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The estimation of rainfall in the Sahelian squall line by the area-threshold method

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Abstract

Radar observations from Niamey (Niger), in the soudano–sahelian region of West Africa, are used to show the applicability of the area-threshold method to the estimation of the mean areal rainfall in squall lines. A squall line, the main rain-bearing system in the sahelian area, is made up of two strongly different entities: a narrow convective line producing heavy rainfall, followed by a wide area of light stratiform rain. The extent of the system is such that it usually cannot be entirely observed in the frame of a single radar snapshot. So the ratio of convective to stratiform rain in the radar snapshot changes while the squall line moves over the radar-observed area. It is demonstrated that, in this case, the area-threshold method can be separately applied to the convective line and to the stratiform area. © 1997 Elsevier Science B.V.

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1. Introduction

For many hydrological or meteorological applications of rainfall measurements, the useful data are neither the point rainfall, nor the spatio-temporal distribution of rain rate but the mean areal rainfall over the area of interest. For climatological models, the volumetric rainfall for a time interval is even sufficient. The area-threshold method enables the estimation of the volumetric rainfall or the mean areal rainrate from only the measurement of the area where the rain rate is larger than a specified threshold. The

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validity of this method has been discussed and experimentally demonstrated for the rainfields associated with deep convective cloud systems and with mid-latitude frontal systems (Doneaud et al., 1984; Chiu, 1988; Rosenfeld et al., 1990; Cheng and Brown, 1993; Short et al., 1993; Sauvageot, 1994a). Most of these systems just as, more generally, most rainfields, can be seen as made up of a mixture of convective and stratiform rain components (Bell and Suhasini, 1994). However the area-threshold method is always used assuming a homogeneous rainfield, i.e., implicitly a constant ratio of convective to stratiform components.

At tropical latitudes, notably in the soudano–sahelian band of West Africa (Fig. 1), most of the rain-bearing clouds are organized as squall lines. Squall lines are typically fast moving meso-scale cloud systems whose prominent features are that the convective and stratiform components are both strongly differentiated and spatially separated (i.e. not mixed) inside the system. The deep convective cells are clustered in a meridionally long and narrow line producing heavy rainfall at the leading edge of the system followed by a zonally wide area of light stratiform rain (Houze, 1977; Roux, 1988, among others). Fig. 2 illustrates these features for a part of a typical squall line observed in Niamey (Niger) using a C band radar (see Section 3 for the observational conditions) in PPI (plan position indicator) and RHI (range height indicator) modes. The convective line is about 40 km wide with a maximum reflectivity factor of about 55 dBZ. It is observed over a length of about 400 km. Fig. 2 is very representative of the sahelian squall lines. The elevation angle of the radar beam is 0.9°. So at a radial distance of 130 km the radar

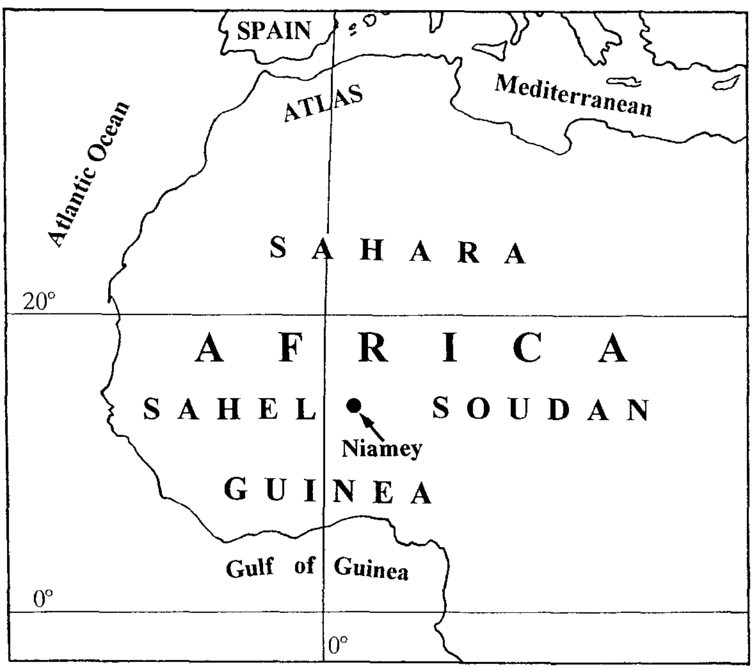

Fig. 1. Map showing the location of the observation site in West Africa.

beam begins to cross the precipitation melting layer, around an altitude of 5 km. In Fig. 2, the eastward limit of the stratiform area is not accurately observed because it is associated with reflectivity factors smaller than the minimum detectable signal of the Niamey radar. Thus, beyond the distance of about 130 km, what is featured on the PPI has to be considered as qualitative information.

It is clear from Fig. 2 that using a single radar does not allow a whole squall line to be observed in a single snapshot. While the squall line moves over the radar-observed

Fig. 2. (a) PPI of the radar reflectivity factor distribution in dBZ through a squall line observed on July 22, 1992 at 1654 LST with the C band radar of Niamey (Niger). The squall line is moving westward at 50 km h^{-1}. The range markers are 50 km from each other. What appears on the figure is only a part of the squall line. (b) The same as (a) but for RHI at 1552 LST. The ordinate is height labelled in km.

area, the ratio of convective to stratiform rain in the radar snapshot changes. This raises a question about the use of the area threshold method for precipitation estimation in squall lines. What does the proportionality between area-threshold and mean areal rain rate become when the ratio of convective to stratiform area changes? The object of the present letter is to discuss this point in the case of sahelian squall lines.

2. Definition

The basic concepts of the estimation of mean areal rain rate over an area from the measurement of the area-threshold have been recently discussed in many papers (Doneaud et al., 1984; Atlas et al., 1990; Krajewski et al., 1992; Braud et al., 1993, among others). The radar-observed area is A_0, and $P(R)$ is the probability distribution of the rain rate over A_0. The area, enclosed in A_0, where the rain rate is higher than the threshold τ, is $A(\tau)$. Thus the mean areal rain rate over A_0 is:

$$\langle R \rangle = \int_0^\infty R P(R)\,\mathrm{d}R, \tag{1}$$

the fractional area where the rain rate is higher than τ is:

$$F(\tau) = A(\tau)/A_0 = \int_\tau^\infty P(R)\,\mathrm{d}R, \tag{2}$$

and the basic relation of the method (Atlas et al., 1990) is:

$$\langle R \rangle = S(\tau) F(\tau). \tag{3}$$

Thus $S(\tau)$, the coefficient of proportionality between $\langle R \rangle$ and $F(\tau)$, can be determined either by regression from the measurement of an ensemble of couples $\langle R \rangle$–$F(\tau)$, using a radar or a rain gauge network, or from the determination of $P(R)$, with any rain-rate-meter, and the computation of $\langle R \rangle$ and $F(\tau)$ through Eqs. (1) and (2). Most observations show that $P(R)$ is lognormally distributed (Atlas et al., 1990; Kedem et al., 1990; Rosenfeld et al., 1990; Bell and Suhasini, 1994; Sauvageot, 1994a; Sauvageot, 1994b, among others). Thus, the parameters of $P(R)$ are m_R and σ_R^2, the mean and the variance of R.

3. Data

The radar data analyzed in the next section were obtained in the framework of the EPSAT-Niger experiment (Lebel et al., 1992) from the site of Niamey (Niger) (Fig. 1). The radar, located at the Niamey airport (2°10′32″E, 13°28′38″N, altitude 230 m), is an old non coherent EEC, WR 100.5 model upgraded with a SANAGA numerical processor (Sauvageot and Despaux, 1990). It is a C band radar with peak power of 250 kW, a pulse repetition frequency of 250 Hz and a half power beam-width of 1.5°. East of the radar a network of 99 tipping bucket rain gauges distributed over a square area of side 100 km were available. The radar reflectivity factor Z was converted to rainfall rate

R using a Z–R relation derived from disdrometer data collected in Niamey (Sauvageot and Lacaux, 1995), viz.:

$$Z = 364 R^{1.36} \tag{4}$$

where Z is in $mm^6 \ m^{-3}$ and R is in $mm \ h^{-1}$. Then the rain gauge network data were used for the calibration of the radar-derived rainfields (Sauvageot, 1994b). Using a single Z–R relation for the whole system rather than separate relations for convective and stratiform precipitation gives almost identical cumulative rainfall estimates (Steiner et al., 1995).

Niamey is situated in the middle of the sahelian soudanese strip (Fig. 1). The area is very flat. The rainy season is associated with the northward migration of the intertropical convergence zone. It lasts about 3 months from early July to late September. The mean annual total rainfall is about 500 mm. Most of the rain generating events are squall lines. Because of the topographic and climatic conditions, the squall lines in the Niamey area have a very simple structure, that is not blurred by local effects (such as induced by orography, coast, etc.).

The data sample used for this study is made up of the squall lines observed during the 1991 rainy season. The radar data have been gathered in three samples: (1) The squall lines (SL): it is the sample constituted by all the SL's, including their convective and stratiform parts. (2) The convective lines (CL): it is the sample made up only of the intense CL's of the leading edge of the system, which means that the stratiform regions have been removed. The cut between convective and stratiform parts is taken at the minimum of the radar reflectivity that locates the transition zone. (3) The stratiform region (SR): it is the sample made up of the stratiform echoes situated to the rear (that is at the East) of the transition zone.

Owing to particular experimental circumstances affecting the working of the radar in the presence of squall lines, such as loss of sensitivity due to a water film on the radome or to a lightning effect on the power supply, some segments of the radar data have been eliminated from the samples because of their poor quality.

Finally the three samples are made up with the following cases of 1991:

SL:	June 20, July 7 and 22, August 18 and 29 and September 6 and 11,
CL:	June 20, July 22 and September 6 and 11,
SR:	June 20, July 7 and 22 and August 18.

4. Results and discussion

Fig. 3 shows the regression between $\langle R \rangle$, the area average rain rate, and $F(\tau)$, the fractional area with rain rate $> \tau$, obtained for the three samples with threshold 1, 5, 10 and 20 mm h^{-1} for SL and CL and 1, 2, 3 and 4 mm h^{-1} for SR. On the graphs the numerical values are indicated for the slope $S(\tau)$, the intercept $I(\tau)$ and the correlation coefficient $r(\tau)$.

What can be seen is that, for the three samples, the relation between $\langle R \rangle$ and $F(\tau)$ is very tight, showing that the area-threshold method works, notably with the stratiform region for which the correlation coefficient is of 0.98 and 0.99.

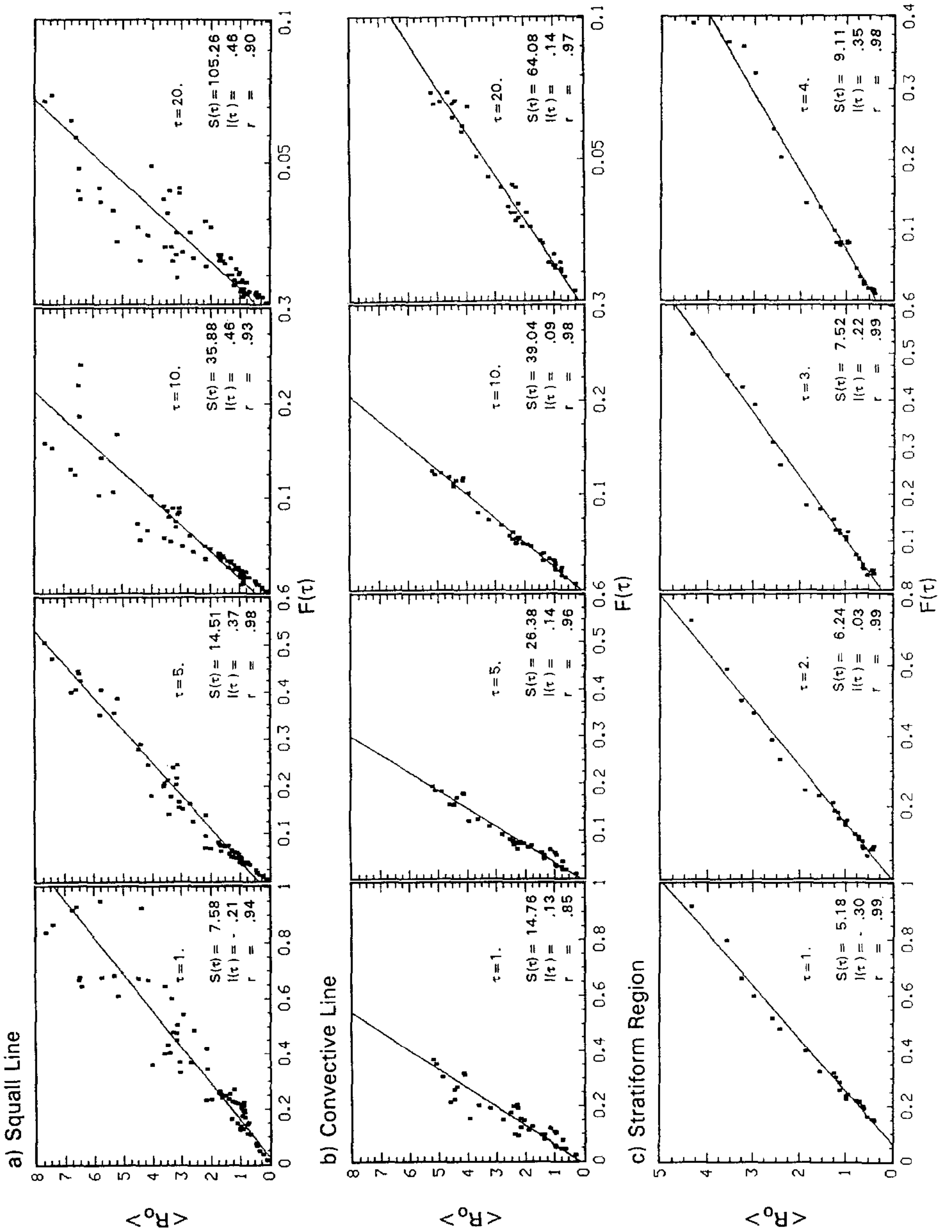
a) Squall Line
b) Convective Line
c) Stratiform Region
<Ro>
F(τ)
τ = 1. S(τ) = 7.58 I(τ) = - .21 r = .94
τ = 5. S(τ) = 14.51 I(τ) = .37 r = .98
τ = 10. S(τ) = 35.88 I(τ) = .46 r = .93
τ = 20. S(τ) = 105.26 I(τ) = .46 r = .90
τ = 1. S(τ) = 14.76 I(τ) = .13 r = .85
τ = 5. S(τ) = 26.38 I(τ) = .14 r = .96
τ = 10. S(τ) = 39.04 I(τ) = .09 r = .98
τ = 20. S(τ) = 64.08 I(τ) = .14 r = .97
τ = 1. S(τ) = 5.18 I(τ) = - .30 r = .99
τ = 2. S(τ) = 6.24 I(τ) = .03 r = .99
τ = 3. S(τ) = 7.52 I(τ) = .22 r = .99
τ = 4. S(τ) = 9.11 I(τ) = .35 r = .98

Table 1
Observed distribution parameters of the 3 samples of Section 3 computed from the rain gauge network data. The sample size is the number of 5 min raingauge data points, γ_1 and γ_2 are the Fisher coefficient of skewness and kurtosis respectively, m_R, σ_r^2, m_y and σ_y^2 are the mean and the variance of R and of $y = \ln R$, respectively

	Sample size	γ_1 (skewness)	γ_2 (kurtosis)	m_R (mm h^{-1})	σ_R^2 (mm h^{-1})^2	m_y	σ_y^2
Squall line	8494	0.15	0.52	7.22	229.97	1.13	1.68
Convection line	4609	0.05	−0.48	11.11	384.50	1.70	1.41
Stratiform region	3885	−1.08	2.55	2.60	7.32	0.59	0.73

The probability distributions of rain rate $P(R)$ for SL, CL and SR calculated from the rain gauge network data qualitatively shows that, as for SL, $P(R)$ for CL and SR is a log–normal distribution. In Table 1, the observed distribution parameters are given. The values of the skewness γ_1 and the kurtosis γ_2 confirm the log–normality of the distributions of CL and SR. SR is slightly dissymmetrical (the mode is higher than the average) and leptokurtic. In Table 1 the mean m_R and the variance σ_R^2 observed for the three samples are also given. The comparison with data from other climatic conditions (Short et al., 1993; Cheng and Brown, 1993; Sauvageot, 1994a) shows that m_R for CL is of the same order as the strongest values observed for convective conditions. m_R for RS is significantly higher than the values corresponding to mid-latitude frontal rain systems. From an extended dataset on the rain rate distribution covering mid-latitude and tropical sites, Sauvageot (1994a) shows that, in nature, the average and the variance of R are linked by the relation:

$$m_R^2 = 5\sigma_R^2 \tag{5}$$

with a correlation coefficient of 0.99. The values of m_R and σ_R^2 given in Table 1 are compatible with Eq. (5) for SL but not for CL and SR. For these two last samples, the observed σ_R^2 (given in Table 1) is 62% and 22% of the value calculated with Eq. (5) from the observed m_R, for CL and SR, respectively. Of course, the cause of this discrepancy is the splitting of the original data in two samples in which the high and the low rain rates are separated: a reduced variance with respect to the whole sample observed in nature results.

In Fig. 4 the curves of $S(\tau)$ and $r^2(\tau)$ (the explained variance) are shown for the three samples. The shape of $S(\tau)$ can be discussed from the relation obtained by substituting Eq. (1) and Eq. (2) in Eq. (3), viz.:

$$S(\tau) = \langle R \rangle \Big/ \int_\tau^\infty P(R)\,\mathrm{d}R \tag{6}$$

For small values of τ, the denominator of Eq. (6) is about 1 and the $S(\tau)$ values are

Fig. 3. Plot of $\langle R \rangle$, the mean areal rain rate, as a function of $F(\tau)$, the fractional area with rain rate $> \tau$, for the samples (a) SL, (b) CL and (c) SR. Each point corresponds to a radar snapshot. τ is the threshold. $S(\tau)$ and $I(\tau)$ are the slope and the intercept given by the regression. The 3 parameters are in mm h^{-1}. r is the correlation coefficient.

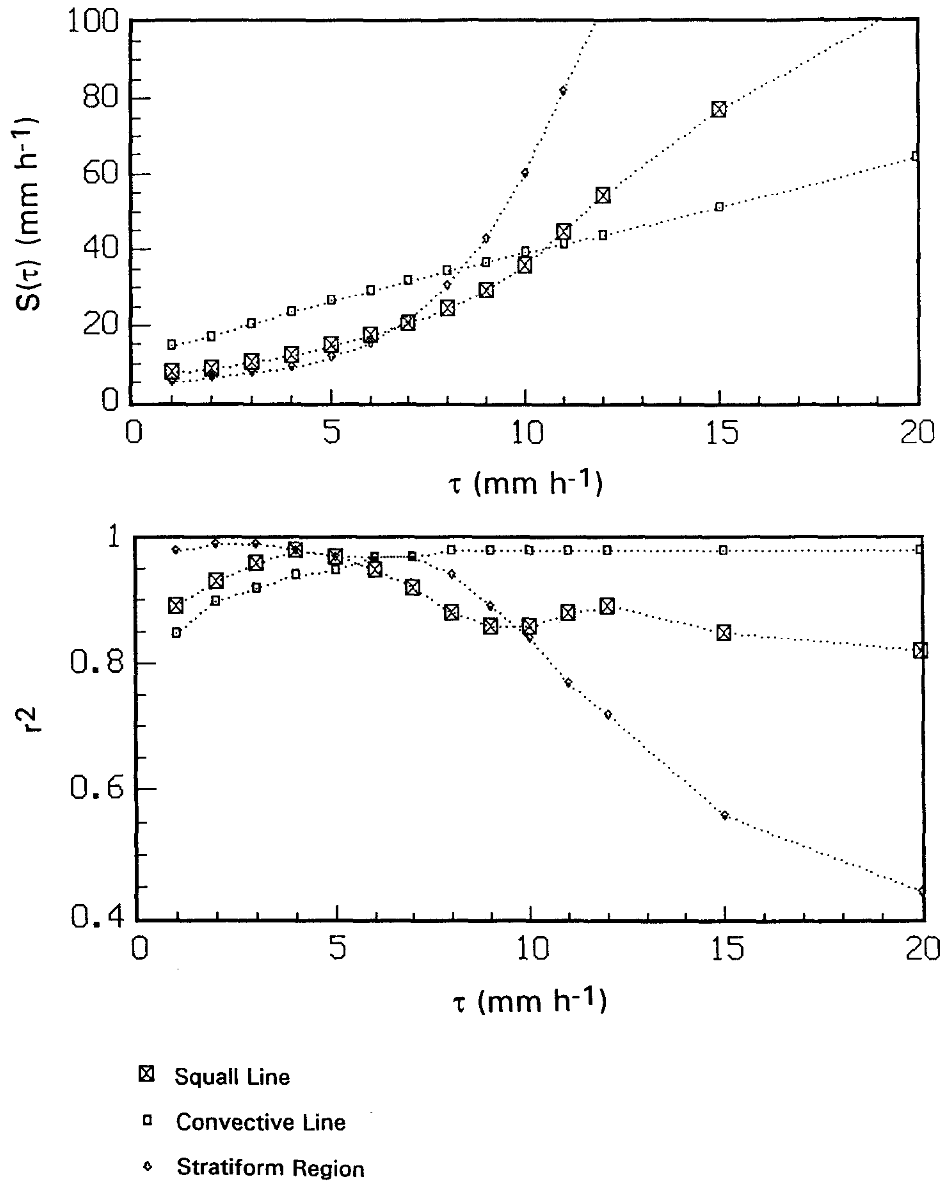

Fig. 4. Proportionality factor $S(\tau)$ and correlation coefficient of the $\langle R \rangle - F(\tau)$ regression for the 3 samples SL, CL and SR.

ordered as the expected rain rate. When τ increases, only the denominator varies and for a given value of τ, it is all the smaller as the expected rain rate is small (Sauvageot, 1994a). For τ larger than about twice the expected value, an upward curvature appears on $S(\tau)$. For CL and RS, the curves $r^2(\tau)$ have their higher values around the expected rain rate as observed by many authors (Kedem et al., 1990; Atlas et al., 1990; Rosenfeld et al., 1990; Krajewski et al., 1992; Sauvageot, 1994a, among others). For SL, the curve $r^2(\tau)$ is bimodal, with the peaks around the expected values of RS and CL.

5. Summary

An original radar dataset has been used to discuss the applicability of the area-threshold method to the soudano–sahelian squall lines, that is, to a strongly dual rainfield. Indeed, in the presence of a squall line, the ratio of convective to stratiform rain inside the radar snapshot changes while the system sweeps the observed area. The data set was segmented in three samples: squall lines, convective lines only and stratiform region only. The probability distribution of rain rate for the three samples is well defined and approximately log–normal.

The optimum values of the parameters τ and $S(\tau)$ to be used to implement the area-threshold method are depending on the parameters of the probability distribution $P(R)$. Indeed, on the one hand, the accuracy of the area averaged rain rate is optimum when the threshold τ is close to m_R and, on the other hand, $S(\tau)$ is a function of m_R and σ_R^2. We have observed from the used dataset that the parameters of $P(R)$ for CL and SR are very different, notably the optimum thresholds are $\tau = m_R = 11$ mm h^{-1} for CL and $\tau = 2.6$ mm h^{-1} for SR, two very distant values, with the corresponding $S(\tau)$ values of 40 and 7 mm h^{-1}, respectively. Fortunately, it was shown that the area-threshold method can be separately applied to the convective and stratiform areas. Notably the linear relation between the mean areal rain rate and the area-threshold in the stratiform region was found to be very robust.

Beyond the specific question of the soudano–sahelian squall lines, the above discussion suggests that, in presence of strongly non homogeneous rainfield, such as some frontal systems or with systems significantly affected by local effects, using separate values of $S(\tau)$ for each sub-areas could be an effective way to increase the accuracy of the rainfall estimates by the area-threshold method.

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