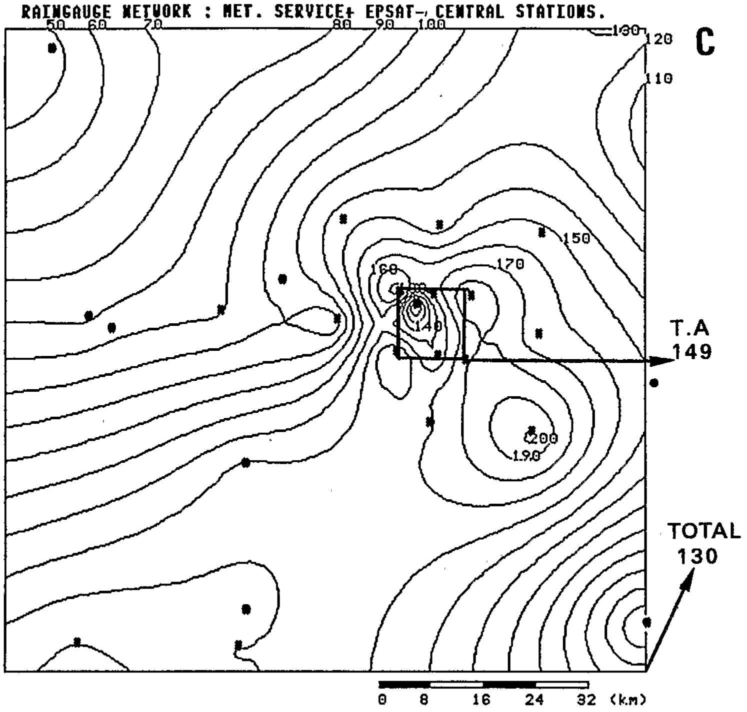


Figure 2. September 1988 monthly rainfall (mm). Comparison of the isohyetal maps obtained with three different networks. **a**: meteorological stations; **b**: meteorological and EPAT(1988) stations; **c**: same as **b** except for the removing of six stations in the Target Area. The numbers on the right side are areal rainfall (i) over the 100 × 100 km^2 square (total) and (ii) over the Target Area (T.A.)

us from deciding whether the 'anomaly' of Birni in Figure 2a is related to a measurement error or to a strong local variation of the rainfall field.

In order to check the influence of the Target Area on the general pattern of the contour map, the central stations were removed (six out of a total of eight have operated properly throughout September 1988). This operation has the consequence of erasing some local irregularities, but the strong central gradient remains clearly visible, again showing that even at the monthly scale the rainfall fields are not as smooth as generally thought.

Areal rainfall

It is of first importance to hydrologists to assess the consequences of such dissimilarities when it comes to computing areal rainfall which is the only meaningful variable in water resources management, the improvement of which is the remote but ultimate goal of the EPSAT-NIGER experiment. Areal rainfall over reference areas was therefore computed using a direct kriging estimation procedure (for more details, see e.g. Bastin *et al.*, 1984; Lebel *et al.*, 1987). The structure function used was a linear variogram with no nugget effect ($\gamma_0 = 0$). While the choice of such a function would deserve to be discussed in more detail, it is believed that the results given below would be only slightly modified by using different structure functions (especially to take into account an obvious linear drift). Two reference areas were chosen: (1) the 100 × 100 km^2 square and (2) the Target Area (10 × 10 km^2). The results of the computation are given in Figures 2a, 2b, and 2c for each network respectively. While the areal rainfall computed over the big square varies little (110, 130, 130 mm), there are large differences between the estimates over the Target Area.

Although these results need to be validated by a more thorough investigation, which is underway using the 1989 data and working at smaller time steps, a tentative interpretation is already possible. At a scale of 100 × 100 km^2, ten stations are enough to provide a fairly good estimate of the monthly areal rainfall. Adding more stations improves slightly the accuracy. Beyond a density of around one gauge for

400–500 km^2, more details are obtained but they are no longer relevant to increase the accuracy of the estimation (it is noteworthy that the values given in Figure 2b and 2c are identical).

At the lower scale of 10 × 10 km^2, the error involved in using the meteorological network (only one station within the Target Area) is probably very large since the computed areal rainfall is only 107 mm against 149 mm and 182 using the two other networks (respectively with six and 12 stations within the area). Note that all the stations were used for the computation and not only those of the Target Area. Here again at least ten stations are probably needed to get a stable estimate of the monthly areal rainfall.

Of course this result is more a provisional rule of thumb than a very precise and definite answer to network design problems in Sahelian regions. In any respect, it does not hold for smaller spatial scales (would it be necessary to install ten gauges over a 10 × 10 m^2 square to get a precise estimate of the montly rainfall over this area?) and it would be of great interest to obtain figures for smaller time steps.

RAINFALL SPATIAL DISTRIBUTION IN SAHELIAN SQUALL LINES: A FIRST GLANCE

At the time of writing this paper, the data of about forty raingauges only had been processed for 1989. The first significant rainfall was observed in mid-June, and by mid-August several interesting mesoscale convective systems were recorded. The most efficient, in terms of rainfall intensities and total amount, was the convective system which gave 155 mm of rainfall at Tafakoira on the 4 August. It may be seen in Figure 3 that, while the isohyetal map of the event is relatively smooth, the point rainfall intensity pattern greatly varies from one station to another as soon as the raingauges are located a few kilometres apart. At Tafakoira

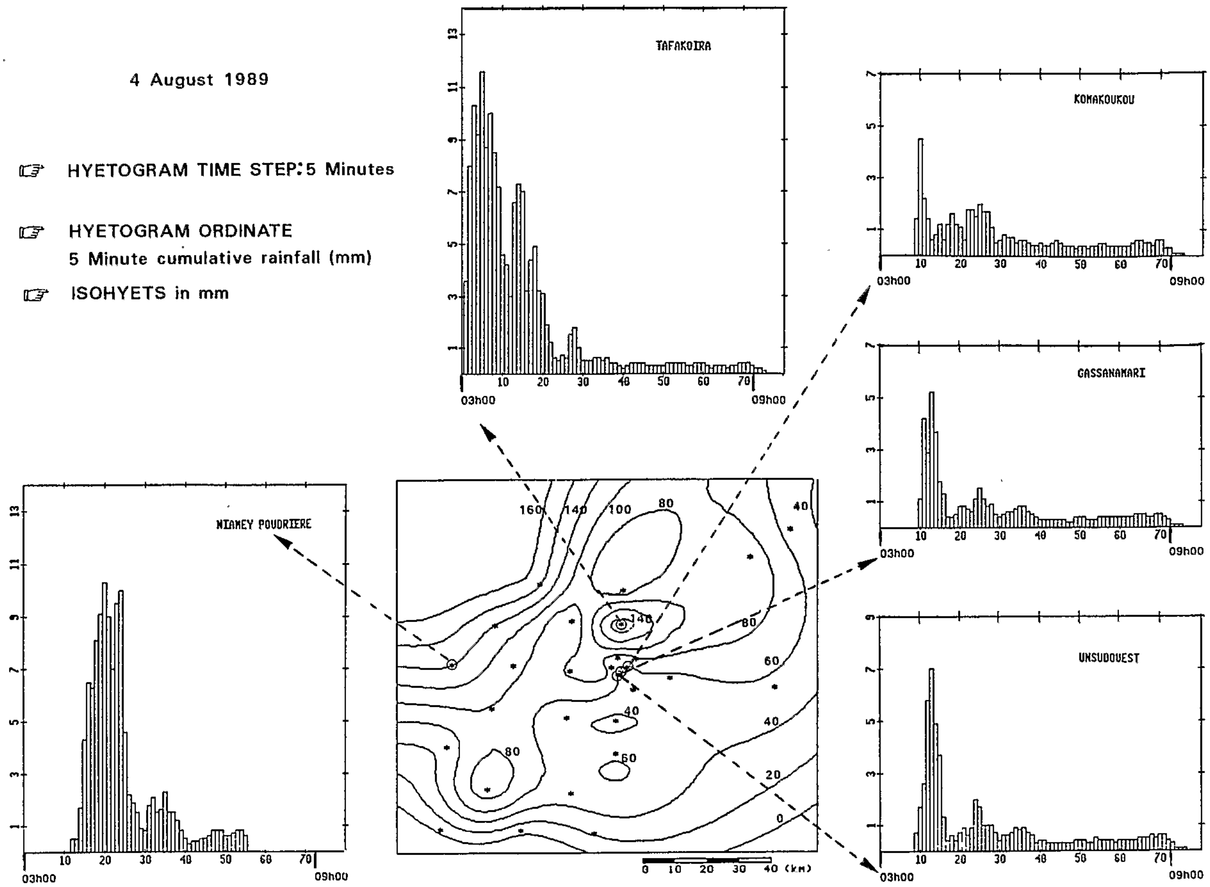


Figure 3. Isohyets of the 4 August storm, with the corresponding hyetograms at five stations

the hyetogram is somewhat different from the typical squall line hyetogram as shown by Hoepffner *et al.* (1989). The structure of this event thus appears rather complex and it would be beyond the scope of this general presentation to study it in detail. By contrast, the two convective systems observed on June 29 and July 11 are simple and representative examples of Sahelian squall lines.

It typically takes between three and six hours to a squall line to pass over the study area. The resulting cumulative rainfall (Figure 4a and 5a) display a good spatial organization but variations across the area may be large, with strong local gradients. Using either a linear (29 June) or a spherical model (11 July) to fit the experimental variogram, gives a fairly similar model between 1 and 30 kilometres, the slope of which is about $0.45\ \mathrm{mm}^2/\mathrm{km}^{-1}$.

The area covered by the network as well as its density allows the study of the squall line movement with an appropriate time step ranging from 15 to 30 minutes. At such time steps the convective part of the squall line is easily identified as well as the movement (Figures 4 and 5). At smaller time steps, strong local variations or the low number of stations affected either hinder the global perception or prevent the drawing of precise rainfall contours. With a time step of 30 minutes the size of the basic 3 mm contour is between 60 and 80 km in the movement direction. This corresponds to a 40–50 km wide rain zone travelling at an average speed of 50 to 60 $\mathrm{km/h}^{-1}$. These observations are in close agreement to those of Roux *et al.* (1984) made during the COPT 81 experiment.

Keeping only the stations affected by the convective zone of the squall line at a given time step, it was possible to study the variogram of 30 minute convective precipitation. The aspect of this variogram depends on the presence of the Target Area stations in the sample. When they are present it is difficult to fit a model accounting for both the small and the large distance behaviour of the experimental variogram. When they are not present the number of stations is often too small to obtain a reliable experimental variogram. The complete network will thus be required to determine the best way to compute areal rainfall at this time step, as far as the squall line convective region is concerned.

A similar study was performed for the stratiform region, the area of which is two to four times as large as the convective one. The rainfall distribution is fairly homogeneous within this region (Figures 4.b_5 and 5,b_5), and the associated variograms are regular (inset in Figure 5.b_5). A spherical model fits the experimental variograms well. The inclusion of the stratiform precipitation in the event cumulative rainfall is one reason for the smoother spatial pattern of the total rainfall as compared to the 30 minute convective rainfall.

It must be underlined that these first results, however partial, are an interesting complement to the squall line studies performed earlier by atmospheric physicists (e.g. Houze, 1977; Rouz *et al.*, 1984). While sophisticated doppler radar measurements allowed the description and understanding of the main features of the squall lines, the ground rainfall produced by such convective systems had yet to be studied in detail in Sahelian regions.

PERSPECTIVES

As a cooperative effort of atmospheric physicists and hydrologists, the EPSAT–NIGER experiment has the important goal of linking a better understanding and description of the squall lines to better estimation capabilities of ground rainfall fields. The first step in that direction is to determine the ability of raingauge networks to provide independently reliable point and areal rainfall estimates at various space and time scales. A preliminary measurement campaign in 1988 and the partial processing of the 1989 EPSAT–NIGER recording raingauge data has given some hints on what might be the future importance of the experimental results.

1. To begin with, it is noteworthy that at medium scales (10 to 100 km in space and 30 minutes to a few hours in time), there is a strong agreement between the atmospheric structures identified by atmospheric physicists and the ground rainfall fields. In particular the separation of a squall line cumulative rainfall into a convective and a stratiform rainfall is often possible. The convective rainfall generally amounts to about two thirds of the squall line cumulative rainfall at a given point; the convective region is sufficiently well organized in space to allow for interpolation at time steps ranging from 30 to 180 minutes with a $12 \times 12\ \mathrm{km}^2$ mesh network. The stratiform rainfall amounts for the remaining component (approximately

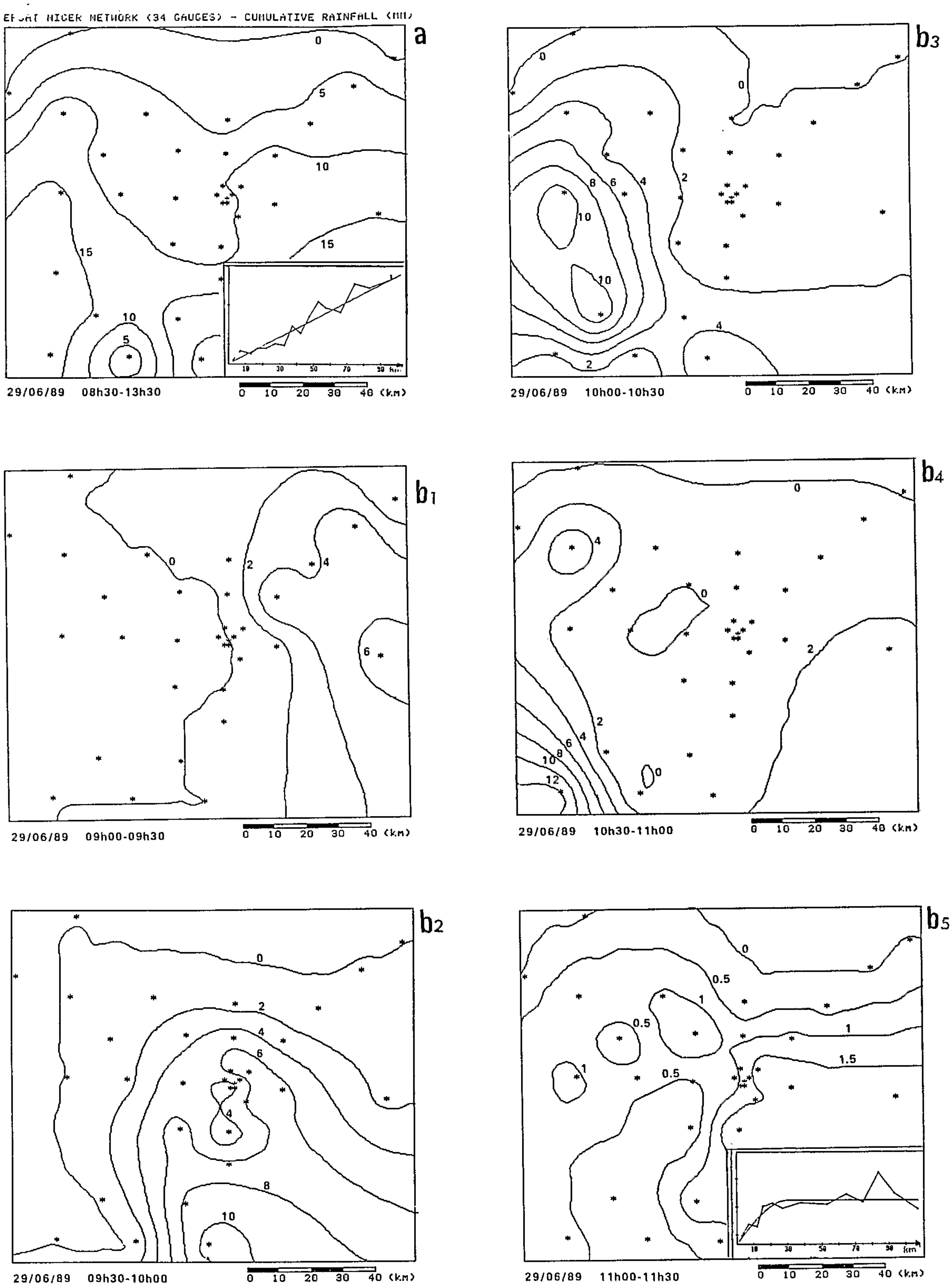


Figure 4. Isohyetal maps of the 29 June squall line. **a**: cumulative rainfall for the whole event (inset: the corresponding variogram). $\mathbf{b}_1$ through $\mathbf{b}_4$: convective rainfall region. $\mathbf{b}_5$: stratiform rainfall region

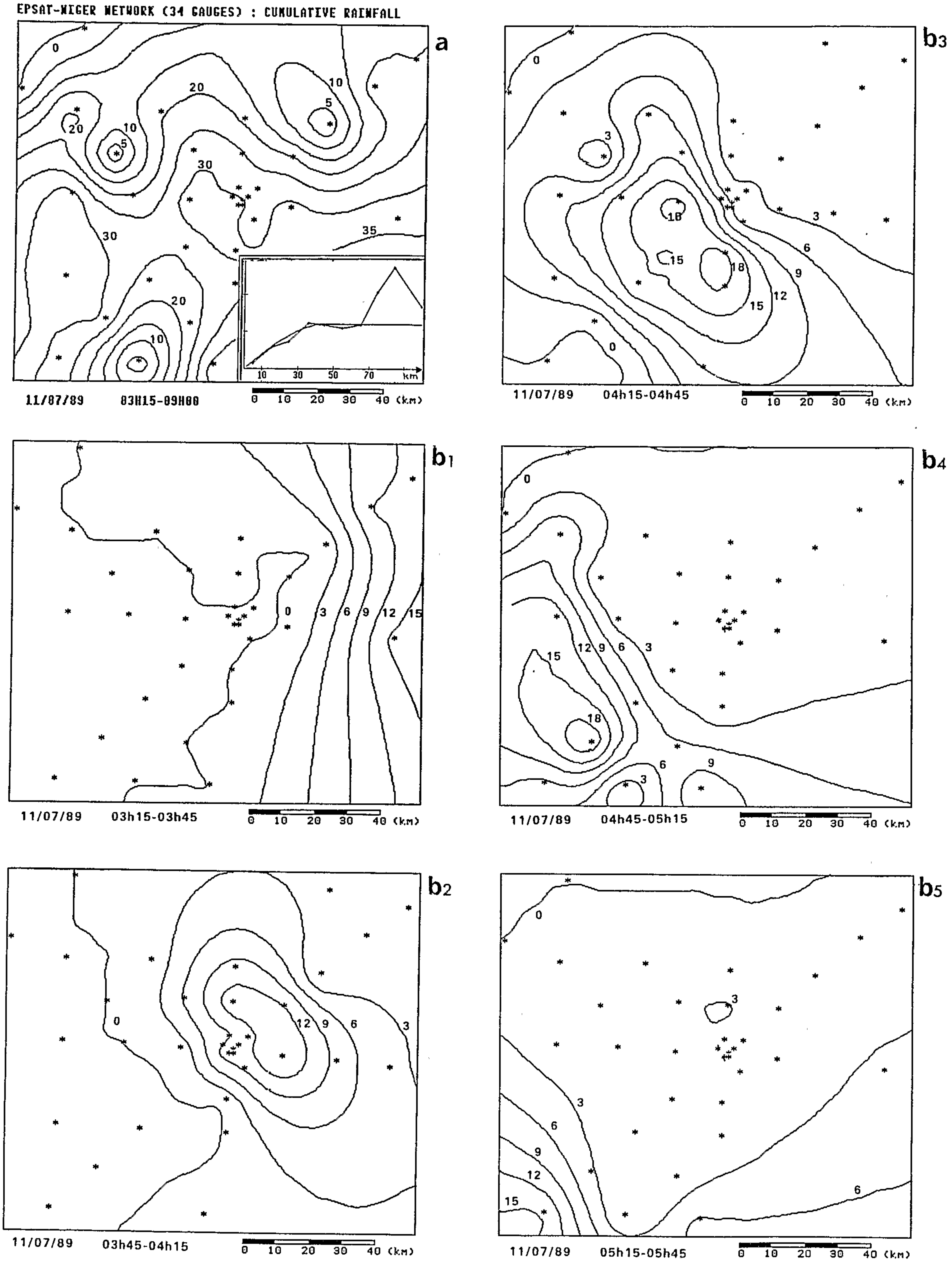


Figure 5. Same as Figure 4 except for the 11 July 1989 squall line

one third) and is more smoothly organized in space than the convective one; it is consequently still easier to interpolate. Given the differences between the convective region and the stratiform region, it is preferable, when possible, to separate these two regions when interpolating the point data or computing areal rainfall. Regarding areal rainfall, it was shown that, at the monthly scale, the network density required to compute reliable areal rainfall varies depending on the surface area concerned. For 10 000 km^2 this density is in the order of one gauge for 500 to 1000 km^2. For 100 km^2 it is about one gauge for 50 to 100 km^2. These figures must be taken as first estimates. They give a rough idea of the ground based instrumentation that would be needed in Sahelian countries to obtain good areal rainfall estimates over small surfaces. Moreover greater densities would have to be considered for smaller time steps. Further work is thus underway to provide more accurate estimates of the error involved in areal rainfall computation, for time steps varying from 30 minutes to a few days. This should be possible as soon as the 1989 data processing is completed.

2. At smaller scales in space (below a 5 km resolution), the spatial variability is very large and possibly may not be described using the geostatistical tools used for larger space steps. The smaller the time step, the greater is this variability and it would probably require radar data to study it in detail. Nevertheless even monthly rainfall display strong irregularities at such small space scales, and the Target Area of the EPSAT-NIGER network could provide the relevant information to get a better appreciation of the hydrological consequences of this fact.
3. The EPSAT-NIGER network covers too small an area to provide a good insight of the ground rainfall fields at larger space scales (a few hundred to a few thousand kilometres). Here remote sensing data (whether radar or satellite imagery) will have to be utilized, and the EPSAT-NIGER network will provide the ground truth which is compulsory to calibrate them.

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