

Contribution of satellite and lightning data to convective rainfall frequency analysis

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Abstract This paper aims to explore to what extent remotely sensed mesoscale convective systems (MCSs) can be associated with ground rainfall. The two MCS identification methods used rely either on infrared satellite images alone or on both infrared images and lightning data. Rain data come from a network of 25 raingauges in Marseilles (France) from 1993 to 1997. The analysis of rainfall is developed conditionally on the occurrence of an MCS. The main results indicate differences in the rainfall distribution functions in terms of bulk features and maximal values. The mean and standard deviation of rainfall accumulations are multiplied by 2.5 when an MCS is identified compared to when no MCS is identified. The same happens for the slope of the distribution of the maximal values. A higher percentage of the total ground rainfall accumulation is detected when lightning data are also considered.

Key words mesoscale convective system; lightning data; rainfall frequency analysis; satellite images

INTRODUCTION

Remotely sensed data from satellites have been widely used in rain studies. Several methods have been developed both to estimate mean areal rainfall accumulations and to delineate rainy areas (e.g. Atlas *et al.*, 1990; Braud *et al.*, 1993; Ebert & Weymouth, 1999). The relationship between convective rainfall and mesoscale phenomena identified by satellite imagery has been analysed in regions like the Sahel (Western Africa) where 95% of the annual rainfall is produced by mesoscale convective systems (MCSs) (Laurent *et al.*, 1998) or in the midwestern United States where MCSs account for most of the average warm-season rainfall (Fritsch *et al.*, 1986). Convective rainfall analysis can be improved by considering lightning data as a marker of convective rain (Greco *et al.*, 2000). This paper explores to what extent remotely sensed MCS trajectories can be associated with the analysis of ground rainfall climatology. First, data sources are briefly described. Then, the results of the rainfall analysis developed

conditionally on the occurrence of an MCS are presented and finally some conclusive remarks are made.

MCSs FROM SATELLITE AND LIGHTNING DATA

Satellite data come from the European geostationary satellite METEOSAT. They are based on infrared images centred over Europe at a resolution of 30 min in time and about 6 km in space. An automated tracking algorithm developed by Météo-France (Morel *et al.*, 1997; Morel & Sénési, 1998) detects cloud shields by thresholding the images both in temperature and area. In this study, cloud shields having an area greater than 1000 km² for a cloud top temperature below -45°C are tracked. Trajectories of cloud systems are built based on the overlapping of cloud shields between successive infrared images. Cloud shields are represented by an approaching ellipse, simplifying its morphological description. The algorithm also handles eventual splitting and merging.

The tracking of cloud systems is followed by a discrimination step which allows one to identify among all the trajectories those which are convective systems, according to two different methods. The first method (hereafter named ISISGRAD) only considers the MCSs reaching at least 10 000 km² during their trajectory, and the discrimination is made after the peripheral brightness temperature gradient (Morel *et al.*, 1997). Morel & Sénési (1998) have shown this method performs significantly well over France during the warm season (April–September). The second method (hereafter named FOUORE) does not consider the minimum pattern size of 10 000 km². It relies on cloud-to-ground lightning data from the Météo-France/Météorage lightning network (Tourte *et al.*, 1988) to identify the convective nature of the clouds. Cloud system trajectories are considered convective if at least one flash is observed during their passage over the study area.

RAINFALL DATA FROM THE CITY OF MARSEILLES

The city of Marseilles is located on the Mediterranean coast east of the Rhône delta. It has about 800 000 inhabitants on an area of 240 km². Mountains up to 650 m high surround the city, which is fairly flat and at sea level. The ground rainfall data come from a network of 25 telemetred tipping bucket raingauges well distributed in space (Fig. 1). Rainfall is measured at a 6-min temporal resolution. The mean annual rainfall in Marseilles is about 600 mm. The data set for this analysis comprises the period from 1993 to 1997. A historic database of 128 years of annual accumulations allows one to check that this 5-year period is reasonably representative of the local rain climatology (see Fig. 2). The data set comprises “normal” years (1993 and 1995), wet years (1994 and 1996) and a dry year (1997).

RAINFALL ANALYSIS CONDITIONAL ON MCS OCCURRENCES

Rainfall and MCS occurrences

To examine the simultaneous behaviour of ground rainfall and MCS occurrences over the study area, a database from April to September (1993–1997) crossing these

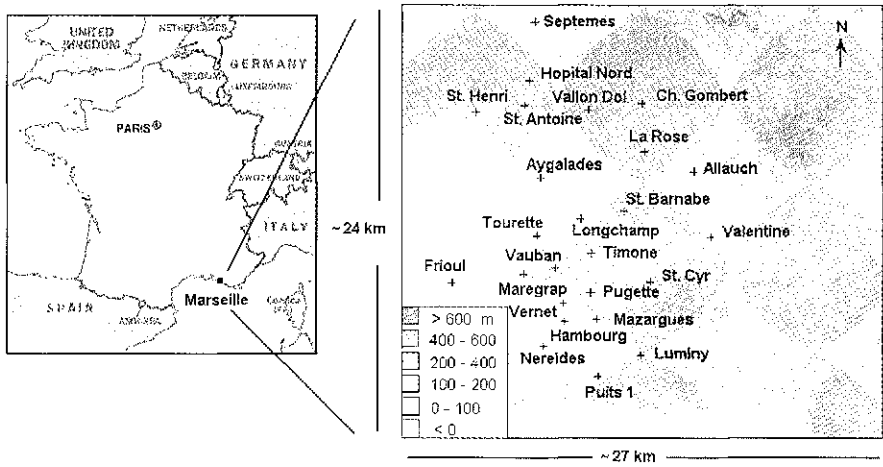


Fig. 1 Location of the study area and of the rain gauges over the city of Marseilles.

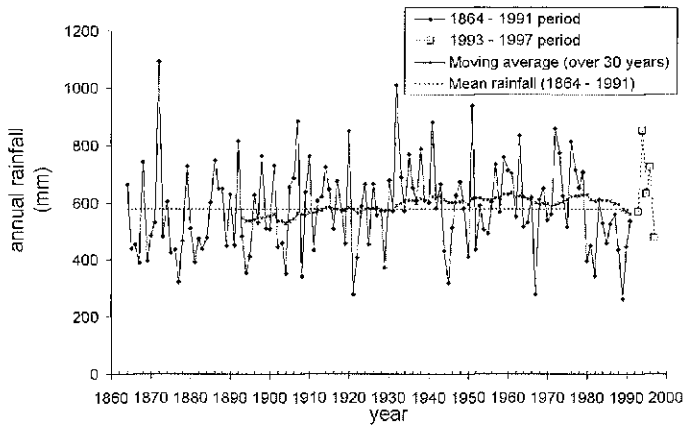


Fig. 2 Time evolution of the annual rainfall in Marseilles since the year 1864.

variables was constructed. For each rain gauge, rainfall half-hour accumulations were computed, allowing mean areal rainfalls to be estimated. The variables studied are:

(a) the indicator function of the mean areal rainfall $R(t)$ at time t over Marseilles:

$$I_{R(t)} = 1 \text{ if the mean areal rainfall is different from } 0;$$

$$I_{R(t)} = 0 \text{ if the mean areal rainfall is equal to } 0.$$

(b) the indicator function of an MCS over Marseilles:

$$I_{MCS(t)} = 1 \text{ if an MCS ellipse is identified over Marseilles at time } t;$$

$$I_{MCS(t)} = 0 \text{ if no MCS ellipse is identified.}$$

Joint and marginal probabilities were then computed, thus allowing the estimation of conditional probabilities (probability of occurrence of one variable with restrictions placed on the second). The total number of rainy half-hourly time steps in the database (i.e. $I_{R(t)} = 1$) is 2750. Consequently, the probability of rain over Marseilles at a given time step is equal to 6% [$2750 / (5 \text{ year}) \times (183 \text{ day/year}) \times (24 \text{ hour/day}) \times (\text{twice/hour})$]. Table 1 shows the total number of MCS trajectories and ellipses which

Table 1 MCS and rainfall occurrences and conditional probabilities.

Number of occurrences	ISISGRAD method	FOUDRE method
MCS trajectories	74	97
MCS ellipses*	471	606
MCS ellipses associated with ground rainfall [†]	231	339
Conditional probability of rainfall given MCS ellipse	0.49	0.56

*cloud shields at every 30 min.

[†]total number of rainy half-hourly time steps in the database is 2750.

passed over the city during the same period and for the two methods studied. A trajectory is made of a series of MCS ellipses identified every 30 min. One can see that a trajectory lasts on average approximately 3 h over the city. Table 1 also shows the number of MCS ellipses associated with ground rainfall (i.e. $I_{R(t)} = 1$ and $I_{MCS(t)} = 1$), which gives a probability to be under an MCS as it rains equals to 8% for the ISISGRAD method and 12% for the FOU DRE method. The probability of rainfall given that an MCS is present is calculated as equal to 49% for the ISISGRAD method and 56% for the FOU DRE method. This means that under an identified MCS the probability for an area of 240 km² to be touched by rain is about 50%.

Statistics of ground rainfall conditional on MCS occurrences

In order to analyse the probability distribution functions of rainfall half-hour accumulations conditionally on MCS occurrences, three data series from the database were constructed:

- *Global rainfall*: all the values of non-zero point rainfalls.
- *Rainfall MCS present*: values of non-zero point rainfalls below an MCS.
- *Rainfall MCS absent*: values of non-zero point rainfalls recorded when no MCS is observed over Marseilles.

Table 2 summarizes some global statistical features of these series. Rain characteristics are drastically different when an MCS is present over the city. Variables like the mean and the standard deviation are multiplied by roughly 2.5 when an MCS is present. The percentile analysis indicates that the difference due to MCS presence is more sensitive for large values. These values are analysed in detail in the next section.

Table 2 Summary statistics of data sets.

Rainfall data	Mean (mm/30min)	Max* (mm/30min)	Median (mm/30min)	Percentile 10% (mm/30min)	Percentile 90% (mm/30min)	Standard deviation (mm/30min)
Global	1.2	63.4	0.6	0.2	2.6	2.35
ISISGRAD:						
MCS present	2.6	63.4	1.2	0.2	5.8	4.61
MCS absent	1.1	38.2	0.4	0.2	2.4	1.80
FOUDRE:						
MCS present	2.3	63.4	1.2	0.2	5.0	4.19
MCS absent	0.9	36.6	0.4	0.2	2.2	1.60

* in all cases, the minimum value is 0.2 mm/30min.

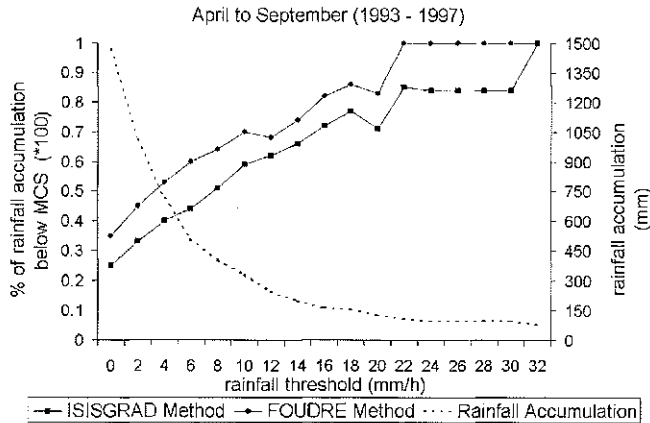


Fig. 3 Percentage of rainfall accumulation below MCSs as a function of rainfall thresholds for the ISISGRAD and FOU DRE identification methods.

While, as seen before, only about 10% of the rainy time steps are related to MCSs, the corresponding rain accumulation is considerably higher. Figure 3 represents the percentage of rainfall accumulation below MCS ellipses for each method studied and for different rainfall thresholds. Rainfall accumulations are computed by adding the mean areal rainfalls of every 30 min, which are higher than a selected threshold. When the threshold is set to zero, one can identify that the rainfall accumulation over Marseilles for the study period amounts to 1500 mm and that roughly 30% of this accumulation corresponds to the occurrence of an identified MCS over the city (25 and 35% according to the ISISGRAD and FOU DRE methods, respectively). If only mean areal rainfalls greater than 10 mm h^{-1} are considered, which represent about 330 mm of rainfall during the study period, then 60% of these correspond to MCS ellipses identified by the ISISGRAD method and 70% by the FOU DRE method. The globally higher percentage of rain explained by the FOU DRE method may be due to the consideration of smaller MCS trajectories (not attaining $10\,000 \text{ km}^2$) or to a better performance of lightning data in the discrimination procedure.

Rainfall at rare frequencies

Rainfalls at rare frequencies are important for design rainfall and flood analysis. In order to synthetically show the effect of the presence of an MCS on strong rainfall statistics, Fig. 4 displays the different cumulative distribution functions of point rainfall half-hour accumulations on Gumbel plots (arithmetic scale for the random variable and double negative logarithmic scale for the cumulated frequency value—the Gumbel standardized variable $u = -\ln(-\ln(Fx))$). Experimental frequencies Fx assigned to every data point were determined by using the Hazen plotting position formula (Haan, 1979). For values of u greater than 2 (i.e. exceeding probabilities lower than 13%), rainfall distribution functions below MCSs differ slightly from those when an MCS is not present for both methods. Regression lines fitted to the linear part of the distributions indicate slopes differing by a factor of 2.5. This parameter is the so called

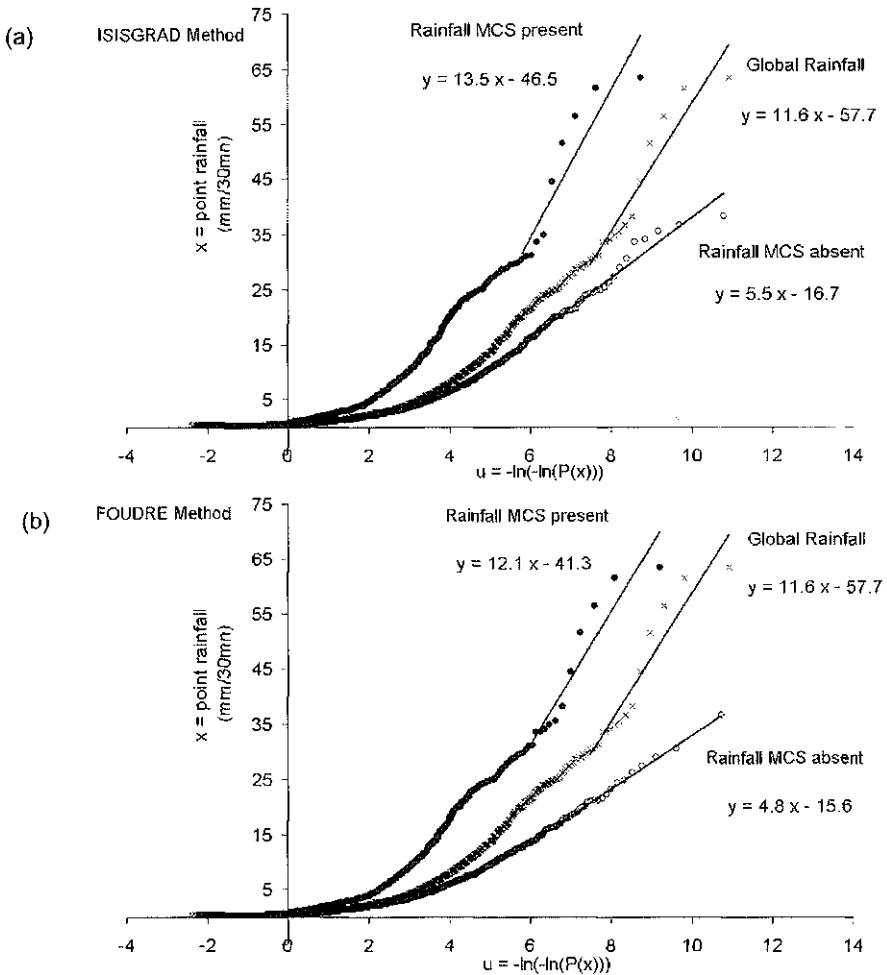


Fig. 4 Cumulative frequency distribution of point rainfall half-hour accumulations presented in a Gumbel plot for the (a) ISISGRAD and (b) FOU DRE methods. Global distribution of all non-zero rainfall values (x) and conditional distributions when an MCS is present (•) or absent (o) are plotted.

gradient of extreme values used in the Gradex Method, a rainfall–runoff probability approach for design floods (Guillot, 1980). The gradients obtained for the different methods are summarized in Table 3. They can be interpreted as indicators of rainfall “risk”. This shows that the risk of having strong rainfalls is about 2.5 times greater below cloud shields of MCSs. The evaluation of the uncertainties associated with these preliminary results falls beyond the scope of this study.

CONCLUSIONS

Two different methods of selecting and tracking MCSs from Meteosat infrared images and lightning data were used in order to analyse ground rainfalls observed in the city of

Table 3 Gradient of strong values (mm/30min).

Regression line $y = ax + b$	Global rainfall	ISISGRAD method:		FOUDRE method:	
		Rainfall MCS present	Rainfall MCS absent	Rainfall MCS present	Rainfall MCS absent
Gradient a	11.6	13.5	5.5	12.1	4.8

Marseilles. Both methods actually allow one to distinguish different subsets in the analysed rainfall data set. These subsets exhibit differences in both their bulk and their extreme features. The mean and standard deviation of rainfalls below MCSs appear to be about 2.5 times greater. The rainfall "risk" is 2.5 times greater below an MCS for both methods. Although rainfalls below MCSs only constitute about 10% of the rain occurrences over the city, they bring more than 30% of the total accumulation of rainfall. A greater percentage of rainfall accumulation is explained by the identification method which includes lightning data to discriminate the convective character of cloud shields. Using this method, MCSs can be identified for smaller sizes and for the whole year with the same accuracy and not only for the warm season, as is currently the case, when the peripheral brightness temperature gradient is used. This highlights the importance of combining satellite and lightning data in rainfall analysis.

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