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AN OBJECTIVE CLASSIFICATION OF RAINFALL EVENTS ON THE BASIS OF THEIR CONVECTIVE FEATURES: APPLICATION TO RAINFALL INTENSITY IN THE NORTHEAST OF SPAIN

MARÍA-CARMEN LLASAT*
Department of Astronomy and Meteorology, University of Barcelona, Barcelona, Spain

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ABSTRACT

A system of rainfall events classification on the basis of their hydrometeorological characteristics is proposed. The objective is the characterization of the different event classes and their application in modelling intensity–duration–frequency curves and design hyetographs. A parameter related to the greater or lesser convective character of the precipitation, designated as β^*, is defined, while its distribution throughout the entire series of the sample is studied. In addition, the main features of the different classes obtained and their relationship to floods and rainfall damage events have been analysed. The intensity series of the Jardí pluviograph (Barcelona, Spain) between 1927 and 1981 is used as a sample series. Copyright © 2001 Royal Meteorological Society.

KEY WORDS: Catalonia, Spain; design hyetographs; IDF curves; long-term rainfall intensity series; rainfall events classification

1. INTRODUCTION

It is well known that pluviometric episodes can have highly diverse characteristics, which is clear from both their spatial and temporal distribution. These characteristics depend on the physical mechanisms responsible for the rainfall or other hydrometeors that occur, which in turn depend upon the particular meteorological situation at the larger or smaller scale. We are thus faced with a problem that presents many factors and is therefore difficult to deal with. The solution of taking the episodes to be of one type or another in terms of their geographical occurrence or their associated synoptic meteorological situation would, though simple, be too simplistic. To make a generalization, for example, that all rains coming from the East are of one type, while rains from the West are of another type would be flawed. This type of solution would, furthermore, call for *ad hoc*, single studies for each working zone.

A more correct solution is to study the nature of the process which gave rise to the precipitation. In this case a distinction could be made, essentially, between precipitation of convective origin and precipitation of stratiform origin, which should not be linked with the classification of the rainfall associated with a storm or rainfall associated with a front, as has unfortunately sometimes occurred. In a simplified form, following the definition proposed by the American Meteorological Society's *Glossary of Meteorology* (Huschke, 1959) and by Houghton (1950, 1968), it would be a matter of associating the first type with clouds of convective type, such as cumulonimbus, and the second, with clouds of stratiform type, such as nimbostratus. Houze (1993) distinguishes between stratiform/convective precipitation on the basis of the vertical air velocity, w. If it is less than the terminal fall velocity of ice crystals and snow, then it is called

* Correspondence to: Department of Astronomy and Meteorology, University of Barcelona, Avda. Diagonal 647, E-08028, Barcelona, Spain; e-mail: carmell@am.ub.es

'stratiform'. Together with this feature, and using the 4-D radar imagery, the 'bright band' near the melting level is a signature that helps to distinguish convective mode from stratiform mode. Steiner *et al.* (1995) proposed two methods for distinguishing between stratiform and convective precipitation in radar echo patterns that are commonly used nowadays.

Convective systems can be subdivided in terms of their structure and life-cycle, into unicellular, multicellular, supercellular or mesoscale convective systems (MCS) or complexes (Byers and Braham, 1949; Browing and Ludlam, 1962; Fujita, 1985; Doswell *et al.*, 1996). In this case, however, the main problem would lie in the need to have information from meteorological satellites and radar, which would hinder the feasibility of the process. Also, within a system of eminently convective origin, it is possible to find rain of stratiform character, or, into the trailing anvil of a MCS, it is possible to find vertical motions of several metres per second, moderate intensity rainfall with a showery character and a certain vertical organization (Doswell, 1993; Houze, 1997). Similar observations are currently giving rise to an ongoing discussion about the physical concept implicit in the term 'convective precipitation', though this clearly lies outside the scope of this paper.

A third possibility would lie in studying the intensity (I) threshold(s) exceeded. For instance, in Spain, the National Meteorological Institute defined, some years ago, the rainfall risk situations during the PREVIMET (specific meteorological surveillance of heavy rains) campaign on the basis of the following thresholds of average hourly intensity

light rainfall $= I \leq 2$ mm/h
moderate rainfall $= 2 < I \leq 15$ mm/h
heavy rainfall $= 15 < I \leq 30$ mm/h
very heavy rainfall $= 30 < I \leq 60$ mm/h
torrential rainfall $= I > 60$ mm/h

However, these thresholds vary considerably from one country to another, which means that it would be difficult to obtain a universal classification on the basis of the different thresholds.

Finally, it should be stated that the mitigation produced by rain in the short-wave radio links brought the problem into the field of telecommunications. Here, it has been observed that rainfall rates above 0.8 mm/min can generate problems in radio links (Vilar and Burgueño, 1991). Analogies were then drawn up, such as convective rain equals rain from storms (Rice and Holmberg, 1973), or development work on more complex expressions including climatic values (Dutton *et al.*, 1974; Dougherty and Dutton, 1978; Dutton and Dougherty, 1979). Establishing an analogy between rain of convective origin and storm-origin rain would involve underestimating the former, since the WMO requires the definition of a thunderstorm to include the presence of lightning, which does not always occur with rainfall of convective origin. Another more widespread analogy involved considering convective rain to be all convective rain within a threshold of 48–50 mm/h (Dutton and Dougherty, 1979; Watson *et al.*, 1982). The problem with this classification would be that not all rain of convective origin exceeds that threshold, while not all rain which does exceed the said threshold is convective in character. On the other hand, it does have the great advantage of being a simple, objective and (up to a point) universal classification.

The objective of this paper was to attempt to blend together the various factors discussed above in order to find an objective method of classification which at the same time has a plausible physical interpretation. This objective also considers the introduction of a parameter permitting classification of the types of pluviometric events and, consequently, one that is useful for subsequent hydrological modelling. To this end the 1927–1981 series of rainfall intensities provided by the Jardí pluviograph situated near the city of Barcelona were used.

Sections 2 and 3 show the background and the preliminary analysis. The β parameter is introduced in Section 4 and it is applied to a rainfall events classification in Sections 5 and 6. Section 7 shows the application of this classification to heavy rainfall events that have produced damage. Finally, Section 8 focuses on conclusions and future researches.

2. BACKGROUND

The Jardí pluviograph is situated in the Fabra observatory, on the slopes of Tibidabo mountain, at an altitude of 414 m a.s.l. and at a distance of 7.5 km from the sea, inland from the city of Barcelona. Given that the operation of this pluviograph has been extensively described in previous publications (Jardí, 1921; Llasat and Puigcerver, 1985, 1997; Puigcerver *et al.*, 1986; Burgueño *et al.*, 1993), suffice to say here that for this work the instantaneous intensity of rainfall was converted into 1-min and 5-min mean intensities (these being the most typically used intervals of measurement in current automatic pluviographs).

The first study carried out on the basis of individual analysis of each precipitation episode recorded on the Jardí pluviograph between 1960 and 1979 showed that some 55% of the annual precipitation was of convective character (in the case of mixed episodes, the convective character was considered to be dominant), while 70% at some stage exceeded an intensity episode of 0.8 mm/min (Llasat and Puigcerver, 1997). Approximately 40% of the annual precipitation was thus of convective character with intensity exceeding 0.8 mm/min at some stage of the episode. This value was at variance with the 32% obtained for precipitation due to storms, a difference that increased when monthly values were considered. For the same period it was found that the rain from episodes of non-convective character, in which the intensity at some point exceeded that threshold, accounted for less than 0.001% of total annual rainfall time, and in no case exceeded an intensity of 3 mm/min (Llasat, 1997).

The discussion of the previous paragraph could be based on terms of a β parameter which relates rains of different origins with total rainfall. This parameter was introduced by Rice and Holmberg (1973) for modelling attenuation in radio links due to rain, being defined as:

$$\beta = \frac{\text{annual stormy precipitation}}{\text{total annual precipitation}}$$

where they seemed to take stormy precipitation as that where the threshold of 0.8 mm/min is exceeded. Given the inherent difficulty of evaluation of this numerator, the authors, along with Dutton and Dougherty (Dutton *et al.*, 1974; Dougherty and Dutton, 1978; Dutton and Dougherty, 1979; Watson *et al.*, 1982) proposed calculating it empirically on the basis of the mean annual precipitation, the mean annual number of stormy days and the maximum monthly precipitation observed over thirty consecutive years. In the case of the precipitation recorded by the Jardí pluviograph, the application of such formulae gave a value of 0.16 (Llasat and Puigcerver, 1985), a value in accordance with that proposed by Rice and Holmberg (1973) for Barcelona, but differing from that proposed by Dutton *et al.* (1974).

Later, and following this same line, the next parameter was defined (Llasat and Puigcerver, 1985, 1997) in which the word 'monthly' may be replaced by the word 'annual', where reference is to be made to annual values.

$$\beta_0 = \frac{\text{monthly precipitation from episodes of convective type}}{\text{total monthly precipitation}}$$

Thus, in light of the above observations, β_0 would, in the case of the Jardí pluviograph series, have the value 0.55. In order to be able to compare this with the proposal made by Rice and Holmberg (1973), all that is required would be to select those episodes which, in addition to being convective, exceed the threshold of 0.8 mm/min, thereby providing a new parameter β_1 defined as

$$\beta_1 = \frac{\text{monthly precipitation from episodes of convective type, which } I_1 > 50 \text{ mm/h}}{\text{total monthly precipitation}}$$

which would mean that β_1 would have a value of 0.38 in the case of the above-mentioned series. If this is compared with the value of 0.37 obtained by Burgueño (1986) for the 1927–1981 series on the same pluviograph and attention is paid exclusively to the factor of there existing, at a particular moment of the episode, a 1-min intensity (I_1) 50 mm/h (independently of whether or not this was convective), then the two values can be seen to be similar. If the monthly distribution is also analysed, then it can be concluded that the error made in equating episodes in which the 1-min intensity of 0.8 mm/min with convective episodes is insignificant. While it is true that the homogeneity of the two time intervals may be debatable, a study carried out on the precipitation series for Barcelona (Rodriguez *et al*., 1999) does confirm this homogeneity. Thus, the hypothesis of assuming an episode to be convective when a threshold of 50 mm/h is exceeded at some point is not unreasonable, and less unreasonable still if it is remembered that the problems (hydrological, radio links, rescue services, etc.) are not usually caused by low intensities. Finally, meteorologically speaking, convective systems of a certain size (from unicellular storms to mesoscale convective storms) usually give intensities exceeding that threshold of 0.8 mm/min.

3. MAKING THE CRITERIA PROPOSED FOR THE 1-MIN SERIES SUITABLE FOR THE 5-MIN SERIES

As stated at the beginning, the new measuring networks usually record the rain at intervals of 5 min or more; for this reason it is useful to take $\Delta T = 5$ min. A similar change also affects the threshold intensity, which can no longer be 50 mm/h, but must, after the increase of time interval, be reduced due to the consequences of the attenuation provoked in the high-intensity peaks. By way of example, it is sufficient to compare the β value calculated on the basis of 1-min intensities exceeding 50 mm/min and the value obtained by working with the 5-min series: 0.182 compared with 0.128, respectively. This is equivalent to saying that

$$\beta_1 = 1.421\beta_5$$

where β_5 refers to the 5-min series and a rainfall rate threshold equal to 50 mm/h.

Figure 1 shows the monthly variation of β_1 and β_5. In both cases the maximum is recorded in July and the minimum is recorded in February. The two-parameter quotient shows that the greatest discrepancies arise during the winter months, while it is in summer that the coefficient is closest to one unit. The explanation for this is to be found in the fact that during the winter the threshold of 50 mm/h is rarely exceeded and, when this does occur, the time over which this intensity is maintained is very short. In summer, on the other hand, the minute-intensity remains above 50 mm/h over relatively long periods of time; that is, very high intensities are reached, so that when the averaged interval is extended to 5 min the threshold imposed continues to be exceeded.

Figure 2 shows the values $\beta_{L,5}$ takes when working with a 5-min series in function of the intensity threshold, L. It can be observed that the proportion of precipitation which exceeds the threshold of 50 mm/h when working with a 1-min series (0.182) is equivalent to that which exceeds the threshold of 36 mm/h when working with a 5-min series, which can be formulated as: $L_1 = 1.428L_5$ for $\beta = 0.182$, which links the intensity thresholds for accumulation times of 1-min, L_1, and 5 min, L_5.

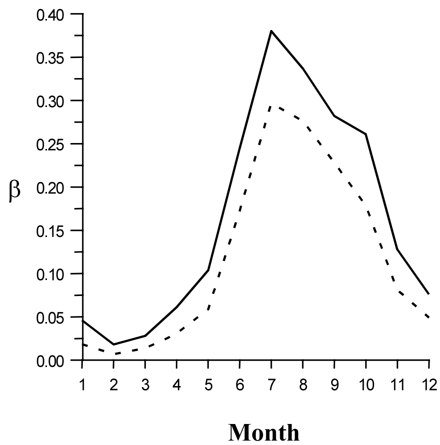

Figure 1. Monthly evolution of β_5 (continuous line) and β_1 (discontinuous line) in basis to the 5-min and 1-min rainfall series of Barcelona, Spain, respectively

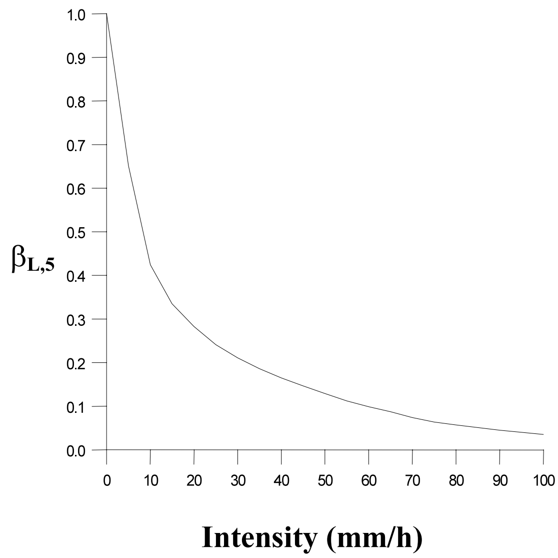

Figure 2. Evolution of the average value of $\beta_{L,5}$ in function of L (intensity threshold in mm/h) in basis to the 5-min rainfall series of Barcelona, Spain

Based on the above equation, a value of 35 mm/h will be taken as the 5-min mean intensity threshold (a multiple of 5 is chosen to facilitate subsequent calculations). From analysis of the 5-min series it can be obtained that for 1.454% of the mean annual time for which it rains, the precipitation presents a mean 5-min intensity exceeding 35 mm/h, responsible for 18.2% of the total annual precipitation.

4. UTILIZATION OF THE PARAMETER β^* FOR CHARACTERIZATION OF EPISODES

The above values relate to the monthly and annual distribution of convective precipitation. In order to model episodes, however, it is useful to have a parameter for each one of them. The methodology proposed here for resolving that objective consists in taking, as a point of departure, a mean intensity threshold within a given time interval, and introducing a parameter which takes account of the ratio between the rainfall which exceeds that threshold and total rainfall in an episode. This parameter is designated as $\beta^*_{L,\Delta T}$ and, unlike the previous ones, is of meteorological rather than climatic character. The expression can be calculated as

$$\beta^*_{L,\Delta T} = \frac{\sum_{i=1}^{N} I(t_i, t_i + \Delta T)\theta(I - L)}{\sum_{i=1}^{N} I(t_i, t_i + \Delta T)}$$

where ΔT is the time interval of accumulation of the precipitation, expressed in minutes, N is the total number of ΔT integration steps into which the episode is subdivided, and $I(t_i, t_i + \Delta t)$ is the precipitation measured between t_i and $t_i + \Delta t$ divided by Δt, i.e. the mean intensity in the said interval expressed in mm/min or mm/h.

$\theta(I - L)$ is the Heaviside function defined as

$(I - L) = 1$ if $I > L$
$(I - L) = 0$ if $I < L$
$(I - L) = 1$ if $I = L$

in which the last condition is proposed by the author. The definition of an episode is quite subjective. In this case it was felt that it is possible to distinguish between two different episodes when the time which elapses between them without rainfall exceeds 1 h, which ensures that the two episodes come from different 'clouds'. If in the above definition, the term 'episode' is replaced by 'month' or 'year', and $\Delta T = 1$ min and $L = 50$ mm/h are taken, we arrive at the definition of β_1 presented in the previous sections. It can be noted, too, that the monthly β_1 value (as defined in the previous section) and the mean monthly value of $\beta^*_{50,1}$ do not have to coincide; indeed, the latter will be slightly lower than the former.

The previous section explained the presupposition of an intensity threshold of 35 mm/h for the 5-min series as against the threshold of 50 mm/h for the 1-min series. Based on this, we will thereafter take $\Delta T = 5$ min and $L = 35$ mm/h, simplifying the notation of $\beta^*_{35,5}$, which will be represented as β^*. The monthly distribution of the percentage of rainfall events with β^* other than zero shows that the maximum occurs in August with 18.3%, followed by September with 15%. In February and March, on the other hand, the percentage falls to 1.9% and 1.8%, respectively (Table I).

In order to obtain more detailed information, the mean intensity of each episode has been represented in terms of its duration for those cases in which $\beta^* > 0$ (Figure 3). It can be observed that, while 88% of the non-convective events ($\beta^* = 0$) present average hourly intensities of less than 40 mm/h and durations of less than 2 h, in the case of events with $\beta^* > 0$, this percentage decreases to 65%. If the same type of curve is constructed for the different seasons of the year it can be observed that, with the exception of autumn, the durations are in general less than 240 min and that, where this value is exceeded, the mean intensities are lower than 10 mm/h. Stated another way, those episodes where, at a given moment, the

Table I. Monthly distribution of rainfall events (N) and total rainfall (P) in Barcelona (1927–1981), discerning the convective cases from the total events

Month	J	F	M	A	M	J	J	A	S	O	N	D
N	339	317	560	650	673	494	293	453	574	641	496	424
$N\beta^* > 0$	10	6	10	25	34	51	35	83	86	89	40	13
$\%N\beta^* > 0$	2.9	1.9	1.8	3.8	5.0	10.3	11.9	18.3	15.0	13.9	8.1	3.1
$P\beta^* > 0$	157	257	289	390	582	999	871	1854	2173	2162	1008	402
$\%P\beta^* > 0$	20.2	16.9	13.3	14.1	19.8	43.3	59.8	64.1	55.4	51.4	34.4	20.6

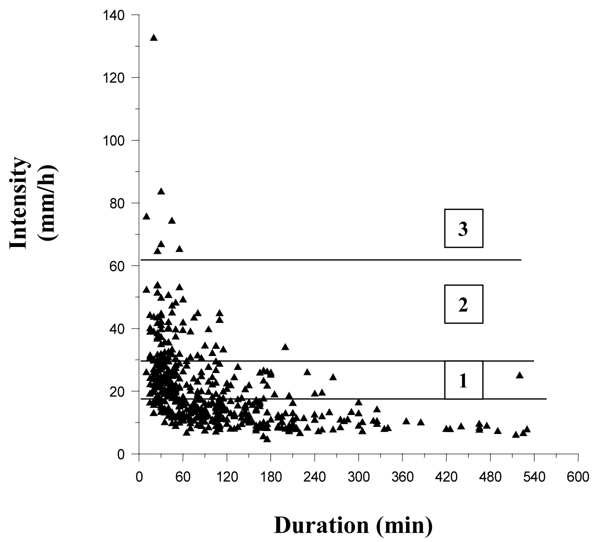

Figure 3. Distribution of the average intensity (mm/h) of the rainfall events with $\beta^* > 0$ in function of their duration. Events are classified in function of their average intensity: (1) heavy rainfall; (2) very heavy rainfall; (3) torrential rainfall

5-min intensity of 35 mm/h is exceeded are generally less than 4 hours in duration. In the case of autumn, this generalization loses a certain amount of validity as a result of the by no means negligible number of episodes with $\beta^* > 0$ and durations ranging between 4 and 8 h. It should also be noted that in neither winter nor spring is the mean intensity of 40 mm/h exceeded. Figure 4 shows the seasonally adjusted curves corresponding to the average intensity-event duration function in the cases in which $\beta^* > 0$ (correlation coefficients are between $r = 0.6$ for the summer and $r = 0.8$ for the spring).

Figure 5 has been constructed in order to show more clearly the differences between the characteristics of those episodes with $\beta^* > 0$ and those others with $\beta^* = 0$, and showing the adjustment curves corresponding to the various seasons of the year for episodes with $\beta^* = 0$. Noteworthy is the fact that in this case the slope of the curves is positive, that is, the episodes of greatest mean intensity are also those of longest duration. Although it might seem unexpected, this result can be explained by the low values of the mean intensities achieved, together with how little the real values match the adjustment curves, with values between $r = 0.2$ for the summer and $r = 0.3$ for the winter. It is interesting to note too that the annual curve lies between those for autumn and spring, while the summer continues to be shown as the season for which the highest mean intensities are recorded.

Analysis of the maximum 5-min intensities achieved in those events with β^* other than zero shows that, except on one occasion, 75 mm/h has never been exceeded in winter, while in spring this threshold rises to 100 mm/h, in summer to 200 mm/h and in autumn to 225 mm/h. Similarly, all these extreme intensities are recorded in episodes with a duration of less than 1 h (in autumn there are some occasional episodes which last 2 h) and with values of β^* close to one unit. Finally, to conclude this discussion, it is worth stressing than the episodes in which the precipitation exceeds the 5-min threshold of 35 mm/h by 50% or more generally have durations in winter of less than 1 h, of less than 2 h in spring, 3 h in summer and 4 h in autumn.

Finally, and for the purposes of information, it would be useful to find the correlation which exists between the mean intensity (I_{av}) of an episode and the maximum 5-min intensity (I_{max}). To that end it is possible to use a potential adjustment of the type

$$I_{max} = aI_{av}^{b}.$$

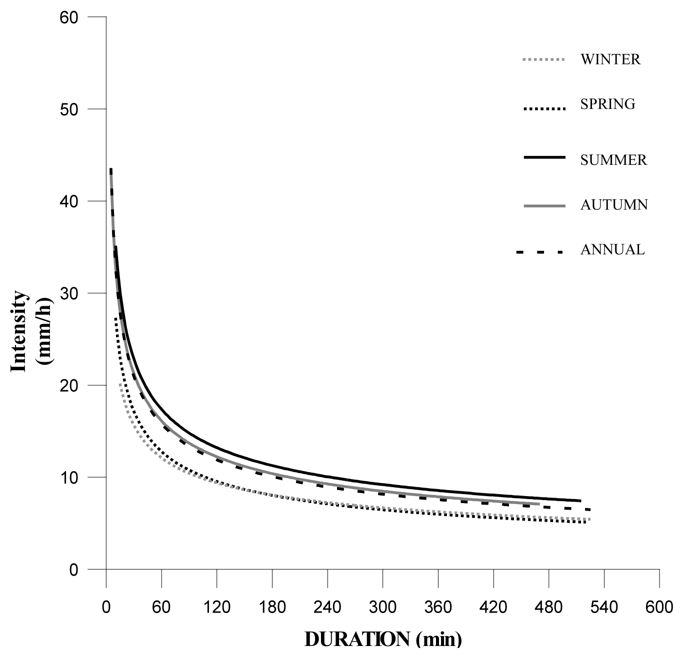

Figure 4. Adjusted curves corresponding to the average intensity duration function in the cases with $\beta^* > 0$

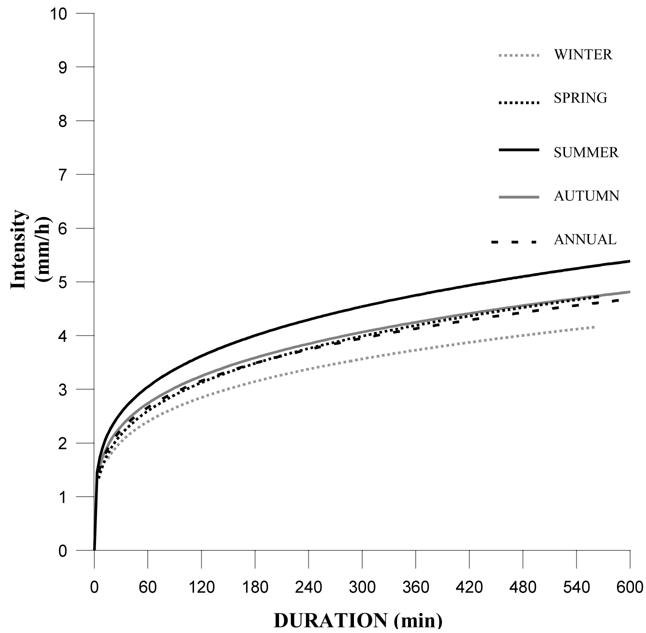

Figure 5. Adjusted curves corresponding to the average intensity duration function in the cases with $\beta^* = 0$

Table II shows the values of the various parameters for the different seasons of the year. A similar correlation could be established between the maximum 5-min intensity recorded on any particular day, $I_{\max}$ and the total accumulated precipitation on that same day, R. Although the correlation is smaller than in the previous case, the usefulness of the formula lies in the order of magnitude it provides

$$I_{\max} = 4.1546R^{0.6014}, \qquad r = 0.8174$$

It may be noted that this adjustment is better for accumulated daily precipitations lower than 20 mm, but gets worse for abundant precipitation.

5. PROPOSAL FOR A CLASSIFICATION OF EPISODES IN TERMS OF THE PARAMETER β^*

If, in analysis of the previous figures, the distribution of the various values of β^* is also taken into account, it can be observed that there is a certain tendency for the values close to one-unit value to pertain to episodes of very short duration and high intensity, while β^* values lower than 0.5 usually pertain to episodes of more than 1-h duration and maximum 5-min intensities never exceeding 150 mm/h. All this suggests the possibility of using β^* as a pluviometric episode characterization parameter.

Table II. Values of the various parameters for the correlation that exists between the mean intensity of an episode and the maximum 5-min intensity for different seasons of the year, in Barcelona

Year	$a = 1.6994$	$b = 1.1871$	$r = 0.8839$
Winter	$a = 1.6704$	$b = 1.2251$	$r = 0.9285$
Spring	$a = 1.6930$	$b = 1.1746$	$r = 0.9234$
Summer	$a = 1.6794$	$b = 1.1705$	$r = 0.9490$
Autumn	$a = 1.6934$	$b = 1.2158$	$r = 0.9357$

Firstly, then, the previous section contains a proposal for use of the term 'convective' for all episodes in which β^* is greater than zero. Secondly, a proposal is made for the following classification of pluviometric episodes according to their greater or lesser convective character:

$\beta^* = 0$ non-convective
$0 < \beta^* \leq 0.3$ slightly convective
$0.3 < \beta^* \leq 0.8$ moderately convective
$0.8 < \beta^* \leq 1.0$ strongly convective

From all of the above it can be seen that 92% of rainfall episodes in Barcelona are non-convective, providing 63.5% of the total precipitation, and that 8% are convective and provide 36.5% of the total precipitation. To go into further detail, 3.8% pertain to slightly convective episodes, 2.9% to moderately convective episodes and 1.3% to strongly convective episodes. In winter, the distribution between moderately convective and slightly convective episodes is quite close (approximately 50% of each type), with the difference that the moderately convective episodes generally last less than 2 h, a threshold which the slightly convective episodes usually exceed. In spring there is a considerable increase in strongly convective episodes (usually lasting less than 1 h), although the most dominant episodes are the moderately convective ones (with durations between half an hour and 3 h). In summer, the number of slightly convective episodes decreases markedly, while the very convective episodes then exceed 40% and can last up to 2 h, while the moderately convective episodes can last some 3 h. Finally, in autumn, the percentage of very convective episodes decreases to become similar to that of the slightly convective episodes, while over 50% of episodes are moderately convective. It is worth stressing that some of the latter can have a duration of 5 h. It is precisely the extraordinary rainfalls and catastrophic floods that are usually linked with moderately convective episodes (though with $\beta^* > 0.5$) of long duration.

Regarding the maximum 5-min intensities, it is worth noting that 55% of the very convective episodes exceed the threshold of 125 mm/h, 63% of the moderately convective are between 75 and 125 mm/h, and 59% of the slightly convective between 35 and 75 mm/h.

6. UTILIZATION OF PARAMETER β^* FOR CHARACTERIZATION OF THE DESIGN HYETOGRAMS

Firstly, the intensity–duration–frequency (IDF) curves were calculated on the basis of the 5-min series of the Jardí pluviograph for each season of the year and for the return periods of 2, 5, 10, 25, 50, 100 and 500 years. Other studies exist of the IDF curves for the above-mentioned pluviograph (Burgueño, 1986) but they refer to the 1-min series and no distinction at all is made in them between the different seasons of the year. As in those studies, a Gumbel-type distribution was taken to be valid for use as an adjustment function (Ven Te Chow, 1988).

Figure 6 represents the seasonal IDF curves. Linking this back to the previous paragraph, it is observed that the episodes with 5-min intensity above 150 mm/h show a return period of 500 years in winter and spring and 10 years in summer and autumn. In this season, the maximum 5-min intensity, corresponding to a return period of 100 years, rises to 230 mm/min. Also worthy of note is the fact that in winter it is necessary to go beyond a return period above 2 years to find episodes whose 5-min intensity exceeds 35 mm/h, i.e. β^* other than zero. Figure 7 shows the annual IDF curves. The similarity between this last figure and the one corresponding to the autumn season can be seen.

Secondly, the design hyetograms were constructed on the basis of the IDF curves by using the alternating blocks method. A change was nevertheless made in the application of this method, by supposing that the maximum intensities in the episodes of heavy intensity are recorded approximately within the first third of the event (in the first half for very brief episodes), which derives from a study carried out using the minute series of the Jardí pluviograph (Lorente and Redaño, 1991). The same paper shows that for episodes of 1 h, approximately 80% of the precipitation falls in the first 30 min. Indeed, for a duration of 20 min the maximum intensity is achieved in the second 5-min interval, i.e. between the

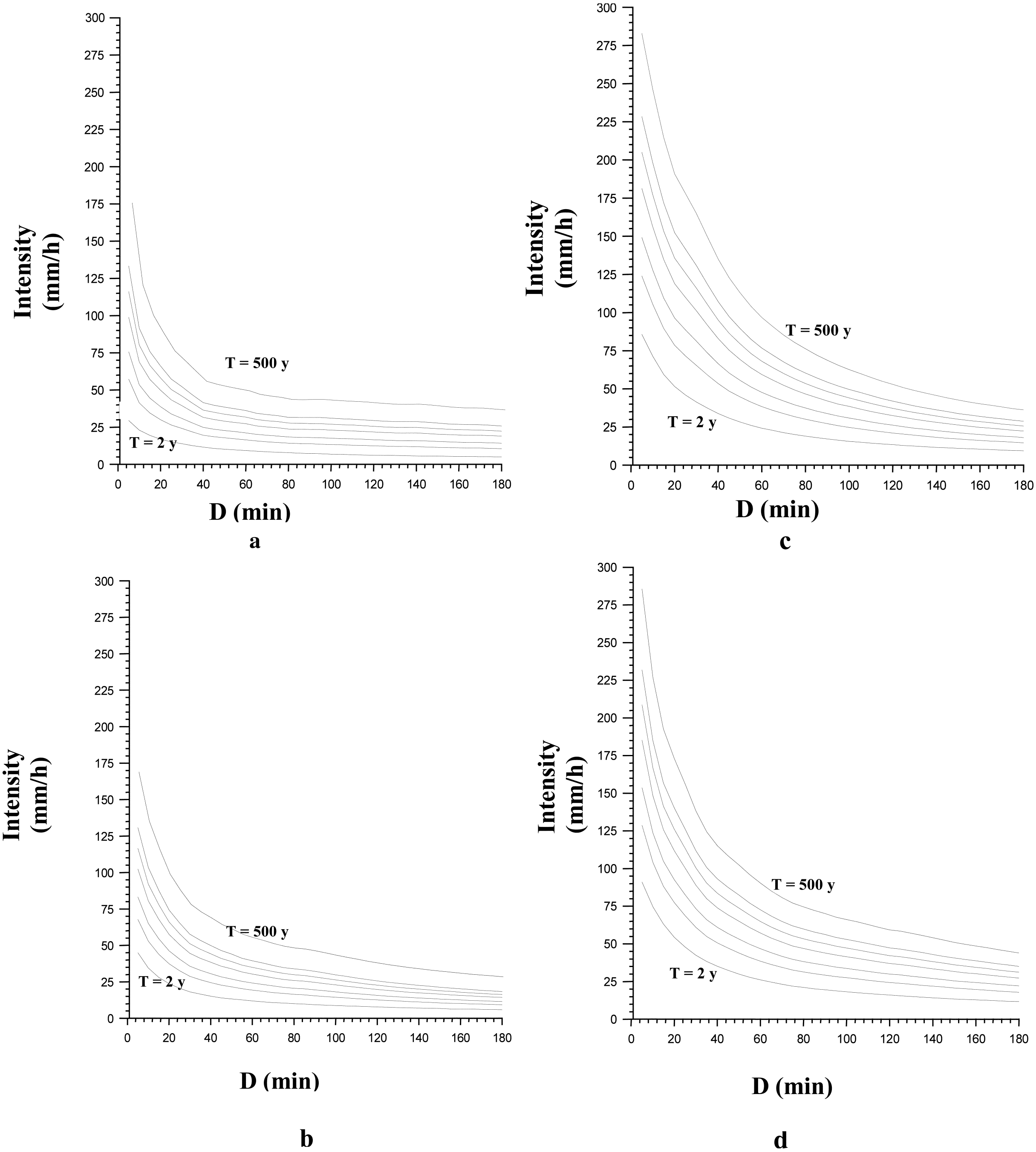

Figure 6. IDF curves for Barcelona in (a) winter, (b) spring, (c) summer and (d) autumn. The curves have been designed for return periods $T = 2$, 5, 10, 25, 50, 100, 500 years

first 5 and 10 min, while for a duration of 90 min this is attained between 25 and 30 min. This curve was therefore used for locating the maximum intensity and the blocks alternated, starting from the left in order to accord greater weight to the first part of the episode.

Figure 8 shows the design hyetogram obtained from the annual IDF curve for a return period of 10 years and supposing an episode duration of 75 min. The preceding methodology was used for constructing

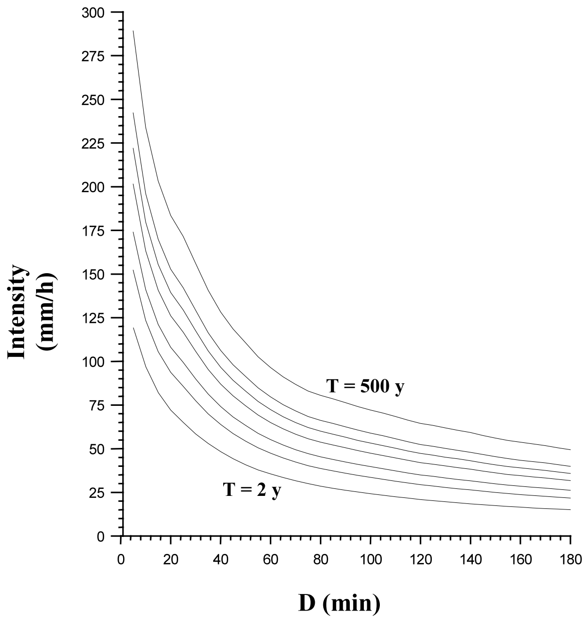

Figure 7. IDF curves for Barcelona for all the year. The curves have been designed for return periods $T = 2$, 5, 10, 25, 50, 100, 500 years

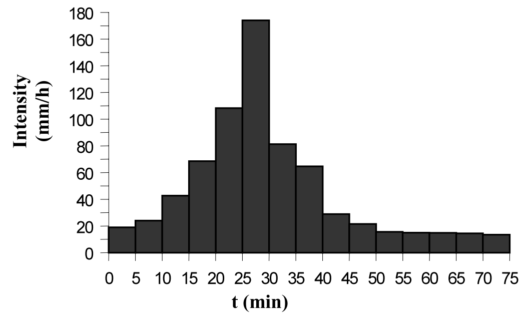

Figure 8. Hyetograph obtained from the annual IDF curve corresponding to a return period of 10 years and duration of 75 min

it. Figure 9 shows the hyetograms corresponding to the seasonal IDFs for the aforesaid duration and return period. It is easy to see the overestimation that would occur if the annual hyetogram was taken as representative of the winter.

Thirdly, each hyetogram was characterized by means of the value of β^*, and β^* has been represented for each season of the year in terms of the return period and of the duration of the corresponding pluviometric episode. One of the results is shown in Figure 10. In line with the observations carried out for the IDF, the return period of 2 years does not appear in the winter graph. The utilization of these curves provides information on the greater or lesser convective character of the episodes. The advantage of this is that it allows a design hyetograph for any duration to be obtained. Thus, for a return period of 2 years and a duration of 20 min, the episodes are very convective, with a β^* value of 0.8 (80% of the precipitation exceeds the 5-min intensity of 35 mm/h) and a mean maximum intensity of 75 mm/h according to the annual IDF. Thus defined, for a return period equal or less than 2 years, convection remains predominant where the duration of the episode is less than 70 mins. Those events for which 50 mm of cumulated rainfall are recorded in 30 min (typical in some Mediterranean regions to characterize heavy rainfall events) have a return period above 10 years (Figure 7) and are very convective (Figure 9).

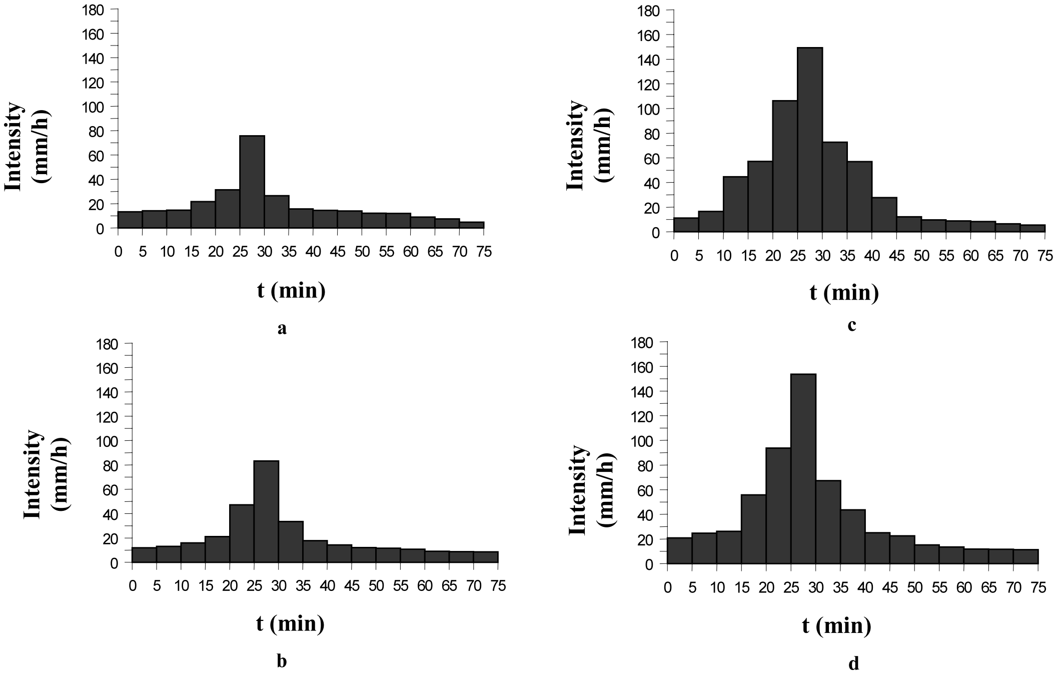

Figure 9. Hyetograph obtained from the (a) winter, (b) spring, (c) summer and (d) autumn IDF curves corresponding to a return period of 10 years and a duration of 75 min.

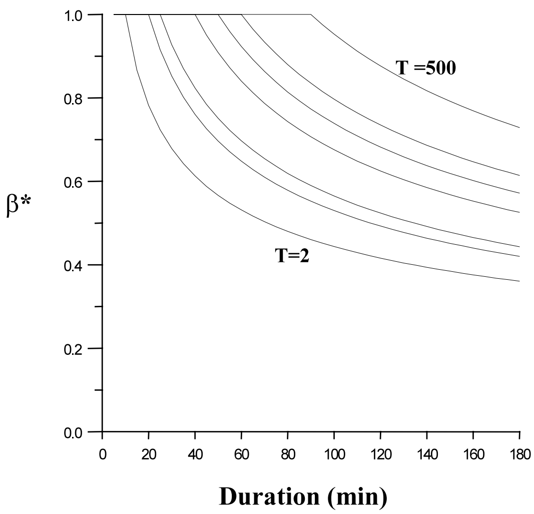

Figure 10. Curves of β^* (all year) corresponding to the hyetographs obtained from the IDF curves. The curves have been designed for return periods $T = 2$, 5, 10, 25, 50, 100, 500 years

These results are in accordance with the maximum life cycles of the usual unicellular or multicellular 'storms'. But catastrophic rainfalls in this region are usually related with rainfall events that last a minimum of 2 h; for this duration the return period for a strongly convective event ($\beta^* > 0.8$) is above 100 years (Figure 10) and the mean 5-min maximum intensity is higher than 60 mm/h, which represents a cumulated rainfall of approximately 60–120 mm.

The same kind of figure can be represented for each season (Figure 11). For instance, for a 2-year return period and an event duration of 40 min, the β^* value is 0.63 (63% of 5-min rainfall rate is above

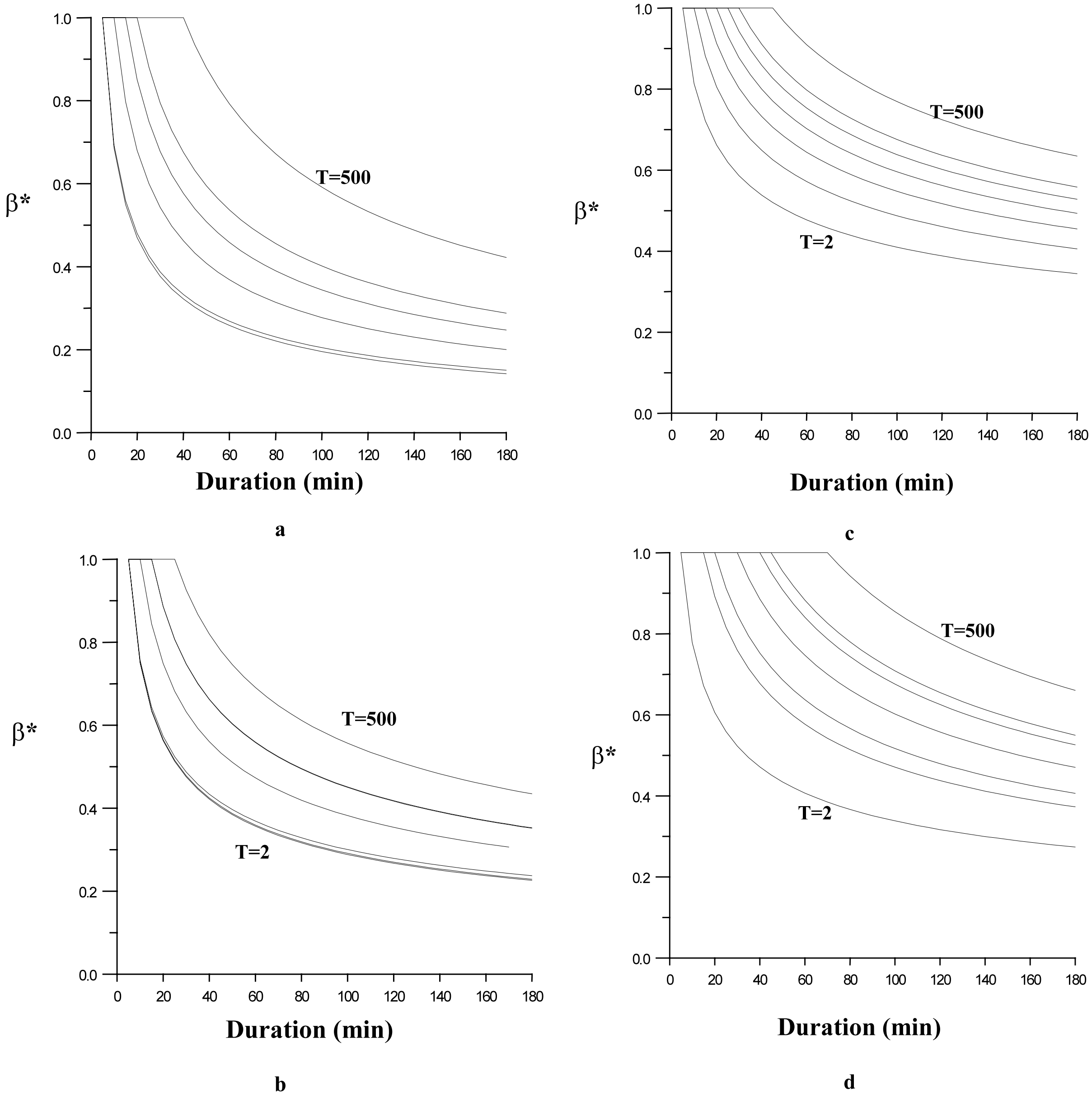

Figure 11. Curves of β^* (all year) corresponding to the hyetographs obtained from the (a) winter, (b) spring, (c) summer and (d) autumn IDF curves. The curves have been designed for return periods $T = 2$ (its value is 0), 5, 10, 25, 50, 100, 500 years

35 mm/min) and the maximum intensity deduced from Figure 7 is 50 mm/h. If the event was recorded in winter, the maximum intensity would be 13 mm/h and the 5-min rainfall rate would always be less than 35 mm/h, but if the event was produced in autumn the maximum would be 38 mm/h and β^* would be 0.48.

After obtaining the design hyetographs in terms of the season of the year, duration and return period, the β^* coefficient has been calculated for each one of them. With this information it is possible to plot the relationship between the β^* values and the event duration for each return period.

7. APPLICATION OF THE β^* CLASSIFICATION TO HEAVY RAINFALL EVENTS THAT HAVE CAUSED DAMAGE

In order to analyse the potential use of this kind of classification to identify rainfall events that have caused damage, the period 1987–1996 has been analysed. The sample consists of those rainfall events that have caused damage in any part of Spain during this period and for which the average rainfall intensity and duration are known. With these conditions 25 heavy rainfall events have been selected, 76% of which have occurred in Catalonia, Spain. Although the greatest part has cumulated rainfall above 100 mm in 24 h, some events have had a very short duration (less than 1 h) but strong intensities. The greatest hourly rainfall measured has been 152.9 mm during the Biescas (Aragón) event (Riosalido *et al.*, 1997). Figure 12 is the same as Figure 3 but these new events have been included. It is interesting to see that all these events are over or above the curve defined by the function

$$I = 734.2D^{-0.6912}, \qquad r^2 = 0.987$$

All of them are convective, but their peculiarity is that their average intensity is above the usual average intensity for the duration.

8. CONCLUSIONS

This paper has centred on seeking a method of objective classification and at the same time a plausible physical interpretation of pluviometric episodes, so that they can be introduced into hydrometeorological modelling. To this end, measurements were made using the 5-min series of intensities, 1927–1981, provided by the Jardí pluviograph sited close to the city of Barcelona, Spain.

For this purpose, and after considering the literature in this field, the parameter $\beta^*_{L,\Delta T}$ has been defined. In the particular case in which $\Delta T = 5$ min and $L = 35$ mm/h, the notation $\beta^*_{35,5}$ has been simplified and represented as β^*. The use of the term 'convective' is then proposed for all those episodes in which β^* is greater than zero. Likewise, and in order to facilitate subsequent work, the hypothesis that all the rain from a 'convective' episode can be treated as such in its entirety was taken to be valid, without any need

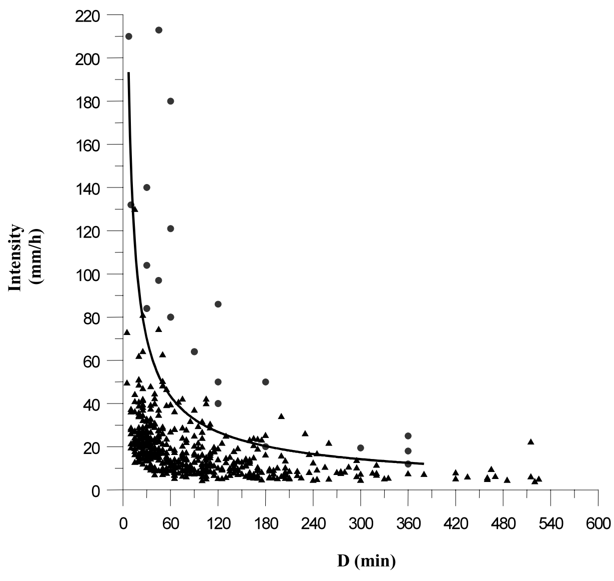

Figure 12. Distribution of the average intensity (mm/h) of the rainfall events with $\beta^* > 0$ as a function of their duration (circles) and the rainfall events that have produced damage (triangles)

to enter into consideration of its internal structure (as long as there is no intention of working in the field of the microphysics of the associated processes).

From analysis of the 5-min series it can be deduced that for 1.454% of the mean annual time for which it rains, the precipitation presents a mean 5-min intensity exceeding 35 mm/h, and is responsible for 18.2% of the total annual precipitation. Between 1927 and 1981 some 8% of the episodes recorded on the Jardí pluviograph exceeded at some time the threshold of 35 mm/h, i.e. they present values of $\beta^* > 0$, providing 36.5% of total annual precipitation. The largest number of events occurs in autumn, with a mean value of 12 episodes; the largest percentage of the total nevertheless occurs in August, with just over 18%, providing 64% of the total precipitation. With the exception of autumn, these are episodes with a duration of less than 4 h, and become shorter with increasing intensity.

It is thus possible to draw up a classification of the rainfall events in the light of their greater or lesser convective character. It can be noted that the strongly convective episodes ($0.75 < \beta^* \leq 1.0$) last less than 1 h, while the slightly convective ones ($0 < \beta^* \leq 0.25$) last for longer than that time threshold. The duration of the moderately convective episodes ($0.25 < \beta^* \leq 0.75$) increases throughout the year from winter to autumn, when they can last some 5 h. This threshold, however, is only exceeded by the slightly convective episodes. In the West Mediterranean Area, while catastrophic rainfall episodes and floods are usually linked with moderately convective episodes of long duration (Llasat, 1997; Llasat *et al*., 1999; Doswell *et al*., 2001), local flash-floods are usually related with strongly convective events produced in summer or in early autumn.

With a view to future modelling of the IDF curves, it is important to note that although the very convective episodes generally last less than 1 h, a high percentage of the non-convective episodes also lies within this time interval. It is therefore advisable first to classify the events making up the pluviometric series and then construct the IDF curves for each class, since the properties of these different kinds of episodes are not the same. Similarly, any rainfall episode lasting more than 5 h is non-convective or slightly convective in nature, and this threshold can be reduced where related strictly to certain parts of the year.

Regarding the dominant meteorological situations for each type of episode, it is difficult to lay down features common to all of them, except for the situations inherent to extraordinary rainfall episodes (Llasat and Puigcerver, 1994; Ramis *et al*., 1994). However, some previous results of the spatial distribution of β^* in terms of the 5-min rainfall rate for a 125 rain gauges distributed in the Internal Basins of Catalonia (approximately 17000 km^2) shows the possibility of drawing up synoptic meteorological configurations for each interval of β^* (Llasat *et al*., 2000). Similarly, work has begun on application of the methodology proposed herein to other series in the Mediterranean area, mainly those showing good correlation with the Barcelona series (Llasat and Rodriguez, 1997). In order to improve Figure 12 research about the damage caused by historical heavy rainfall events has been started within the framework of the SPHERE European project.

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REFERENCES

Browing KA, Ludlam FH. 1962. Airflow in convective storms. *Quarterley Journal of the Royal Meteorological Society* **88**: 117–135.

Burgueño A. 1986. Distribución de la intensidad de la lluvia y de su duración en Barcelona. Memoria para optar al grado de Doctor en Ciencias Físicas, Universidad de Barcelona.

Burgueño A, Vilar E, Puigcerver M. 1993. Estadístiques de la intensitat de pluja a Barcelona amb aplicació a les telecomunicacions. Llibre homenatge al Dr. Jardí; 41–61.
Byers HR, Braham RR. 1949. *The Thunderstorm. Report of the Thunderstorm Project*. United States Department of Commerce: Washington, DC.
Doswell CHA III. 1993. Flash flood-producing convective storms: current understanding and research. Report of the Proceedings of the US–Spain Workshop on Natural Hazards; 97–107.
Doswell Ch A III, Brooks HE, Maddox RA. 1996. Flash flood forecasting: an ingredients based methodology. *Weather and Forecasting* **11**: 560–581.
Doswell ChA III, Ramis C, Romero R, Alonso S. 2001. A diagnostic study of three heavy precipitation episodes in the western Mediterranean region. *Weather and Forecasting* **13**: 102–124.
Dougherty HT, Dutton EJ. 1978. Estimating year-to-year variability of rainfall for microwave applications. *IEEE Transactions on Communications COM-26* **8**: 1321–1324.
Dutton EJ, Dougherty HT. 1979. Year-to-year variability of rainfall for microwave applications in the USA. *IEEE Transactions on Communications COM-27* **5**: 829–832.
Dutton EJ, Dougherty HT, Martin RF Jr. 1974. Prediction of rainfall and link performance coefficients at 8 to 30 GHz. Inst for Telecomm. Sciences. Off. of Telecom. US Dep. of Comm. Rept. N° AD/A-000 804.
Fujita TT. 1985. Mesoscale classifications: Their history and their application to forecasting. In *Mesoscale Meteorology and Forecasting*, Ray PS (ed.). American Meteorological Society: Boston; 18–35.
Houghton HG. 1950. A preliminary quantitative analysis of precipitation mechanisms. *Journal of Meteorology* **7**: 363–369.
Houghton HG. 1968. On precipitation mechanisms and their artificial modification. *Journal of Applied Meteorology* **7**: 851–859.
Houze RA Jr. 1993. *Cloud Dynamics*. Academic Press: New York.
Houze RA Jr. 1997. Stratiform precipitation in regions of convection: a meteorological paradox? *Bulletin of the American Meteorological Society* **78**: 2179–2196.
Huschke RE. 1959. *Glossary of Meteorology*. American Meteorological Society: Boston.
Jardí R. 1921. Un pluviògraf dintensitats. *Notes dEstudi*, *Servei Meteorològic de Catalunya* **I**: 3–10.
Llasat MC. 1997. Meteorological conditions of heavy rains. FRIEND Projects H-5-5 and 1.1, UNESCO; 269–276.
Llasat MC, Puigcerver M. 1985. Un intento de aplication a la Península Ibérica de un modelo empírico de precipitation. *Revista de Geofísica* **41**: 135–144.
Llasat MC, Puigcerver M. 1994. Meteorological factors associated with floods in the north-eastern part of the Iberian Peninsula. *Natural Hazards* **9**: 81–93.
Llasat MC, Puigcerver M. 1997. Total rainfall and convective rainfall in Catalonia, Spain. *International Journal of Climatology* **17**: 1683–1695.
Llasat MC, Ramis C, y Lanza L. 1999. Storm tracking and monitoring using objective synoptic diagnosis and cluster identification from infrared meteosat imagery: a case study. *Meteorology and Atmospheric Physics* **71**: 139–155.
Llasat MC, Rigo T, Montes JM. 2000. Orographic role in the temporal and spatial distribution of precipitation. The case of the Internal Basins of Catalonia (Spain). In *Proceedings of the EGS Plinius Conference on Mediterranean Storms*, Maratea, Italy. October 1999; 41–56.
Llasat MC, Rodriguez R. 1997. Towards a regionalization of extreme rainfall events in the Mediterranean area. FRIEND97-Regional hydrology: concepts and models for sustainable water resource management. *IAHS Publications* **246**: 215–222.
Lorente J, Redaño A. 1991. Relation between maximal rainfall rates for different time intervals in the course of a storm. *Atmospheric Research* **27**: 561–566.
Puigcerver M, Alonso S, Lorente J, Llasat MC, Redaño A, Burgueño A, Vilar E. 1986. Preliminary aspects of rainfall rates in the north east of Spain. *Theoretical and Applied Climatology* **37**: 97–109.
Ramis C, Llasat MC, Genovés A, y Jansà A. 1994. The October-87 floods in Catalonia. Synoptic and mesoscale mechanisms. *Meteorological Applications* **1**: 337–350.
Rice PL, Holmberg NR. 1973. Cumulative time statistics of surface-point rainfall rates. *IEEE Transactions on Communications COM-21* **10**: 1131–1136.
Riosalido R, Ferraz J, Alvarez E, Cansado A, Martín F, Elízaga F, Camacho JL, Martín A. 1997. A flash flood event in the Spanish Pyrenees: the Biescas case. In *INM/WMO International Symposium on cyclones and hazardous weather in the Mediterranean*, Palma de Mallorca. April 1997; 151–158.
Rodriguez R, Llasat MC, Wheeler D. 1999. Analysis of the Barcelona precipitation series 1850–1991. *International Journal of Climatology* **19**: 787–801.
Steiner M, Houze RA Jr, Yuter S. 1995. Climatological characterization of three-dimensional storm structure from operational radar and rain gauge data. *Journal of Applied Meteorology* **34**: 1978–2006.
Ven Te Chow. 1988. *Applied Hydrology*. McGraw-Hill: Austin, TX.
Vilar E, Burgueño A. 1991. Analysis and modelling of time intervals between rain rate exceedances in the context of fade dynamics. *IEEE Transactions on Communications* **39**: 1306–1312.
Watson PA, Gunes M, Potter BA, Sathiaseelan V, Leitas DJ. 1982. Development of a climatic map of rainfall attenuation for Europe. Final Report of the European Space Agency, ESTEC CONTR. No. 4162/79/NL. Postgraduate School of Electrical and Electronic Engineering, University of Bradford, UK.

