*Hydrological Sciences -Journal- des Sciences Hydrologiques,*37,3, 6/1992

Rainfall estimation in the Sahel: the EPSAT-NIGER experiment

T. LEBEL
ORSTOM, Mission au Niger, BP 11416, Niamey, Niger
H. SAUVAGEOT
Laboratoire d'Aérologie, Centre de Recherches Atmosphériques, Campistrous, 65300 Lannemezan, France
M. HOEPFFNER
ORSTOM, Laboratoire d'Hydrologie, BP 5045, 34032 Montpellier cedex, France
M. DESBOIS
Laboratoire de Météorologie Dynamique, 91128 Palaiseau cedex, France
B. GUILLOT
ORSTOM, Centre de Météorologie Spatiale, BP 147, 22302 Lannion cedex, France
P. HUBERT
URA CNRS 1367, Ecole des Mines de Paris, 35 rue Saint Honoré, 77305 Fontainebleau, France

Abstract EPSAT-NIGER (Estimation of Precipitation by SATellite - NIGER experiment) has been designed to improve the understanding of the precipitation systems of Sudano-Sahelian Africa and to develop operational rainfall estimation algorithms for this region. It is based on the combined use of a very dense raingauge network (93 gauges over a study area of 16 000 km^2) and a C-band weather radar system. The experiment is scheduled to last three years, 1990-1992. The network pattern, a regular grid with nodes spaced at 12.5 km and a 16 gauge target area where the distance between stations is decreased to 1 km, has allowed for some preliminary studies on the rainfall distribution at various space and time scales. Whereas the long term average rainfall gradient is uniform, rainfall increasing north to south, a single rainy season can be markedly different. The local variability may be extremely large. That variability is enhanced at smaller sampling time steps and the computation of reference areal rainfall for satellite imagery validation is extremely sensitive to the design of the ground-based validation system. The joint processing of gauge and radar data has led to the identification of a few typical features of the drop size distribution of the African squall lines, which could lead to deriving specific algorithms for radar calibration in this region. The data provided by EPSAT-NIGER will be used in various international projects for the assessment of water input from the atmosphere to the continent over the Sahel.

Estimation des précipitations au Sahel: l'expérience EPSAT-NIGER

Résumé Le projet EPSAT-NIGER (Estimation des Précipitations par SATellite - expérience NIGER) est une expérience destinée à améliorer

Remplace ex non trouvé

Open for discussion until 1 December 1992

notre connaissance des systèmes précipitants de l'Afrique Soudano-Sahélienne, et à mettre au point des algorithmes opérationnels d'estimation des pluies sur cette région. Elle s'appuie sur l'utilisation conjointe d'un réseau de pluviographes (93 postes sur 16 000 km^2) et d'un radar météorologique bande C. Sa durée prévue est de trois ans (1990-1992). La géométrie du réseau, une grille régulière dont la maille mesure, 12.5 km de coté, dotée d'une cible où la distance entre postes descend à 1 km, a permis de mener à bien des études préliminaires sur la répartition des pluies à différentes échelles de temps et d'espace. Le gradient pluviométrique sud-nord des moyennes interannuelles est fortement altéré quand on travaille sur une saison particulière. La variabilité locale des cumuls saisonniers peut être extrêmement importante. Des écarts de 60% sur moins de 10 km ont été enregistrés. L'exploitation conjointe des données sol et radar conduit à mettre en évidence certaines particularités des lignes de grains et s'avère prometteuse pour mettre au point une vérité sol adaptée à la validation des données satellitaires.

RAINFALL IN THE SAHEL: A KNOWLEDGE DEFICIT

The severe drought affecting the Sahel for more than twenty years has clearly demonstrated the fragility of the human and ecological equilibria in this part of Africa. Precipitation deficits accumulated over recent years are largely responsible for the present desertification of the region and for the increasing difficulties in survival encountered by its inhabitants. The irregular temporal and spatial variation of rainfall controls the survival of the vegetation systems. The temporal variability affects the time of the beginning of the rainy season, the length of the vegetative period, and the intervals between rainy events. During a rain event, the fluctuations of intensity govern the amount of precipitated water that can be retained in the soil, and thus be used by the vegetation. The main feature of the spatial variability of the Sahelian climate is the consistent south-to-north gradient of the mean annual rainfall (e.g. Leroux, 1983). However, over any given rainy season, the isohyetal maps are much less regular. Despite the results of a few studies, using a geostatistical approach (Thauvin & Lebel, 1991) or fractal method (Hubert & Carbonnel, 1989, 1991), there are presently no satisfactory operational methods for the modelling of the Sahelian rainfall variability, whether at the annual or rain-event scale. This is largely the consequence of a lack of suitable measurements. In such vast, semi-arid and underpopulated regions, the practical difficulties and costs of installing and maintaining the appropriate raingauge networks make measurements difficult to obtain.

SATELLITE RAINFALL ESTIMATION: THE NEED FOR AN APPROPRIATE VALIDATION

Hydrologists, agronomists and climate modellers all need better rainfall estimation algorithms, though at different scales. Climate modellers ask for representative measurements and rainfall distribution models to compute the representative measurements and rainfall distribution models to compute the water budget at large scales and improve, using general circulation models (GCMs), the parameterization of latent heat transfer from the tropical to the temperate regions. Hydrological scales are more in the range of a few to a few hundred square kilometres. Agronomists need to assess the variability of rainfall accumulated over periods of one to a few days, over areas as small as a few hectares. Presently the annual, monthly and decadal rainfall fields over the Sahel are known with an accuracy far too low to meet the needs of those three communities. For some time now it has been expected that satellite imagery, since it provides complete coverage of the Earth, could make up for the shortcomings of raingauge networks. That coverage is especially well suited to the intertropical zones, since the best resolution in time is obtained from geostationary satellites positioned above the Equator. The convective nature of the Sahelian precipitation is another good reason for relying on satellite data for rainfall estimation, as was shown by Barrett & Martin (1981). Following the work of Griffith *et al.* (1981) over the high US plains and of Woodley *et al.* (1980) and Richards & Arkin (1981) in tropical regions (within the framework of the GARP Atmospheric Tropical Experiment (GATE)), it appeared straightforward to use the approach in the Sahel. While the GATE study was concerned with oceanic regions displaying marked differences from the Sahel, Carn & Lahuec (1987), Thiao *et al.* (1990) and Dugdale *et al.* (1991), have derived various methods of satellite rainfall estimation over the Sahel for time periods greater than a month. A true validation of those methods remains to be carried out, based on ground truth that was not available until recently. In fact, Griffith (1987), among others, has underlined the sensitivity of the satellite algorithms to the ground truth used to calibrate them. Moreover, the potentiality of geostationary satellite data for rainfall estimation over smaller time periods was demonstrated by Wylie & Laitsch (1983) and Negri & Adler (1987) to be very poor. In the Sahel, with few exceptions (for instance, Hubert *et al.*, 1987), only results at time steps greater than one month are available.

There are thus two goals for a rainfall estimation experiment in the Sahel: (a) improving satellite estimates at large time steps (above one month) by refining the algorithms and defining a proper ground truth; and (b) studying in detail rainfall variability at small time and space scales. More specifically the aims of EPSAT-NIGER are:

(i) characterizing the nature of ground truth;
(ii) studying the influence of ground truth accuracy on satellite data validation;
(iii) comparing ground- and satellite-based rainfall estimates;
(iv) investigating the dependence of spatial variability on rainfall integration in time;
(v) deriving from the above the optimal combination of sensors to be used for rainfall estimation at various scales, taking into account the required degree of accuracy and the size of the elementary zones of estimation; and
(vi) improving current satellite algorithms or developing new ones by using

different types of data or calibration procedures.

The first item is especially important, for there is a strong body of opinion that the discrepancies between ground- and satellite-based rainfall estimates are due to a lack of accuracy of the first rather than the indirect nature of the second. It is widely accepted that any areal rainfall estimate using a gauge network involves a certain amount of uncertainty (e.g. Lebel *et al.*, 1987). This uncertainty should be quantitatively assessed on a case by case basis when a gauge network is used for providing the ground truth. The EPSAT-NIGER network makes this assessment possible at a research (very dense network) and an operational (lower density) level.

LOCATION AND CLIMATE OF THE STUDY AREA

The EPSAT-NIGER region of study is located in the vicinity of Niamey, Niger, at a latitude of 13°30′. The rainfall distribution over western Africa is determined by the position of the meteorological equator and its two associated structures: the ITF (InterTropical Front) and the ITCZ (InterTropical Confluence Zone). The ITCZ rarely exerts its influence over continental areas north of 12°N of latitude, a limit which is also (not coincidentally) the southern boundary of the Sahel. Thus rainfall in the Sahel (hence in Niamey) depends almost exclusively on the position and structure of the ITF which is characterized by marked wind shears and moisture discontinuities, often at such low levels as below the 700 hPA surface, and is consequently not likely to produce extended and continuous rainfall. The Sahelian rainfall is therefore mostly of convective origin, either from isolated cumulo-nimbus phenomena or from organized cloud formations, often evolving in the form of squall lines. Such squall lines are the most characteristic feature of the Sahelian climate during the rainy season. They move in a general east/southeast to west/southwest direction at a velocity of 50 to 70 km h^{-1}.

The relief around Niamey is fairly uniform (the maximum elevation is 275 m and the minimum 175 m) which minimizes local topographic effects on the rainfall system dynamics. The mean annual rainfall is about 560 mm (564 for the 1905-1989 period and 562 for the 1950-1989 period) with a north-to-south increasing gradient of about 100 mm per degree, that is in the order of 1 mm km^{-1} (Fig. 1). The past 20 years (1968-1989) have seen a lasting drought with an average annual rainfall of 495 mm.

Niamey is host to several institutions specialized in hydrometeorology. It was chosen by the CILSS (Comité Permanent Inter-Etats de Lutte contre la Sécheresse dans le SAHEL) for installing its agrometeorological monitoring centre (AGRHYMET). AGRHYMET is equipped with the hardware required for the reception and processing of the NOAA and METEOSAT meteorological satellite data. Niamey is also the location of ACMAD (African Centre of Meteorology Applied to Development), and finally, the Direction de la

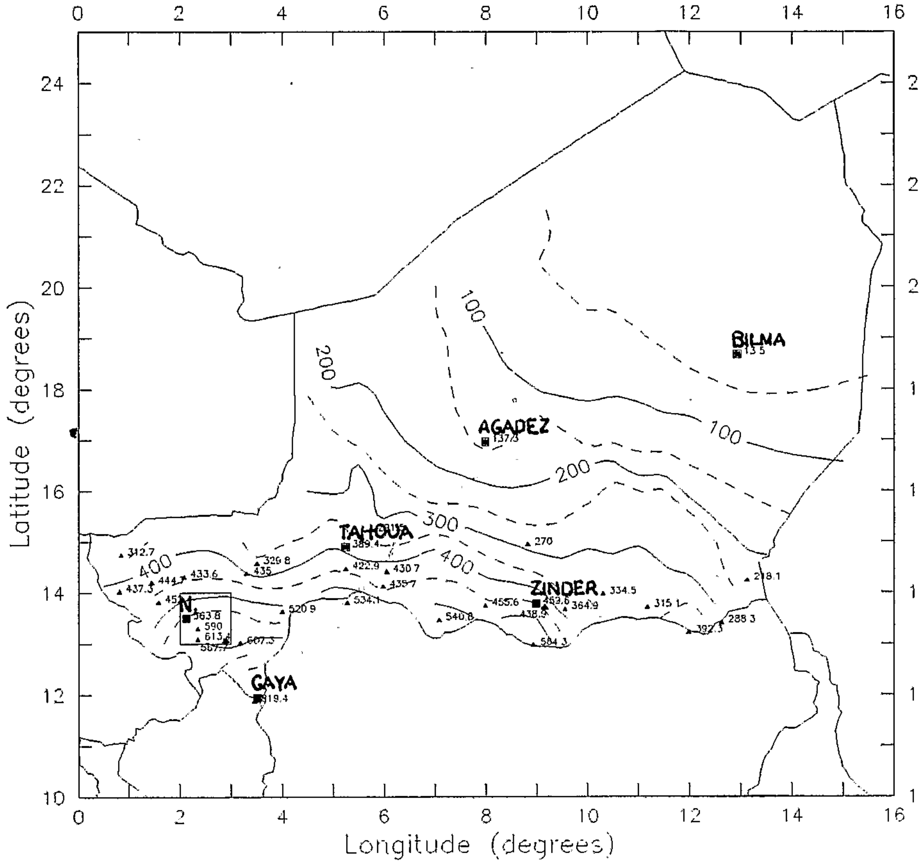


***Fig. 1** Mean annual rainfall over Niger (1950-1990); the EPSAT-NIGER study area is the square surrounding Niamey.*

Météorologie Nationale (DMN) operates a C-band weather radar system at the airport, southeast of the town.

EXPERIMENT DESIGN AND DURATION

The experiment has been designed to:

(a) compute, with a reasonable accuracy, areal rainfall estimates from direct ground-based measurements only;

(b) quantify the small scale variability; and

(c) monitor the mesoscale rainfall systems, which requires a spatial coverage large enough to study their successive stages of development.

A dense gauge network and a weather radar system are both needed to achieve those aims. One hundred static memory recording raingauges were acquired to study the sampling properties of ground networks. In 1990, 95 were installed, 93 of them at a normalized height of 1.5 m. At two sites (numbers 11 and 54 in Fig. 2), the 1.5 m raingauge was doubled with one at ground level for purpose of comparison. The 93 sites are spread over a study area limited by 1°40'E and 3°00'E in longitude, 13°N and 14°N in latitude, i.e. about 16 000 km^2 (Fig. 2). The area is divided into a 10 000 km^2 reference area east of Niamey (2°10' to 3°00' in longitude) and a 6000 km^2 extension area to the west (1°40' to 2°10'). Over the reference area the network is a regular grid with 64 nodes spaced at approximately 12.5 km. This basic mesh is of the same size as a group of 9 Meteosat pixels in the infrared band. Roughly in the middle of the network, a target mesh has been equipped with 16 gauges arranged in increasing density towards the centre of the mesh, where 4 raingauges form a square with 1 km sides. In addition, two gauges have been installed on a small watershed close to the target area. The reference area is thus equipped with a total of 82 raingauges, and the extension area by 11 gauges.

The mean area per gauge over the reference area is 156 km^2 for the basic network (64 gauges uniformly spread over the reference area) and 9 km^2 over the target area. Those two values characterize the EPSAT-NIGER ground network. This is well above the 6000 km^2 per gauge which is the mean value of the Niger national raingauge network, south of 16°N of latitude. As for the recording raingauge network, its density is one gauge per 20 000 km^2 which implies that the measurements are uncorrelated for time steps under 24 h.

Beyond the limits of the gauge network study area, the DMN weather radar system (EEC WR 100-5 type) provides an extensive spatial coverage as far as 350 km away. It has a 1.5° beam width, a 5.4 cm wavelength (5600-5650 Mhz) and a peak power of 250 kw. Its pulse width is 2 μs. The radar will be used for quantitative purposes for distances up to around 100 km. Discarding the inner 20 km radius circle, which is interfered with by ground clutter, leaves an area of about 30 000 km^2. The numerical acquisition and colour display of the data are handled by the SANAGA system (Système d'Acquisition Numérique pour l'Analyse des Grains Africains), which was developed for this experiment (Sauvageot & Despaux, 1990).

The installation of the raingauges and implementation of SANAGA were carried out in 1988 and 1989, allowing for the testing of SANAGA and of the acquisition and power supply systems of the recording raingauges (Roux, 1990), as well as for some preliminary studies. The full setup was ready at the beginning of the 1990 rainy season. In order to account for the interannual variability of the climate, the experiment will last for three years, until 1992, when it becomes part of the HAPEX-SAHEL experiment (Lebel, 1990). At least three years are required to record enough events. Given an average number of 30 to 40 events a year, one can expect to end up with 20 to 40 events in each sub-sample if two or three categories of events are considered. Finally, the difficulties associated with field measurements and the uncertainty regarding the radar reliability are other reasons for implementing the experiment for a few years.

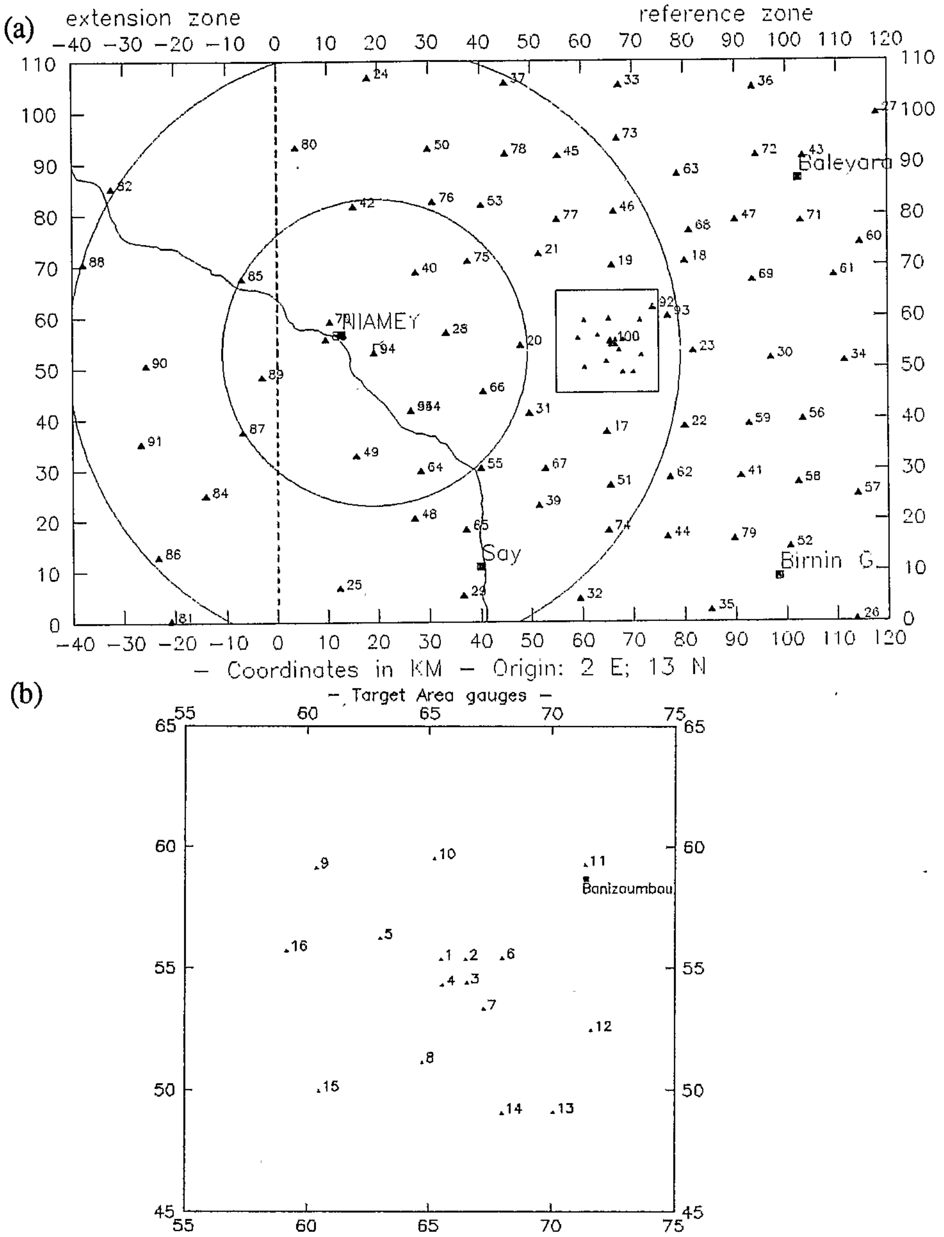


***Fig. 2** The recording raingauge network.*

PRELIMINARY STUDIES

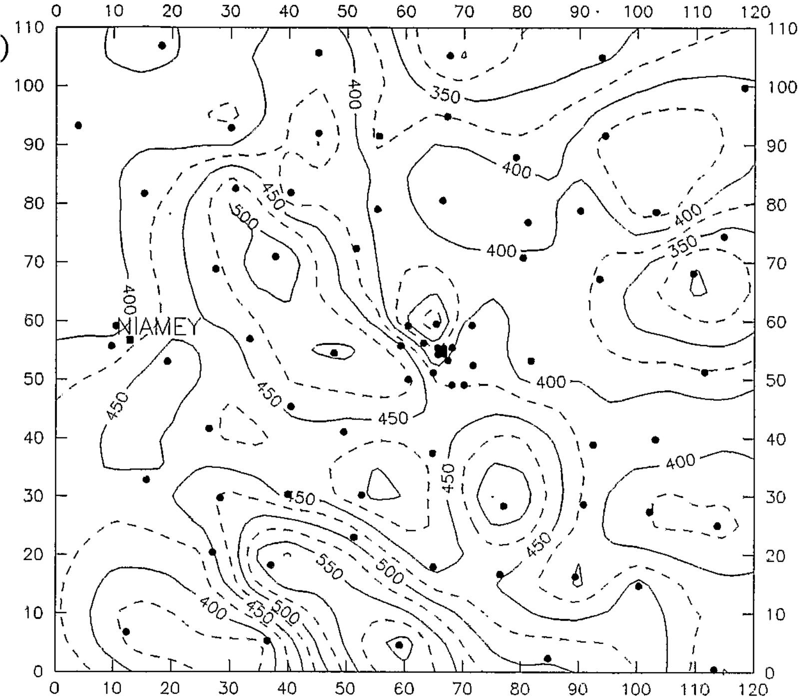
By the end of 1989, the raingauge network was installed in the reference area. It was thus possible to start a preliminary investigation on how dependant the computation of gauge-based areal rainfall is on the network density. For monthly rainfall over the target area, it was shown that differences of up to

100% could be found between the areal estimates retrieved from the meteorological service network and the EPSAT-NIGER network (Thauvin & Lebel, 1991). This is a clear indication that, even at large time steps, the validation of satellite algorithms requires ground truth networks a lot denser than those of the current operational networks. The EPSAT-NIGER network provides that opportunity. It tests the ground truth accuracy against the network density, the surface area concerned (between 1 and 10 000 km^2) and the time scale.

A second important point to address is just how pertinent it is to characterize rainfall spatial variability from the data of a single rainy season that can happen to be either drier or wetter than "normal", as was the case in 1990. In Niamey (ORSTOM station), 393 mm was recorded, as compared with 585 mm in 1989 (Lebel *et al.*, 1991). In that area, as seen earlier, the increasing north-to-south rainfall gradient is approximately constant and equal to 100 mm per degree of latitude. The mean annual rainfall $M(x,y)$ may thus be written: $M(x,y) = 600 - (L - 13) \times 100$, where $M(x,y)$ is in mm and L is the latitude in degrees. The yearly rainfall for a given year k (here 1990), is then given as $M_k(x,y) = M(x,y) + d_k + e(x,y)$, where d_k represents the average deviation from the mean for year k (in 1990 the mean deficit over the study area was 130 mm), and $e(x,y)$ is a random component spatially organized but with fluctuations dependent on the scale considered. Figure 3 shows the isohyetal maps of $M_k(x,y)$ and $e(x,y)$ for 1990. Such a model assumes that large scale averages retain the general climatic gradient, as confirmed when the seasonal rainfall is averaged over sufficiently large latitudinal strips, as in Fig. 4. By contrast, the random component $e(x,y)$ displays strong spatial variability even at small scales. In Fig. 5 a difference of 180 mm (60%) is observed over 10 km. Such variations in seasonal rainfall contradict the belief that storm rainfall variability is smoothed out by averaging over a whole season in the Sahel. Since the experiment will last three years, it will be possible to study: (a) the frequency in space and time of such small scale variations; and (b) how they are related to the overall pattern of the rainy season (for instance is one more likely to observe strong relative differences for a dry year than for a wet year?).

The radar calibration is the third point which has been addressed at this early stage of the experiment. The radar is partly intended to quantify rainfall on a sub-grid of the gauge network grid. Among the numerous factors interfering in the calibration process, those related to the radar system itself will have to be thoroughly checked, since it is an ageing system. Ground clutters will be used as calibration targets for each image until they are reached by the rain, which occurs only at the end of the rainy event over the study area (Fig. 6). As for the factors linked to the precipitation system, preliminary studies of the Z (radar reflectivity)-R (rainfall rate) relationship by Chamsi & Sauvageot (1989) have shown that for tropical squall lines, the parameters a and b of the standard relationship $Z = aR^b$ vary depending on the region considered within the squall line. The frontal convective part comprises a large proportion of large rain droplets, which leads to the coefficient b being significantly smaller

(a)



data interpolated using the model $M_k(x,y) = 470 - y + e(x,y)$ with M in mm and y in km, $y = 0$ at latitude 13°N, and residuals $e(x,y)$ interpolated by kriging using a spherical variogram with a range of 30 km

(b)

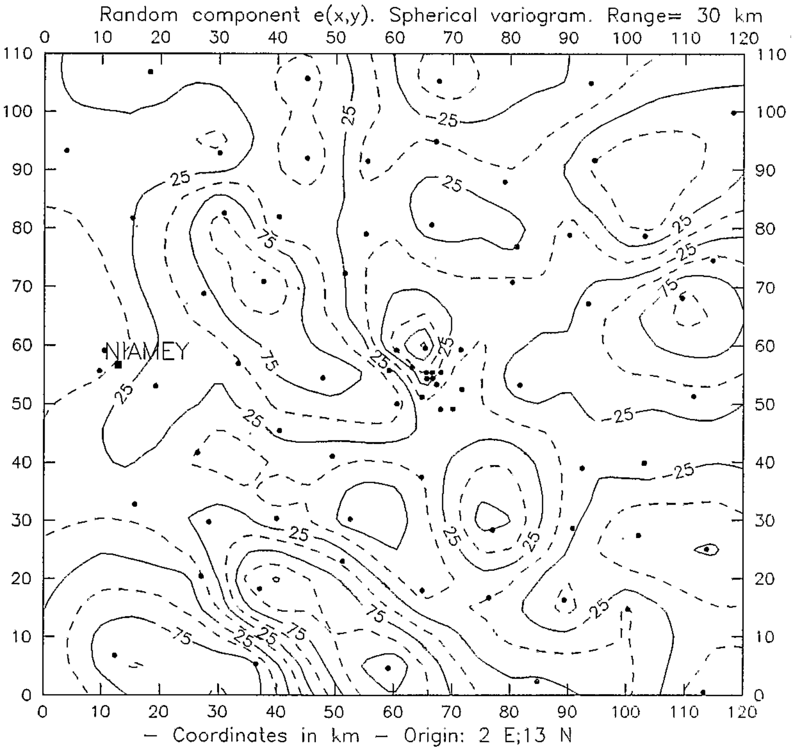


***Fig. 3** The 1990 rainy season over the reference area: (a) isohyetal map of the seasonal rainfall $M_k(x,y)$; (b) isohyetal map of $e(x,y)$.*

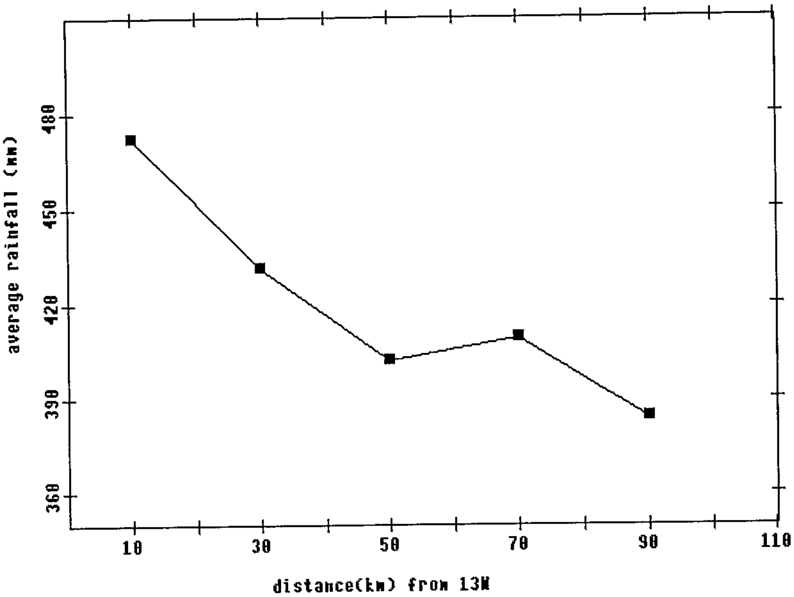


Fig. 4 Average seasonal cumulative rainfall computed for latitudinal strips 20 km wide across the study area (120 km); the average north-to-south increasing gradient is close to the mean climatological value of 1 mm km^{-1} although it is less regular for the two most northern strips.

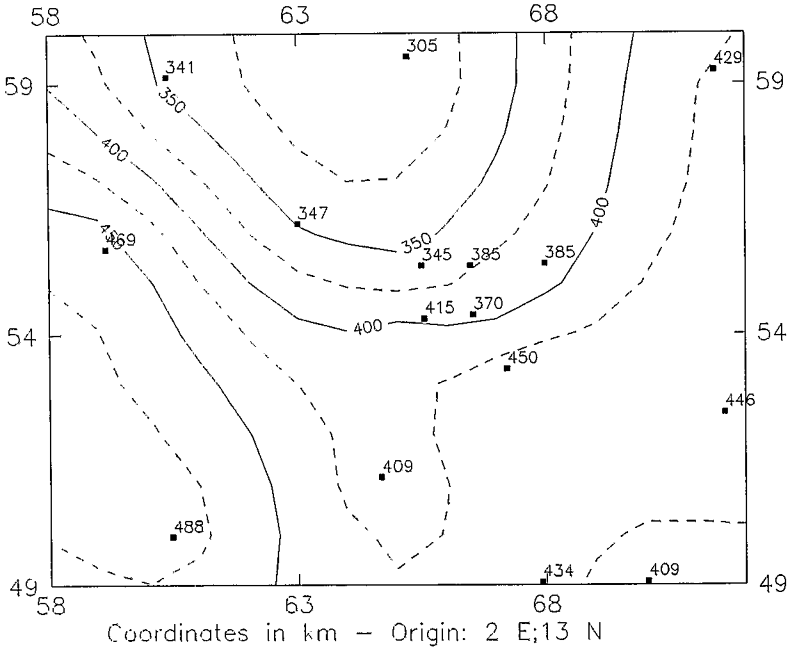


Fig. 5 Detailed map of the 1990 seasonal cumulative rainfall over the target area; a difference of 183 mm (about 60%) is observed over a distance of less than 10 km.

than the standard value, and the coefficient *a* being greater. The reverse holds for the stratiform mixture at the rear of a squall line. This bears important implications for the transformation of the *Z* values into rainfall rates *R*, since it will be impossible to apply a single *Z-R* relationship to a whole image. On the other hand, if the relationships identified prove to be stable, it could greatly facilitate the radar calibration. Figure 6(c) shows an example where the isohyets computed from the ground data accumulated over 5 minutes fit the radar display fairly well, with, however, a number of discrepancies at small scale.

Another point worth investigating is the stratification between well organized extensive precipitation systems (among them the squall lines) and other, more localized events. This is of interest to the validation of satellite images and climate studies alike. It is often asked whether the present dry period has resulted from a reduction in the number of squall lines, or whether it is the mean value of each rainfall event that has decreased. The rainfall events were classified according to their spatial extent. The first class (events from extensive systems) accounts for 60% in 1989, and 64% in 1990, of the seasonal rainfall (Lebel *et al.*, 1991). The scaled climatological variogram (Lebel & Bastin, 1985) inferred from the data of those large extension events is similar in 1989 and 1990. An exponential model ($\gamma(h) = \gamma_0 + (\gamma_0 - \beta)\exp(1 - h/\alpha)$) was fitted to the experimental variogram (Fig. 7). The range of correlation is in the order of 60 km, both in 1989 and 1990, which suggests some sort of stability in the spatial structure of those events from one season to another.

CONCLUSIONS AND PERSPECTIVES

The EPSAT-NIGER experiment is set in a context of renewed interest in tropical climatology. Among the various projects aiming at a better understanding and parameterization of the tropical climatic mechanisms, two at least will directly benefit from the EPSAT-NIGER project. They are HAPEX-SAHEL, the goal of which is to study the land surface processes in the Sahel with a view to incorporate their better descriptions in GCMs, and TRMM (Tropical Rainfall Measurement Mission, Simpson *et al.*, 1988), which studies the distribution and variability of precipitation and latent heat release on a monthly average over tropical areas of about 10^5 km^2. HAPEX-SAHEL will make use of the rainfall estimates provided by EPSAT-NIGER, since the two study areas are identical. As for TRMM, Bell *et al.* (1990) have stressed the importance of simulating the sampling errors involved in the TRMM estimates. Such simulations require detailed and accurate ground data which are missing today. In fact, the present simulations are based on the GATE data, which were collected over the ocean during a few months only. It is thus desirable to obtain other data sets giving access to more relevant information on the spatio-temporal variability of tropical rainfall, especially within Africa.

In EPSAT-NIGER, the association of hydrologists and atmospheric

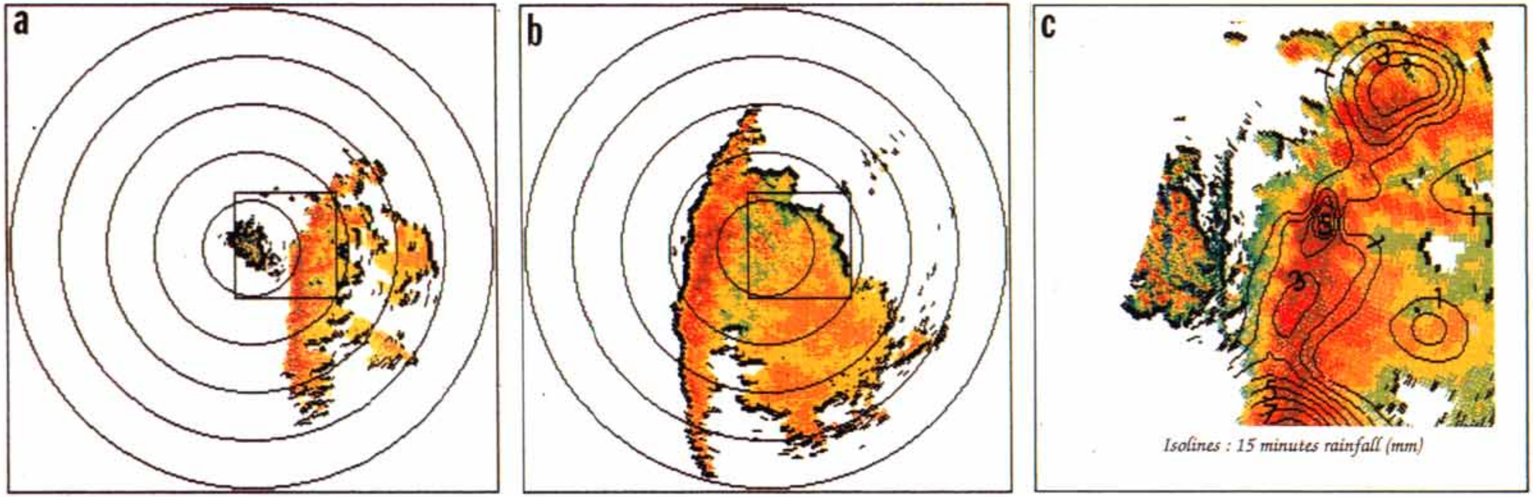
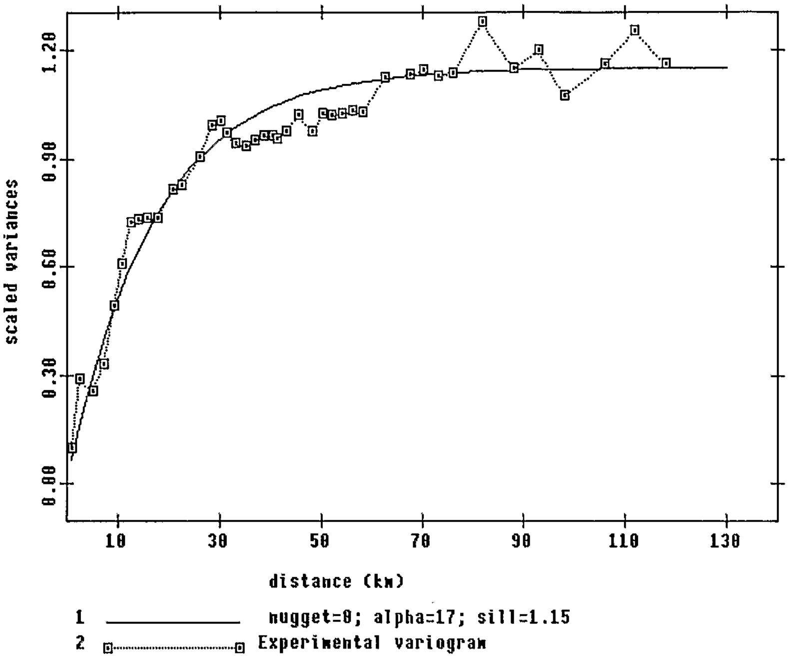


Fig. 6 *The squall line of 27 July as seen by the weather radar system at (a) 08.30 h and (b) 10.30 h: the convective front is clearly visible in the two images, the stratiform mixture at the rear is visible only in the image of 10.30 h, the 5 min isohyets fit the radar display fairly well; (c) a zoom in over the reference area: strong echoes are in red, brown and grey; weak echoes (no rain) are in blue and green; yellow corresponds to light rainfall.*



each event first scaled by its own experimental standard deviation; experimental variogram computed as mean variogram of the 15 events (detailed procedure in Lebel & Bastin, 1985); model fitted to this experimental variogram of the exponential type: $\gamma(h) = \gamma_0 + (\gamma_0 - \beta)\exp(1 - h/a)$ where h is the distance, γ_0 the nugget, β the sill and a the shape parameter (for $h > 60$ there is no further significant increase in γ)

***Fig.** 7 Scaled climatological variogram derived from a set of 15 events from extensive systems observed in 1990.*

physicists reflects the desire for increased collaboration expressed recently at the conference *Mesoscale Precipitation: Analysis, Simulation and Forecasting* held at the Massachussetts Institute of Technology, Boston, USA, in September, 1988. EPSAT-NIGER will provide those two scientific communities with data of a resolution and an accuracy unmatched until now, and an additional knowledge of great interest both to climate modellers and water balance scientists. That is of the utmost importance if one is to implement efficient water resources management schemes in regions of Africa threatened with desertification.

Furthermore, EPSAT-NIGER will provide simultaneously a global and detailed view of rainfall over an area of several thousand square kilometres, thus going well beyond the limits of a few tenths of square kilometres characterizing most of the hydrological studies in Africa. An obvious extension of EPSAT-NIGER will be the implementation of the new algorithms developed within the framework of the experiment in an operational mode. This could be done through the AGRHYMET facilities.

Finally EPSAT-NIGER should also benefit the development of precipitation models. In fact, the efficiency of such models is often impeded by a lack of appropriate data, since, as emphasized by Rodriguez-Iturbe (1986), quantitative models of precipitation "should be validated and rooted in measurements and data". It is implied, in the use of the conditional, that such requirements are not always met.

Acknowledgements The EPSAT-NIGER experiment is a joint project of the Direction de la Météorologie du Niger (DMN) and ORSTOM. The authors wish to thank all the DMN staff who made the realisation of the experiment possible, and especially the Director, M. Boulama, as well as the ORSTOM team based in Niamey. EPSAT-NIGER is also deeply indebted to L. Le Barbé, ORSTOM representative in Niger, for his perseverance and advice which created the conditions for successful cooperation between DMN and ORSTOM. One of the most important aspect of that collaboration was the enlightening scientific discussions held throughout the first year of the experiment.

REFERENCES

Barrett, E. C. & Martin, D. W. (1981) *The Use of Satellite Data in Rainfall Monitoring*. Academic Press, London.

Bell, T. L., Abdullah, A., Martin, R. L. & North, G. R. (1990) Sampling errors for satellite-derived tropical rainfall: Monte Carlo study using a space-time stochastic model. *J. Geophys. Res.* **95** (D3), 2195-2205.

Carn, M. & Lahuec, J. P. (1987) Estimation des précipitationsau Niger au cours de la saison des pluies 1986 à partir de l'imagerie IR METEOSAT. Bilan et critique des méthodes utilisées. *Veille Clim. Satel.* **17**, 40-48.

Chamsi, N. & Sauvageot, H. (1989) Variabilité spatio-temporelledes paramètres de la relation Z-R dans les lignes de grains tropicales. *Veille Clim. Satel.* **27**, 16-18.

Dugdale, G., McDougall, V. D. & Milford, J. R. (1991) Rainfall estimates in the Sahel from cold cloud statistics: accuracy and limitations of operational systems. In: *Soil Water Balance in the Sudano-Sahelian Zone* (Proc. Niamey Workshop, February 1991). IAHS Publ. no 199, 65-74.

Griffith, C. G., Augustine, J. A. & Woodley, W. L. (1981) Satellite rain estimation in the US high plains. *J. Appl. Meteorol.* **20**, 53-66.

Griffith, C. G. (1987) The estimation from satellite imagery of summertime rainfall over varied space and time scales. NOAA Technical Memorandum ERL ESG-25, US Department of Commerce, NOAA/ERL, Boulder, Colorado, USA.

Hubert, P. & Carbonnel, J. P. (1989) Dimensions fractales de l'occurrence de pluie en climat soudano-sahélien. *Hydrol. Continent.* **4**, 3-10.

Hubert, P. & Carbonnel, J. P. (1991) Fractal characterization of intertropical variability and anisotropy. In: *Non Linear Variability in Geophysics*, ed. D. Schertzer & S. Lovejoy, Kluwer Academic Publishers, Dordrecht, The Netherlands, 209-213.

Hubert, P., Thiao, W., Cadet, D., Carbonnel, J. P. & Desbois, M. (1987) Comparaison des données satellitaires infrarouge et des mesures au sol concernant l'épisode pluvieux du 12 au 13 juin 1986 dans la région de Ouagadougou (Burkina Faso). *Veille Clim. Satel* **20**, 31-36.

Lebel, T. & Bastin, G. (1985) Variogram identification by the mean-square interpolation error method with application to hydrologic fields. *J. Hydrol.* **77**, 31-56.

Lebel, T., Bastin, G., Obled, C. & Creutin, J. D. (1987) On the accuracy of areal rainfall estimation: a case study. *Wat. Resour. Res.* **23** (11), 2123-2134.

Lebel, T. (1990) H. comme HAPEX: Hydrologie hors bassin versant. In: *Le Transfert d'Echelle*. Proc. 4th Séminaire Informatiques ORSTOM, pp 493-506, ed. C. Mullon, ORSTOM Editions (Collection Colloques et Séminaires), Paris, France.

Lebel, T., Cazenave, F., Gathelier, R., Gréard, M., Gualde, R., Kong, J. & Valero, T. (1991) EPSAT-NIGER, campagne 1990. ORSTOM-DMN.

Leroux, M. (1983) *Le Climat de l'Afrique Tropicale*. Ed. Champion, Paris, France.

Negri, A. J. & Adler, R. F. (1987) Infrared and visible satellite rain estimation. Part I: a grid cell approach. *J. Clim. Appl. Meteorol.* **26**, 1553-1564.

Richards, F. & Arkin, P. (1981) On the relationship between satellite observed cloud cover and precipitation. *Mon. Weath. Rev.* **109**, 1081-1093.

Rodriguex-Iturbe, I. (1986) Scale of fluctuation of rainfall models. *Wat. Resour. Res.* **22** (9), 15S-37S.

Roux, C. (1990) Rapport de campagne EPSAT-NIGER 1989. ORSTOM, Direction de la Météorologie National du Niger.

Sauvageot, H. & Despaux, G. (1990) SANAGA, un système d'acquisition numérique et de visualisation de données radar pour la validation des estimations satellitaires de précipitation. *Veille Clim. Satel.* **31**, 51-55.

Simpson, J., Adler, R. F. & North, G. R. (1988) A proposed Tropical Measuring Mission (TRMM) satellite. *Bull. Am. Met. Soc.* **69**, 278-295.

Thauvin, V. & Lebel, T. (1991) EPSAT-NIGER. Study of rainfall over the Sahel at small time steps using a dense network of recording raingauges. *Hydrol. Process* **5**, 251-260.

Thiao, W., Cadet, D. L. & Desbois, M. (1990) A note on: Estimation of rainfall due to squall lines over West Africa using METEOSAT imagery. *Meteorol. Atmos. Phys.* **42**, 69-76.

Woodley, W. L., Griffith, C. G., Griffin, J. S. & Stromatt, C. S. (1980) The inference of GATE convective rainfall from SMS-1 imagery. *J. Appl. Meteorol.* **19**, 388-408.

Wylie, D. P. & Laitsch, D. (1983) The impacts of different satellite data on rain estimation schemes. *J. Clim. Appl. Meteorol.* **22**, 1270-1281.

Received 14 March 1991; accepted 25 October 1991