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Estimation of the probable maximum precipitation in Barcelona (Spain)

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ABSTRACT: The main objective of this study is to estimate the probable maximum precipitation (PMP) in Barcelona for durations ranging from 5 min to 30 h. To this end, rain records from the Jardí gauge of the Fabra Observatory located in Barcelona (1927–1992) and the urban pluviometric network supported by Clavegueram de Barcelona, S.A. (CLABSA, 1994–2007) were analysed. Two different techniques were used and compared: a physical method based on the maximization of actual storms, and the Hershfield' statistical method. The PMP values obtained using the two techniques are very similar. In both cases, the expected increasing behaviour of the PMP with duration was found, with the increase especially notable for the mesoscale durations 2–9 h, and not significant from 12 h on up. This result seems to be related to the scale of the meteorological situations producing high intense rainfall amounts over our territory. Copyright © 2010 Royal Meteorological Society

KEY WORDS probable maximum precipitation; statistical analysis; storm maximization

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1. Probable maximum precipitation: conceptual definition and estimation methods

Probable maximum precipitation (PMP) is defined as '*the greatest depth of precipitation for a given duration meteorologically possible for a given size storm area at a particular location at a particular time of year, with no allowance made for long-term climatic trends*' (WMO, 1986). Hydrologists use the PMP magnitude and its spatial and temporal distributions to calculate the probable maximum flood (PMF), which is one of several conceptual flood events used in the design of hydrological structures, for maximum reliability and safety. Typically, PMF is estimated for the catchment area of a dam in order to design a spillway to minimize the risk of overtopping.

Procedures for determining the PMP are admittedly inexact: results are estimates and a risk statement has to be assigned to them. Quoting Koutsoyiannis (1999), the PMP approach 'by no means implies zero risk in reality'. The National Research Council (1994) estimates the return period of the PMP in the USA as between 10^5 and 10^9 years. Koutsoyiannis (1999) developed a method for assigning a return period to PMP values obtained using the frequency factor method (Hershfield, 1961, 1965). A similar study (Papalexiou and Koutsoyiannis, 2006) performed on PMP estimates obtained from the moisture maximization method results in a small, although not negligible, exceedence probability.

To estimate the PMP in a place a variety of procedures based on the location of the project basin, availability of data and other considerations have been proposed (e.g. Wiesner, 1970; Schreiner and Reidel, 1978; WMO, 1986; Collier and Hardaker, 1996). Most of them are based on meteorological analysis, whereas some are based on statistical analysis. Probably the most frequent physical method is the maximization and transposition of actual storms. This method involves the classification of storms by calculating the storm efficiency, E, which is defined as the ratio of maximum observed rainfall, P, to the amount of precipitable water, PW, in the representative air column during the storm (NERC, 1975). If no vertical soundings are available, it is assumed that the air mass in the storm is saturated and the vertical humidity profile is represented by the dew point temperature at the surface following the saturated pseudo-adiabatic lapse rate. Using the moisture maximization method, the PMP is calculated by multiplying the storm efficiency by the maximized precipitable water, MPW, estimated by the climatological maximum dew point of the corresponding month at the surface located at the site of interest. This maximum dew point can be estimated as the maximum historical value from a sample of at least 50 years length, or as the 100-year return period value for samples shorter than 50 years (WMO, 1986). Among the statistical methods for estimating the PMP, the most widely used is the method of Hershfield (1961), based on the frequency

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analysis of the annual maximum rainfall data registered at the site of interest.

To estimate the PMP over Barcelona for durations from 5 min to 30 h, we applied the moisture maximization method as well as the Hershfield' statistical method to rain records from the Jardí gauge of the Fabra Observatory located in Barcelona (1927–1992) and the urban pluviometric network supported by Clavegueram de Barcelona, S.A. (CLABSA, 1994–2007).

2. Estimation of the PMP in Barcelona: physical approach

Several storms registered in Barcelona during the period of study were selected for maximization. From data recorded by the Jardí gauge (1927–1992), the 44 rain events classified by Casas *et al*. (2004) according to their meteorological scale were considered. These events presented a return period longer than 5 years for some of the durations considered, which ranged from 5 min to 30 h. The same consideration was taken into account by Casas *et al*. (2010) to select 11 extreme storms from rainfall registered by the Barcelona urban network between 1994 and 2001. Therefore, a total of 55 severe storms were considered to be maximized. For each of these storms, and for every duration t, the efficiency $E(t)$ as $P(t)/PW$ was calculated. Figure 1 shows the efficiencies obtained for 30 min and 24 h. Since, in the region studied, local storms are predominant in summer and at the beginning of autumn, the highest efficiencies are observed at this time of year for short durations ($t < 1$ h). For longer durations, the highest values are observed at the end of autumn and the beginning of winter, and are related to extreme rainfall events caused by medium and large scale meteorological processes acting together, as mesoscale convective systems embedded in synoptic formations.

To estimate the maximized precipitable water MPW for the selected storms, the climatological maximum dew point of the corresponding month in Barcelona had to be found. A 50-year long sample (1955–2005) of four daily measurements of the dry- and wet-bulb temperatures recorded at the Fabra Observatory in Barcelona was available. From this sample, the maximum 12-h persistent dew temperature was calculated for 10-day intervals throughout the year, i.e. three maximum values for every month (Figure 2). Using these values, the MPW was estimated for every storm, thus obtaining its maximization. The PMP for every duration t can then be calculated by Equation (1):

$$\mathrm{PMP}(t) = \mathrm{MPW} \times \mathrm{E}(t) \qquad (1)$$

For every duration, the maximum value from all those calculated for each of the 55 maximized severe storms using (1) was considered as the PMP. Table I shows the estimated storm efficiencies and PMP values.

The estimated values of the PMP in Barcelona using this technique are shown in Figure 3 for several durations that range from 5 min to 30 h. As expected, the PMP values increase with duration. The increasing rate is especially notable for the interval from 2 to 9 h, corresponding to mesoscale durations. From 12 h on up, the PMP does not increase significantly. This result seems to be related to the scale of the meteorological situations that produce high intense rainfall amounts over the territory. The PMP values obtained correspond to four particular storms from the 55 rainfall events considered, which contribute to different durations. The local storm on 9 October 2001 (091 001) provided the value of the PMP for 5 min. The rain event that occurred on 13 September 1952 (130 952) contributed to the 20- and 25-min PMP values, whereas that occurred on 21 September 1995 (210 995) provided the PMP values for 10 and 15 min and for the interval from 30 to 55 min. In both cases, the synoptic situation was favourable for the formation of a mesoscale convective system that produced

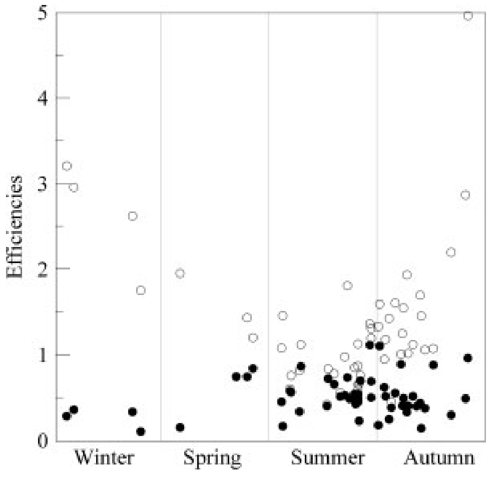

Figure 1. Efficiencies corresponding to 55 severe storms recorded in Barcelona (1927–2001), for 30 min (black circles) and 24 h (white circles).

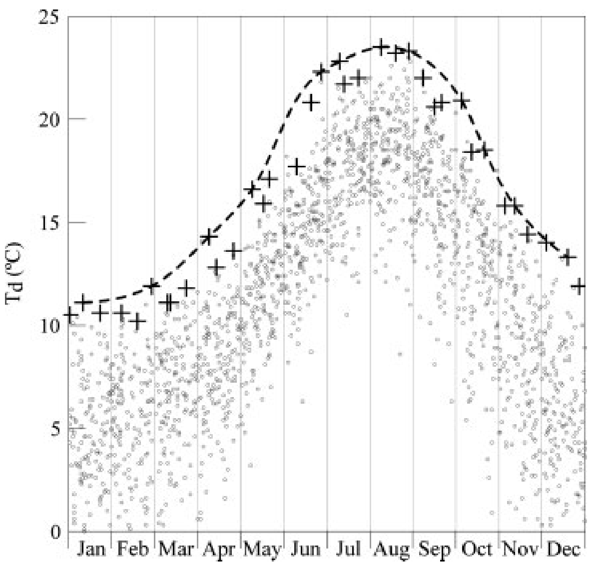

Figure 2. Twelve-hour persistent dew temperature in Barcelona (1955–2005). The maximum values observed for 10-day intervals throughout the year have been remarked (bold crosses).

Table I. Storm efficiency E(t) and PMP values for every duration t, estimated using the physical approach.

t (min)	5	10	15	20	25	30	35	40	45	50	55	60
E(t)	0.41	0.57	0.78	0.93	1.07	1.12	1.18	1.22	1.26	1.28	1.37	1.46
PMP (mm)	37	54	75	86	99	104	111	116	119	121	122	128
t (min)	120	240	360	540	720	840	960	1080	1200	1320	1440	1800
	2.66	3.93	4.46	4.84	4.87	4.87	4.87	4.89	4.92	4.93	4.96	5.03
PMP (mm)	178	264	300	326	327	327	327	329	330	331	333	338

intense precipitation. In the wide range from 1 to 30 h, the PMP values are provided by one single rain event that occurred on 5 and 6 December 1971 (051 271). In this case, a cut-off low system was located over the Iberian Peninsula, whereas an intense high pressure system centered over Europe was blocking its eastward and North-eastward motion. The synoptic situation therefore had a very slow time evolution, which favoured the formation of mesoscale convective systems and extreme rainfall over the Eastern coast of the Iberian Peninsula with medium and long duration.

3. Estimation of the PMP in Barcelona: statistical approach

The Hershfield technique for estimating the PMP is based on Chow's (1951) general frequency equation:

$$\mathrm{PMP} = \overline{X}_n + k_m\ \sigma_n \tag{2}$$

and

$$k_m = \frac{X_M - \overline{X}_{n-1}}{\sigma_{n-1}} \tag{3}$$

where: x_M, $\overline{X}_n$ and σ_n are the highest, mean and standard deviation for a series of n annual maximum rainfall values of a given duration; $\overline{X}_n$ and σ_{n-1} are the mean and standard deviation, respectively, for this series excluding the highest value from the series; and k_m is a frequency factor. To evaluate this factor, initially

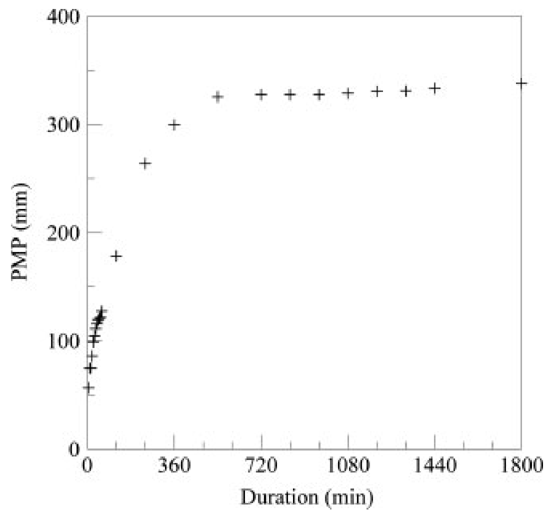

Figure 3. PMP values in Barcelona calculated using the physical approach, for durations from 5 min to 30 h.

Hershfield (1961) analysed 2645 stations (90% in the USA) and found an observed maximum value of 15 for k_m, and so he recommended this value to estimate the PMP using Equation (2). Later, Hershfield (1965) found that the value 15 was too high for rainy areas and too low for arid areas. Furthermore, it was too high for rain durations shorter than 24 h, so he constructed an empirical nomograph (WMO, 1986) with k_m varying between 5 and 20 depending on the rainfall duration and the mean $\overline{X}_n$. Koutsoyiannis (1999) fitted a generalized extreme value (GEV) distribution to the frequency factors obtained from the 2645 stations used by Hershfield and found that the highest value 15 corresponds to a 60 000-year return period, at the low end of the range considered by the NRC (1994).

In a previous work (Casas *et al.*, 2008), the 1-day PMP values at 145 locations in Catalonia, NE Spain, were estimated using a statistical approach. From their annual maximum daily rainfall series, and following Hershfield's procedure (Hershfield, 1961, 1965), different statistical parameters including frequency factors, k_m, were calculated. Based on the 145 stations, the k_m values were plotted against the mean $\overline{X}_n$, to consider an appropriate enveloping curve that would give reliable estimates of 1-day PMP for Catalonia (Rakhecha *et al.*, 1992). One of the 145 stations used was Barcelona, with a 55-year annual maximum daily rainfall series. The equation that corresponds to the enveloping curve ($k_m = -7.56\ \ln\ \overline{X}_n + 40.5$) assigned a frequency factor of $k_m = 9.1$ to the Barcelona daily rainfall mean value of 63.6 mm, resulting in an estimated 1-day PMP of 357 mm for this station. Notice that the PMP value for 24 h obtained in Section 2 by applying the physical approach is 333 mm (Figure 3).

From the annual maximum rainfall series recorded by the Jardí gauge and the urban pluviometric network, a new statistical estimation of the PMP in Barcelona has been carried out.

3.1. Statistical analysis using annual maximum rainfall series recorded by the Jardí gauge

The 66-year annual series of true maximum rainfall amounts for durations between 5 min and 30 h obtained by Casas *et al.* (2004) from the Jardí records (1927–1992) was used. These are true maxima because the amounts were calculated using unrestricted time intervals for any particular observation time, instead of the usual fixed intervals between a beginning and an ending time. Table II shows the statistical parameters and the

Table II. Mean $\overline{x}_n$, coefficient of variation CV, maximum value x_M and observed frequency factor k_m of the Jardí annual maximum rainfall series for durations t from 5 min to 30 h.

t (min)	$\overline{X}_n$ (mm)	CV	x_M (mm)	k_m
5	11.9	0.32	21.6	2.8
10	18.2	0.33	34.4	2.9
15	23.1	0.33	42.0	2.7
20	26.0	0.35	47.5	2.5
25	29.0	0.37	54.7	2.5
30	31.0	0.38	57.2	2.3
35	32.5	0.37	58.2	2.2
40	33.8	0.37	59.6	2.1
45	35.0	0.37	64.2	2.3
50	35.6	0.38	70.6	2.7
55	36.3	0.38	72.1	2.7
60	37.1	0.39	72.6	2.6
65	37.9	0.39	73.1	2.5
70	38.5	0.39	73.5	2.5
75	39.7	0.39	76.2	2.5
120	44.0	0.45	108.0	3.5
240	49.9	0.50	159.7	5.2
360	53.7	0.48	181.3	6.3
540	57.7	0.48	197.1	6.6
720	60.5	0.47	198.3	6.1
840	62.8	0.47	198.3	5.7
960	64.5	0.47	198.3	5.4
1080	66.0	0.46	199.0	5.2
1200	67.7	0.47	200.2	5.0
1320	68.6	0.46	200.4	4.9
1440	69.5	0.46	201.8	4.8
1800	72.0	0.47	204.5	4.5

observed frequency factors for all the durations considered.

The mean value of the annual maximum rainfall in 24 h is 69.5 mm (Table I). This true rainfall value is slightly higher than the mean value calculated by Casas *et al*. (2008) using fixed daily intervals. In fact, the WMO (1986) recommends a multiplicative factor of 1.13 for annual maximum rainfall amounts registered in a single fixed time interval to yield values closely approximating those obtained from analysis based on true maxima. To compare these values with those calculated by Casas *et al*. (2008), this factor has to be considered. The mean true value of 69.5 mm in 24 h approximately corresponds to 61.5 mm for a 24-h fixed interval. The enveloping curve obtained by Casas *et al*. (2008) assigns a frequency factor of 9.4 to this mean value: higher than any of the observed frequency factors, which vary from 2.1 to 6.6 (Table II; Figure 4). The highest frequency factors were found for durations between 6 and 12 h, presenting a maximum of 6.6 for approximately 9 h. As in Section 2, this result seems to be related to the meteorological scale of the most severe rain events recorded in the region, which are generally related to some of the following mechanisms: deep convection, very active fronts, orographic uplift, mesoscale convective systems and very often, the presence of a low-level cyclonic centre (Jansà *et al*., 2001). All these meteorological features, which produce precipitation with a very high efficiency, are typically included in the β-mesoscale with characteristic durations that range from 2 to 10 h. As the purpose of this work is to obtain PMP, the maximum value of 9.4 was considered as a maximized frequency factor for any duration. In fact, for the same location, the frequency factor, k_m, for an established return period is not expected to depend on the duration (Koutsoyiannis, 1999). Using Equation (2), the PMP for every duration was calculated (Table III; Figure 5). The PMP(t) values were fitted by the empirical function (3) with a regression coefficient of 0.997:

$$\mathrm{PMP}(t) = 60.5 \ \ln \ t - 67.7 \tag{3}$$

in which t is the duration in min and the PMP is in millimetres.

The 66-year true maximum rainfall annual series was fitted by the Gumbel distribution, using the L-moments method. According to the fitting distribution functions, the PMP values obtained show return periods of between 150 000 and 900 000 years, at the low end of the range estimated for the PMP by the NRC (1994); between

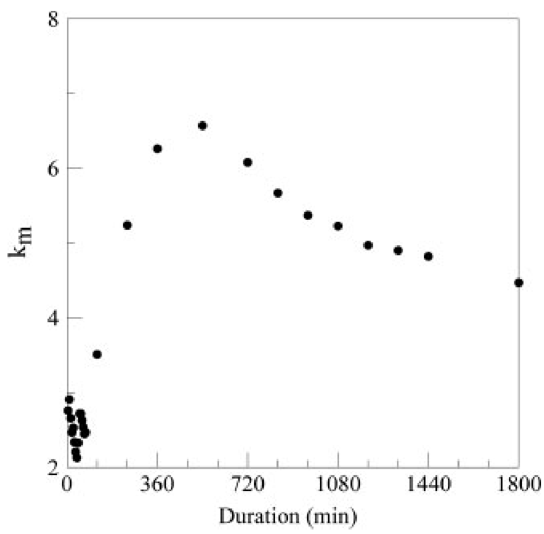

Figure 4. Observed frequency factor k_m of the Jardí annual maximum rainfall series, for every duration.

Table III. PMP values in Barcelona for every considered duration t in minutes, estimated from the Jardí gauge records.

t (min)	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75
PMP (mm)	47	74	94	112	130	141	146	152	158	164	167	171	175	179	186
t (min)	120	240	360	540	720	840	960	1080	1200	1320	1440	1800			
PMP (mm)	231	285	297	315	328	338	346	352	363	365	371	392			

10^5 and 10^9 years. Figure 6 shows the fit corresponding to the series of true maximum rainfall in 24 h, with 360 000 years the return period assigned by the Gumbel distribution to the value of 371 mm obtained for the PMP in 24 h (Table III).

3.2. Statistical analysis using annual maximum rainfall series recorded by the urban pluviometric network of Barcelona

The statistical technique of estimating the PMP was also applied to the maximum precipitation annual series recorded by the pluviometric network managed by CLABSA in Barcelona from 1994 to 2007 (23 tipping-bucket gauges working in a urban area of 100 km^2 approximately), for durations from 5 min to 30 h. The enveloping curve (Casas *et al*., 2008) assigns a frequency factor of 9.9 to the precipitation of 57.1 mm, which is the mean of the series corresponding to 24 h. Considering this frequency factor for all durations and using Equation (2), the PMP values were calculated (Table IV; Figure 7). These PMP values are lower than those calculated from the Jardí series, especially in the range 4–12 h, probably because for the CLABSA series the number of years available is small (14 years), and the mesoscale storms that usually cause the highest rain intensities over the region are not correctly represented.

Using both the physical and statistical approaches, the PMP estimates obtained are very similar for all durations. Even though for large synoptic durations (16–30 h) the statistical method provided PMP values that are slightly higher than the physical approach, all the estimates differ by less than 10%. For 24 h, all the PMP values estimated range from 333 to 371 mm.

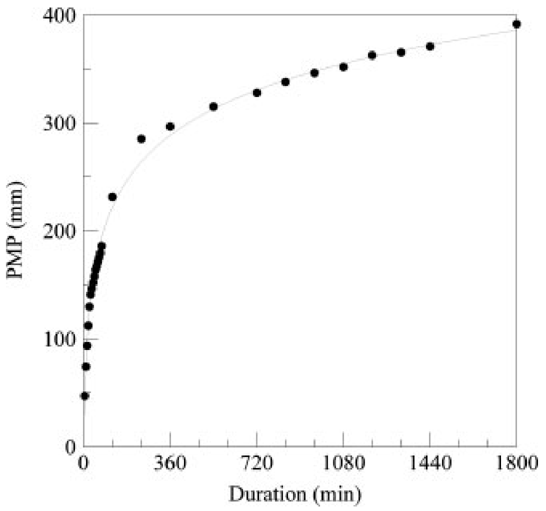

Figure 5. PMP values in Barcelona for durations from 5 min to 30 h, estimated from the Jardí gauge records using the statistical approach. These values have been fitted by the empirical function (3).

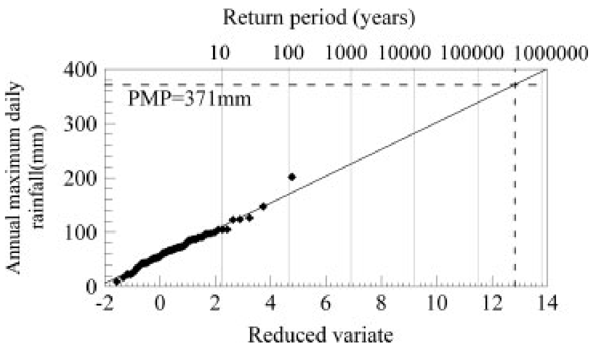

Figure 6. Gumbel frequency distribution corresponding to the maximum precipitation in the 24-h Jardí series. The return period assigned to the PMP value of 371 mm is 360 000 years.

4. Conclusions

The efficiency of 55 severe storms registered in the urban area of Barcelona has been calculated for several durations in the considered range. For durations shorter than 1 h, the highest efficiencies are observed in summer and at the beginning of autumn, when local storms are predominant. For 12 and 24 h, the highest values are observed at the end of autumn and the beginning

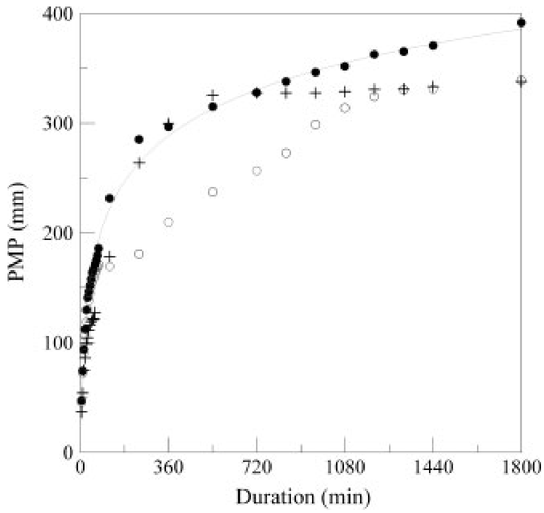

Figure 7. PMP values in Barcelona for durations from 5 min to 30 h, estimated from the urban pluviometric network records (white circles) and the Jardí gauge records (black circles) using the statistical approach, and from the Jardí and CLABSA records using the physical approach (crosses).

Table IV. PMP values in Barcelona for every considered duration t in minutes, estimated from the urban pluviometric network records.

t (min)	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75
PMP (mm)	54	74	91	102	118	130	138	144	153	160	162	169	174	181	183
t (min)	120	240	360	540	720	840	960	1080	1200	1320	1440	1800			
PMP (mm)	206	217	243	261	276	298	314	323	329	334	336	340			

of winter, related to extreme rainfall events caused by medium- and large-scale meteorological processes acting together, as mesoscale convective systems embedded in synoptic formations.

The maximum 12-h persistent dew temperature in Barcelona was calculated for 10-day intervals throughout the year, i.e. three maximum values for each month. The maximum precipitable water corresponding to the 55 severe storms considered was also calculated, and their maximization obtained.

Both physical and statistical approaches were applied satisfactorily to obtain the PMP in Barcelona for several durations ranging from 5 min to 30 h, with very similar results. As expected, an increasing behaviour of the PMP with duration was found in both cases. However, the rate of increase is especially notable for the interval 2–9 h, corresponding to the mesoscale durations, whereas the PMP does not increase significantly from 12 h on up. This result seems to be related to the scale of the meteorological situations that produce high intense rainfall amounts over our territory. Even though for long synoptic durations the statistical technique yields PMP estimates that are slightly higher than those calculated using the physical approach, all the estimates differ by less than 10%. Particularly for 24 h, all the PMP values estimated range from 333 to 371 mm.

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