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EPSAT-Niger : A PILOT EXPERIMENT FOR RAINFALL ESTIMATION OVER WEST AFRICA.

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Introduction.

The EPSAT (Estimation des Précipitations par SATellite) program was set up in France in 1985 to provide a cooperative framework for researchers interested in exploring the possibilities of estimating precipitations using satellite data. The program has rapidly focused on the intertropical regions, where it seems that satellite data were both the most convenient (notably with respect to geostationary satellites) and bearing the best prospect of significant progress due to a general lack of measurement capabilities and of tropical meteorologal knowledge. In the mean time, researchers from other countries, especially U.K. researchers, have joined in.

This rather unformal network of scientists meets twice a year to discuss the major scientific objectives and to decide on specific experiments. The EPSAT-NIGER experiment, which is presented here, has the specific objectives of both improving our knowledge of sahelian precipitation systems and deriving operational algorithms to estimate precipitation using any appropriate combination of remote and ground based sensors depending on the temporal and spatial resolutions needed.

The spatio-temporal variability of precipitation in the Sahel is very large at all scales. At the storm scale, 80% of the precipitation occuring over the Sahel originates in squall lines or local convective systems displaying a great spatial variability. At the interannual and regional scales, the semi-arid zone of west Africa (the Sahel) has been subject to a persistent drought for the past twenty years. Whilst there are serious disagreements among scientists regarding the climatic significance of this drought (i.e. whether it is additional evidence of a major climatic change of just a normal oscillation), the local populations are learning first hand the dramatic consequences of drought and seasonnal precipitation variations on a fragile agricultural activity. A good estimate of the spatial and temporal rainfall distributions would thus be very useful, especially if available on a real or slightly delayed time basis, both from a climatical and economical points of view.

As a matter of fact the precipitations of the tropical regions are a major source of energy from the terrestrial energy budget, through latent heat being released into the atmosphere. It is widely anticipated that a more accurate knowledge of tropical precipitations would thus greatly enhanced the forecasting capabilities of the General Circulation Models (GCM). The climatic variations associated with the irregularity of the sahelian precipitation regimes are thought to be linked with perturbations at a larger scale (El nino Southern Oscillation for instance). While these interactions are still not well understood (not to say proved), any progress in this field of teleconnections requires a much more precise description and understanding of the tropical precipitations systems than currently available.

Besides the problems stated above, a good understanding of the proces involved and the deriving of good rainfall estimation methods could lead to a better management of the agricultural and pastoral ressources of the countries concerned. These countries are already working in that direction through the AGRHYMET center ("Centre Regional de Formation et d'Application en Agrométéorologie et Hydrologie Opérationnelle") in Niamey which centralizes the rainfall data given by their operational raingauge networks and dispatch them to various technical services all over the region. The efficiency of this work is still relatively poor due to the low density of the recording raingauge networks. From an economic point of view, these countries can ill afford heavy investments in telemetered raingauge networks or wheather radar systems without having a clear idea of the potential benefits of a given solution. On the other hand, meteorological satellites provide a virtually free coverage of tropical regions, but require a cumbersome and up to now never fully satisfying calibration methodology for use as rainfall measurement devices.

The previous researchs devoted to satellite based rainfall estimation over West Africa are of two types. In a first approach, one concentrates on the evolution of cloud clusters that constitutes the squall lines. Thiao et al. (1988) defined a convection index V which is a measure of the cloud volume for top temperatures below -40°c. This index is calculated at the hourly scale and its variation in time is correlated with the mean hourly rainfall over the area concerned, yielding the following expression :

$$P = aV + b/V.dV/dT + C$$

where a,b,c are coefficients which have to be calibrated. While there is a global coherence between the respective evolutions of P and V, Thiao et al.(1989) found that using constant coefficients whatever the cloud clusters considered is impossible, thus rising the question of how to calibrate those coefficients. In another approach the satellite image is processed pixel by pixel. Lahuec et al (1986) count the number of cloud occurences for cloud top temperatures below -40°c.for each meteosat pixel. This counting is performed using one image every three hours. Assad et al.(1986) determine the maximum surface temperature T_S for periods of five days. A synthesis of the two methods was performed by Carn and Lahuec(1987), generally yielding good results for monthly rainfall estimation. Nevertheless the estimation is not satisfactory over some regions : north of the latitude 14°N, centre Senegal, lac Tchad and for certain periods especially at the beginning of the rainy season.

Other experiments have also led to the development of specific algorithms such as GATE (e.g. Stout et al., 1979, Woodley et al.,1980) and a comparison of several methods was performed by Wylie and Laitsch(1983) to study the impacts of different satellite data on rainfall estimation schemes for the great plain states in the U.S. There is thus a whole range of methods already developed, but their very number shows that none is totally satisfactory and thus explains why the spatial agencies and meteorological services do not yet provide a satellite based estimate of rainfall.

Today large international projects, such as TRMM and BEST, aims at studying the precipitation cycle in tropical regions, using active remote sensors embarked aboard satellites. In a first step, the main goal of the EPSAT-NIGER experiment is to determine what kind of calibration (raingauges and radar) is needed to use the data provided by the more classical radiometers already available on geostationary satellites.

Experimental site and instrumentation.

The region of study. Since satellite imagery does not provide a direct measurement of rainfall but of indices (soil temperature; cloud top temperature, etc...) correlated with precipitation, any attempt at using satellite data for precipitation estimation requires a calibration by other sensors. Precipitation measurement may be performed with raingauges and radar systems, none of which are free of shortcomings. Raingauge networks are not dense enough to provide a correct vision of rainfall spatial variability at small time scales. Radars are limited in their range of investigation, have to be carefully calibrated using gauge data, are partly blind in mountainous areas, and above all are very costly which is a major impediment to the development of an integrated wheather radar network in West Africa. This is why the crucial point in such a project is the setting up of an appropriate validation network of raingauges, spread over an area covered by a radar. This dense local network acts as a complement of the low density networks covering the whole region and allows the study of the precipitation at smaller scales. Given the accessibility of a radar, thanks to the coooperation of the national meteorological service of the Republic of Niger and the favorable context provided by AGRHYMET, it was thus decided to establish this network over a square measuring one degree in latitude and one degree in longitude, the location of which is shown in figure 1.

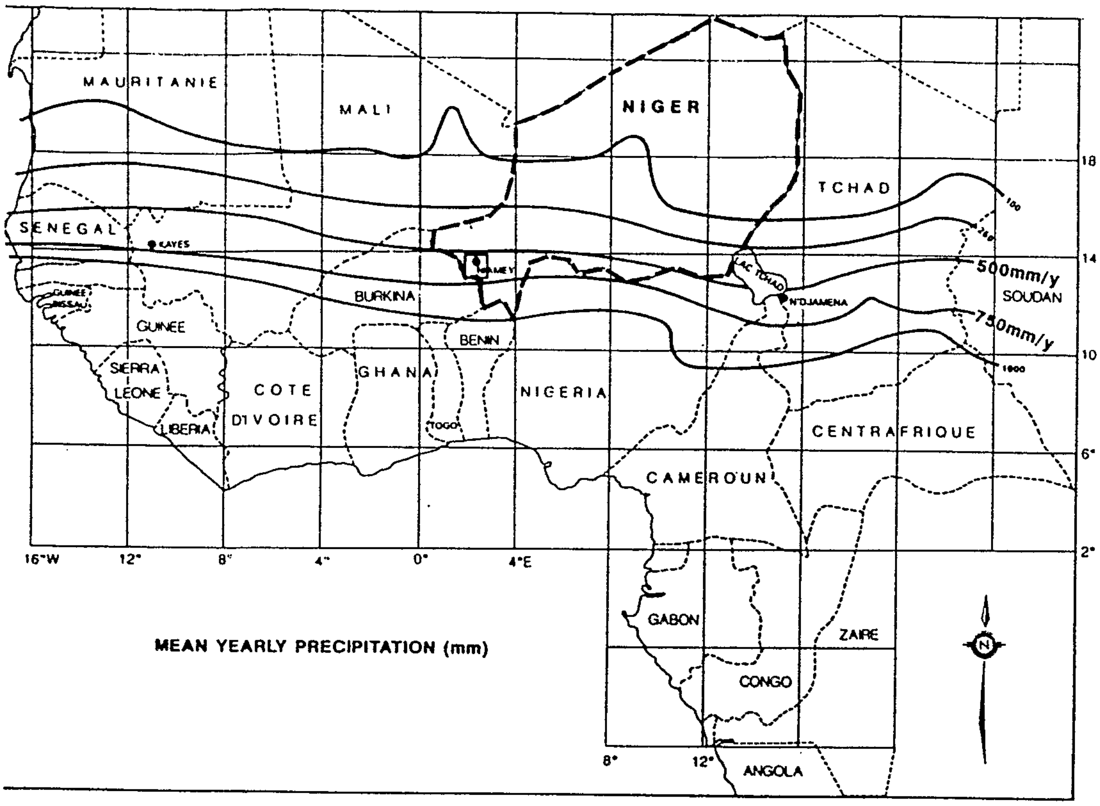


Fig. 1. Location of the EPSAT-Niger field site

The raingauge network. A total of a hundred static memory recording raingauges are available for the sake of the experience. A basic network of seventy eight gauges covers the square degree with a pseudo regular grid pattern (fig. 2), and nineteen others will be located on sites of specific interest for the radar calibration, three gauges beeing put aside as backup. In 1988 thirty seven stations were installed as shown in figure 2. As for 1989, sixty one gauges were set up by mid august and the remaining seventeen by the end of the rainy season. The basic mesh of the network is a square of twelve by twelve kilometers, with a target of fourteen gauges covering the central mesh, allowing the study of the spatial variability at a scale of one kilometer. Note that the basic mesh of twelve by twelve kilometers corresponds roughly to the aggregation of nine meteosat pixels in the infrared chanel. Even though the static memory recording technique provides two months of autonomy for each gauge, the survey of the network includes field maintenance at a cycle varying from one to two visits a month depending on the location of the station (distance from Niamey; accessibility). The overall reliabilty of the material appeared satisfactory as shown by the summary of the 1988 campaign (avaibility rate over 90%), which is of primary importance since the accessibility problem is accute in a region where paved roads are rare.

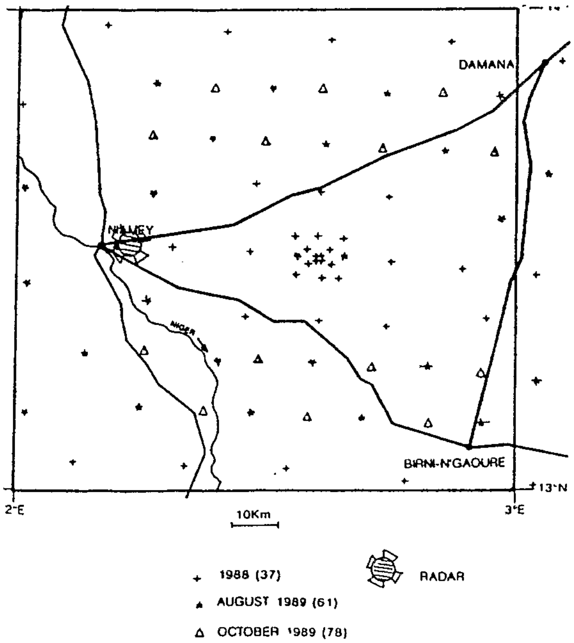


Fig. 2. EPSAT-Niger recording raingauge network.

The radar system. The ASECNA (Association pour la Sécurité de la Navigation Aérienne) owns a radar located at the Niamey airport and operated by the Niger meteorological service for purpose of meteorological survey. This radar is an EEC type WR 100 option 5. The wavelength is 5.4 cm (5600-5650 Mhz), the peak power is 250 kw, the recurence frequency 250 hz and the impulse width 2 µs (600m). Till this year this radar was not digitized, hence his data wer not available for a posteriori rainfall studies. The SANAGA digitizing system was thus developped by the Laboratoire d'Aérologie de Lannemezan (France), and since the beginning of August 1989, it is possible to store the digitized reflectivity measurements on magnetic cartridges and to visualize the reflectivity fields on a color screen. The system operates on a micro computer and is radar independent, which means that it could be easily installed on other African radars. Thanks to the location of the airport (North West of Niamey) and the flat topography, the radar is almost completely free of ground clutters over the region of study, which allows to perform measurements at the basic site of .8°, the width of the main beam being 1.5°. Alternative measurements at higher sites are also performed in order to analyse the effect of the beam heigth on the reflectivity measurement.

Satellite imagery. For rainfall studies over West Africa the METEOSAT satellite is especially well suited since its suborbital point is 0° in latitude and 0° in longitude. The period of measurement is half an hour for three chanels : 0.4 - 1.1 (Vis); 5.6 - 7.6 (Water Vapor); 10.2 - 13.2 (IR). Other satellite images will also be used in the future, notably those provided by the microwave chanels of the SMM/I sensor of the american satellite DMSP.

First results.

The raingauge measurements. The data processing of the 1988 and 1989 data gave some interesting indications about the spatial structure of the rainfall fields at the storm scale. The way in which this structure is caught depending on the network density is presented in detail in a companion paper by Thauvin and Lebel.

Spatial variability of the radar parameters in tropical squall lines. Precipitation measurement by radar consists at first to interpret radar reflectivity factor Z in term of precipitation intensity R, using an approximate Z-R relation, then to correct (or calibrate) the estimates against pluviographic network data. The accuracy of the method depends on the dynamic and microphysical structure of the observed rainstorm systems and on the grid spacing of the calibrating network.

As a first approach to the radar calibration problem in the sahelian region as selected for EPSAT, a precampaign was organized during the rainy season of 1988. The 5,5 cm wavelength meteorological radar, at this time not digitized, was used for qualitative observations of rainstorm structures, and a Joss-Waldvogel type disdrometer (Campistron et al., 1987) for the measurement of drop size distributions. Time resolution of the disdrometer data was set at 1 min. If N (D) is the number density by drop diameter D, we have :

$$Z = \int_{D_{min}}^{D_{max}} N(D)\, D^6\, dD \quad \text{and}$$

$$R = \frac{\pi}{6} \int_{D_{min}}^{D_{max}} N(D)\, D^3\, V(D)\, dD$$

where V(D) is the terminal fall speed of drops of diameter D.

Z-R relations have the general form of a power function :

$$Z = aR^b$$

where a and b are coefficients (or parameters) which depends on N(D). They can be analytically calculated if N(D) is known. In the real case of an experiment where N(D) vary with space and time, a and b can be obtained by a least square fitting, from a set of measured pairs of Z and R values. These pairs can be obtained either from a pluviograph (R) and a radar (Z) measuring just above the pluviograph, or, using the above formula, from a disdrometer giving the temporal series of N(D). We used the second method in our first study of Z-R of the Niamey rainstorms.

In 1988, 17 rainstorms were observed. Most of them had a squall line structure. The main conclusions concerning these squall lines can be summarized as follow.

The hyetogram of tropical squall line classically shows first a convective region of heavy short-lived precipitation followed by a large stratiform region of continuous light precipitation (see for example Houze, 1977). We find that this structure is associated with a systematic pattern of the variations of the a and b parameters. In other words, to each region of the squall line, identified from the rain rate R and its derivative, there are corresponding values of these 2 parameters. The observed values are nearly the same for the corresponding regions of all the studied squall lines. A comparative study with disdrometer data gathered in Congo, on precipitating systems of same structure (tropical squall lines), gives similar results. The case of 8 July 1988 presented in Fig. 3, 4, 5 and 6 examplifies these results. Fig. 3 is a photograph of the radar display in azimuthal scan mode showing the squall line echo. The receiver gain was

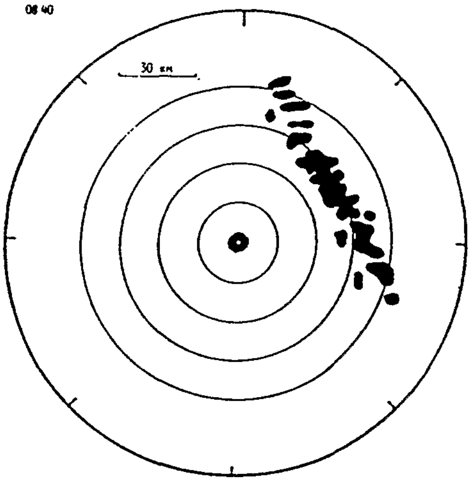


FIG. 3. Radar echoes at 8.40, 8TH July 1988.

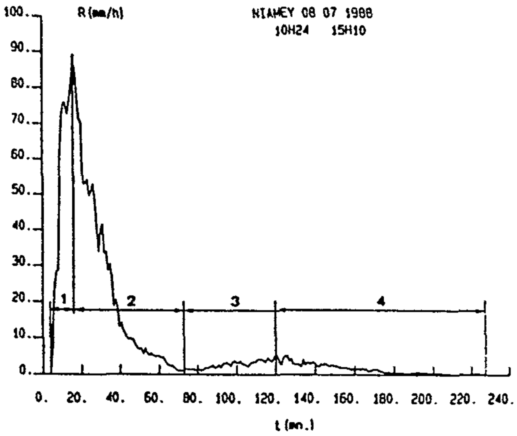


Fig. 4. The hyetogram of the 8 th july 1988 rainfall at Niamey.

reduced so that only the precipitation rates higher than about 30 mm h^{-1} (i.e. the convective region) appear on the display. Fig. 4 is the hyetogram (R in mm h^{-1} versus time in minutes) deduced from the disdrometer measurements. We have identified four regions, numbered 1 to 4, corresponding to the growing and the decreasing stages of the convective and stratiform rain, respectively. Fig. 5 is a plot of the Z-R pairs deduced from disdrometer data. Four different symbols have been used to identify the four groups of points associated with the four regions. The regression line fitted to each group and the corresponding equation and correlation coefficient are also indicated. Fig. 6 shows typical drop size distributions corresponding to these four regions, with the value of the relevant parameters.

Our tentative conclusion from these results is that the structure of the precipitation field associated with tropical squall lines is simpler than those usually observed in the other parts of the world. This is due to the particular dynamic organisation of this type of system, which influences the microphysical processes of precipitation growth. The systematic pattern of variation of the Z-R parameters observed in tropical squall line ought to facilitate and simplify the precipitation measurement by radar in these systems.

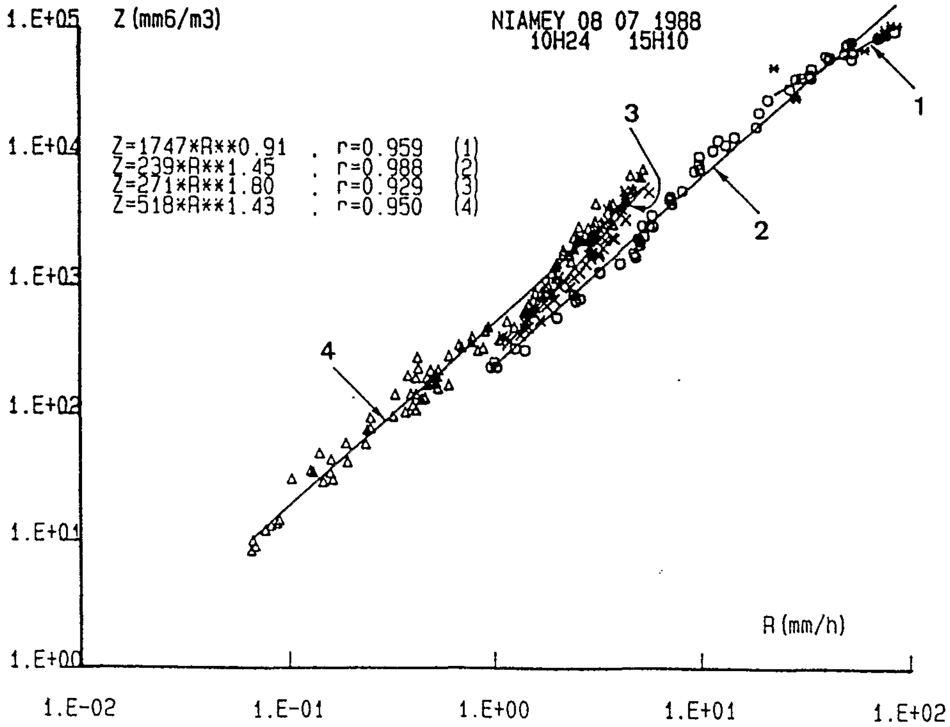
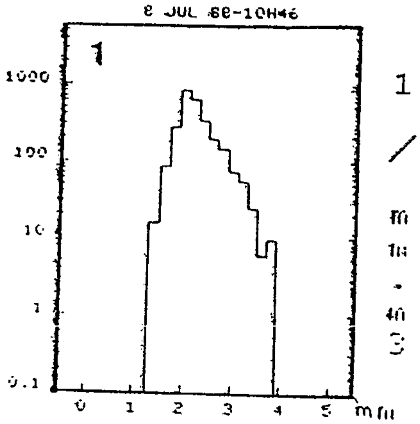
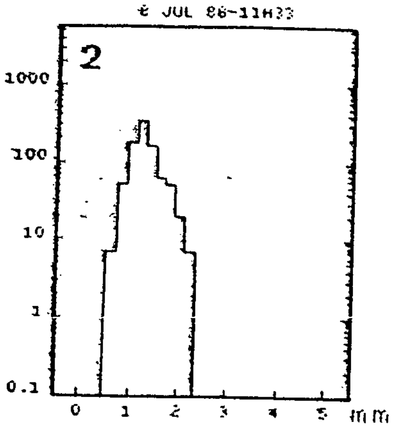


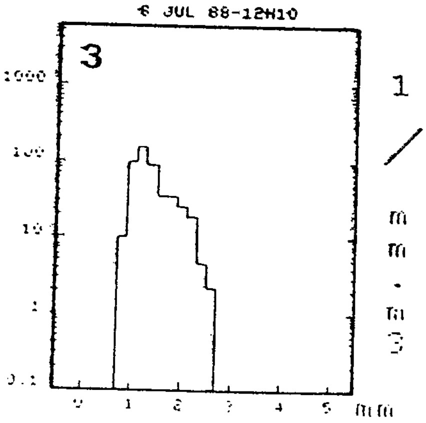
Fig. 5. Values of Z (radar) and R (disdrometer) for the four domains identified in figure 1. The curve equation is plotted along with the correlation coefficient.



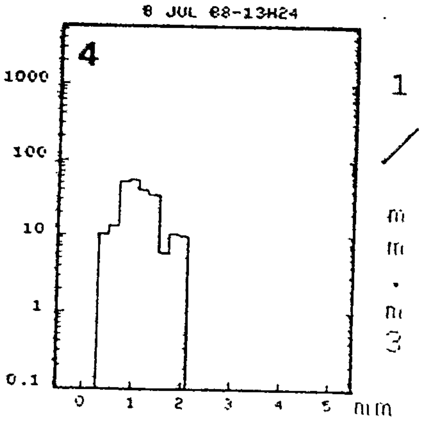
NG = 1111
R(mm/h) = 87.472
DO(mm) = 2.329
W(g/m³) = 3.384
Z(dBZ) = + 50.202
NO(/mm.m³) = 15546.4
LA(1/mm) = 1.951



NG = 248
R (mm/h) = 4.034
DO(mm) = 1.405
W(g/m³) = 0.212
Z(dBZ) = + 31.671
NO (/mm.m³) = 7149.8
LA(1/mm) = 3.211



NG = 142
R (mm/h) = 3.197
DO(mm) = 1.675
W(g/m³) = 0.154
Z (dBZ) = + 32.249
NO (/mm.m³) = 2846.5
LA(1/mm) = 2.763



NG = 58
R (mm/h) = 0.825
DO(mm) = 1.417
W(g/m³) = 0.044
Z (dBZ) = + 24.969
NO (/mm.m³) = 1407.9
LA(1/mm) = 3.174

Fig 6 Drop size distribution as given by the disdrometer for the four domains identified in figure 1. The drop size is in mm (X axis) and the number of drops in mm-1 m-3 (Y axis). Sampling duration : 1 minute. NG : total number of drops. R : rainfall intensity. DO : median volume diameter. W : water content. Z : radar reflectivity factor. NO and LA : parameters of the Marsall Palmer distribution.

Infrared Meteosat Data. As compared to previous works cited above (e.g. Thiao et al.,1989 or Carn and Lahuec, 1986), the relatively small area covered by the EPSAT calibration network dictates that a study of the coherence between ground observed rainfall and cloud top temperature at smaller scales can now be made. The subject was roughed out by correlating every thirty minutes the numeric count of each meteoat pixel in the infrared chanel with the ground rainfall measured in a raingauge located within this pixel, using the 38 raingauges of the 1988 rainy season. The results of this approach were not fruitful and no systematic relation was observed between the occurence time of the maximum numeric count (minimum temperature) and the occurence time of the maximum five, ten or even thirty minutes rainfall intensity. Correlating the maximum numeric count of a given pixel with the total rainfall measured at the corresponding raingauge for the whole rainfall event yielded better results, showing that some averaging may improve the relationshop between satellite and ground based data. In this respect it is believed that an appropriate spatial averaging is the best direction to explore but this requires a denser network than the one which was available in 1988. As a matter of fact, the analysis of the gauge data presented by Thauvin and Lebel (this conference) shows that the spatial variability of rainfall at small time steps is such that it necessitates a mean interdistance between gauges well below twenty kilometers if it is required to compute areal rainfall. Only by computing reliable mean rainffal over relevant surface areas (i.e. 3x3 meteosat pixels or more will it be possible to find the satellite data which correlated the best with the ground rainfall, and this should be possible with the complete network presented in figure 2.

Perspectives.

Contrary to many hydrometeorological experiments relying on heavy instrumentation, the EPSAT-Niger experiment will last for several years (at least up to 1992), thus allowing to minimize the risks of carrying out the measurements on a climatically "abnormal" year. The elapsed period, the results of which have been briefly presented above, hence constitutes a period of adjustment and testing, both for the sensors and measurements devices, which are operated in a physically hostile environment, and for evaluating the logistics of such an operation.

The complete network presented in figure 2 will be available in 1990, as well as an additional 20 raingauges located west of the radar for purpose of tracking the squall lines moving away from the radar. This will allow the carrying out of precise studies regarding the spatial rainfall distribution , thus helping to determine the range of temporal resolution at which it is possible to work for a given raingauge network density in sahelian regions. Furthermore, it will be possible to evaluate the contribution of conventional radar measurements in terms of additional information, better estimation of the instantaneous precipitation fields and possibilities of reducing gauge network densities while maintaining equal estimation capabilities. This first set of studies shoukd prove very useful for the water resources management of the sahelian countries, as it is illusory to correctly manage an unknown resource.

It is additionally considered to use an association of several conventional radars located a few hundred kilometers apart in order to study whether it would be realistic and useful to set up a wheather radar network covering, at least partially, the sahelian and neighbouring countries.

The final objective remains of course to determine the true potential of satellite data as far as rainfall estimation in these regions is concerned, and the means necessary to allow for their calibration. At time steps smaller than the decade, there is little hope to get precise estimates using only geostationnary satellites. Nevertheless the development of operational and powerful algorithms for time steps larger than ten days, based on optimal gauge and radar calibration specific to these regions, would be a dramatic progress per se. In addition the setup of a dense calibration-validation network, covering several thousands square kilometers should also allow the test of the improvement that can be expected from the usage of microwave sensors embarked aboard satellites, especially to work at small time steps. Here may lay the true future of satellite rainfall estimation in sahelian countries (and elsewhere), allowing, perhaps, a bypass of the intermediate radar stage, which is necessary today but is costly and cumbersome.

Acknowledgments : the publication of this presentation of an ongoing experiment is an opportunity to thank the ASECNA and the Niger meteorological service for their interest and participation in this operation. Without their involvement, it would have been impossible to carry the project out. We are also indebted to all the members of the EPSAT group who were helpful in launching the project and especially to those in ORSTOM who performed the field work of installing and maintaining the raingauge network, and those in the Laboratoire d'Aérologie for the development of the radar digitizing system. The gauges were purchased under a special funding from ORSTOM and the radar updating was funded by the french ministry of cooperation.

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