The Estimation of Probable Maximum Precipitation

The Case of Catalonia

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A brief overview of the different techniques used to estimate the probable maximum precipitation (PMP) is presented. As a particular case, the 1-day PMP over Catalonia has been calculated and mapped with a high spatial resolution. For this purpose, the annual maximum daily rainfall series from 145 pluviometric stations of the Instituto Nacional de Meteorología (Spanish Weather Service) in Catalonia have been analyzed. In order to obtain values of PMP, an enveloping frequency factor curve based on the actual rainfall data of stations in the region has been developed. This enveloping curve has been used to estimate 1-day PMP values of all the 145 stations. Applying the Cressman method, the spatial analysis of these values has been achieved. Monthly precipitation climatological data, obtained from the application of Geographic Information Systems techniques, have been used as the initial field for the analysis. The 1-day PMP at 1 km^2 spatial resolution over Catalonia has been objectively determined, varying from 200 to 550 mm. Structures with wavelength longer than approximately 35 km can be identified and, despite their general concordance, the obtained 1-day PMP spatial distribution shows remarkable differences compared to the annual mean precipitation arrangement over Catalonia.

Key words: **probable maximum precipitation; spatial rainfall distribution; objective analysis**

Conceptual Definition of Probable Maximum Precipitation

Probable maximum precipitation (PMP) has been defined as "the greatest depth of precipitation for a given duration meteorologically possible for a given size storm area at a particular time of year, with no allowance made for long-term climatic trends."[1] Hydrologists use the PMP magnitude and its spatial and temporal distributions to estimate the probable maximum flood (PMF), which is one of a range of conceptual flood events used in the design of hydrologic structures for maximum reliability and safety. Typically, PMF is estimated for a dam catchment in order to design a spillway to minimize the risk of overflowing.

Prior to the 1950s, the concept of an upper limit to precipitation potential was known as maximum possible precipitation. The name was changed to PMP, reflecting the uncertainty surrounding any estimate of maximum precipitation.[2] Quoting Benson,[3] "The 'probable maximum' concept began as 'maximum possible' because it was considered that maximum limits exist for all the elements that act together to produce rainfall, and that these limits could be defined by a study of the natural

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Trends and Directions in Climate Research: Ann. N.Y. Acad. Sci. 1146: 291–302 (2008).
doi: 10.1196/annals.1446.003

process. This was found to be impossible to accomplish—basically because nature is not constrained to limits.” Procedures for determining PMP are admittedly imprecise, their results are estimates and a risk statement has to be assigned to them. The PMP approach “by no means implies zero risk in reality”.[4] The National Research Council[5] estimates the return period of the PMP in the United States as between 10^5 and 10^9 years. Koutsoyiannis[4] developed a method for assigning a return period to PMP values obtained using the frequency factor method.[6,7] A similar study[8] applied to PMP estimates obtained from the moisture maximization method results in a small, although not negligible, exceedance probability. The multifractal method also provides a framework to assign a risk of exceedance for the PMP[9] and to infer the magnitude of extreme precipitation consistent with engineering design criterion, the design probable maximum precipitation (DPMP).

Methods of Estimating PMP

To estimate the PMP in a place, a variety of procedures based on the location of the project basin, the availability of data, and other considerations have been proposed (e.g., see Refs. 1, 10–12). Most of them are based on meteorological analysis, while some are based on statistical analysis. PMP estimation techniques have been listed by Wiesner[10] as follows: (a) the storm model approach; (b) the maximization and transposition of actual storms; (c) the use of generalized data or maximized depth, duration, and area data from storms; these are derived from thunderstorms or general storms; (d) the use of empirical formulae determined from maximum depth duration and area data or from theory; (e) the use of empirical relationships between the variables in particular valleys (only if detailed data are available); and (f) statistical analyses of extreme rainfalls. These methods are not totally independent.

Probably the easiest way to estimate the theoretical upper limit for precipitation on a basin for a given duration is the use of empirical formulae [methods (d) and (e)] to represent local or world maximum precipitation values. Methods (b) and (c) involve the classification of storms by calculating the storm efficiency, which is defined as the ratio of maximum observed rainfall to the amount of precipitable water in the representative air column during the storm.[13] 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 multiplying the storm efficiency by the maximized precipitable water, 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.[1] The storm model approach [method (a)] seeks to represent the precipitation process in terms of modifications to the thermodynamics of the ascent of a single parcel of air, taking into account the storm dynamics mechanism and the orography.[14] In order to determine PMP by means of a storm model, the upper limits of moisture and wind are estimated. As an example, the physically based method formulated in the U.K. by Collier and Hardaker[12] objectively estimates the PMP on the basis of maximization of the physical factors involved in the production of very heavy convective rainfall as solar heating, orographic uplift, and mesoscale convergence. Input wind fields are required in order to correctly estimate the convergence term. Collier and Hardaker[12] suggested the use of the Doppler weather radar, if available, to measure the actual wind field. Other radar measurements can be very useful to estimate the total rainfall at the ground and the storm efficiency, which was found by Collier and Hardaker[12] to be a function of storm duration and storm type, as well as to estimate the precipitation area in order to calculate the area reduction factor and verify the precipitation model.[15,16]

Among the statistical methods to estimate the PMP (f), the most widely used is the method of Hershfield,[6] which is based on the frequency analysis of the annual maximum rainfall data registered at the site of interest. The Hershfield technique of estimating PMP is based on Chow's[17] general frequency equation:

$$\mathrm{PMP} = \bar{X}_n + k_m \sigma_n, \tag{1}$$

and

$$k_m = \frac{X_M - \bar{X}_{n-1}}{\sigma_{n-1}}, \tag{2}$$

where X_M, $\bar{X}_n$ and σ_n are the highest value, the mean, and the standard deviation, respectively, for a series of n annual maximum rainfall values of a given duration, $\bar{X}_{n-1}$ and σ_{n-1} are, respectively, the mean and the standard deviation for this series excluding the highest value from the series, and k_m is a frequency factor. To evaluate this factor, Hershfield initially[6] analyzed 2645 stations (90% in the United States) and found an observed maximum value of 15 for k_m, recommending this value to estimate the PMP using Equation (1). Later, Hershfield[7] found that the value 15 is too high for rainy areas and too low for arid areas, whereas it is too high for rain durations shorter than 24 h, so he constructed an empirical nomograph[1] with k_m varying between 5 and 20 depending on the rainfall duration and the mean $\bar{X}_n$. Koutsoyiannis[4] fit a generalized extreme value 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, which is at the low end of the range considered by the National Research Council.[5]

Douglas and Barros[9] have applied multifractal analysis techniques to systematically determine physically meaningful estimates of maximum precipitation from observations in the eastern United States. The multifractal approach provides a formal framework to infer the magnitude of extreme events, independently from empirical adjustments (named as fractal maximum precipitation[9]), as well as an objective estimated of the associated risk in order to infer the magnitude of extreme precipitation consistent with the engineering design criterion (the DPMP[9]).

The discussed methods of estimating PMP may be used either for individual basins or for large regions encompassing numerous basins of various sizes. In the latter case, the estimates are referred to as generalized or regional estimates.[1] The transposition of actual storms (b) is limited to regions with similar topographic features to those of the catchment where the storms were registered. The generalized methods involve a deterministic approach to increase the transposition area using all available data over a large region, including adjustments for moisture availability and differing topographic effects on rainfall depths. A method for developing generalized estimates of PMP is to define terrain profiles over the entire region of interest (as the optimum moisture inflow direction or slope orientation) and to evaluate PMP between them using maps, such as mean annual precipitation or precipitation-frequency maps, which adequately depict the geographic distribution or precipitation. Generalized estimates of PMP are usually presented on an index map showing isohyets of PMP for a particular duration, size of area, and month, which can be adjusted to other durations, basin sizes, and months.[1]

In our region, Catalonia, maximum annual daily rainfall series registered by 145 well-distributed pluviometric stations with variable length in the period 1911–2001 were available. Since the statistical technique has the advantage of taking into account actual precipitation data and its application is simple and fast, after considering our data resources, we decided to use it for the estimation of the 1-day PMP.

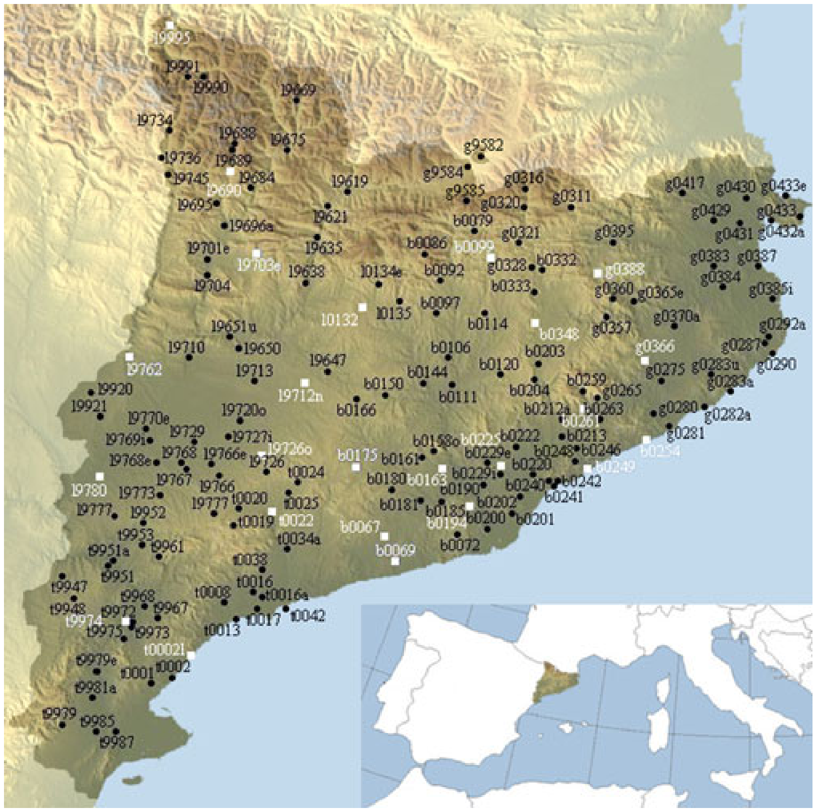

Figure 1. Pluviometric stations used in this study. Test stations in white. (In color in *Annals* online.)

The Case of Catalonia—Analysis of the Data

In order to estimate 1-day PMP over the Catalonian territory using the statistical approach, annual maximum daily rainfall series from 145 pluviometric stations of the Instituto Nacional de Meteorología (Spanish Weather Service) in Catalonia (Fig. 1) have been selected.[18] The criterion for selecting the series was based on their length and homogeneity. For this study, series shorter than 15 years or those that did not pass the homogeneity test of sequences with a significance level of 0.05 have been rejected. The selected stations (with variable length during the period 1911–2001) constitute a pluviometric network with a mean density of 0.45 stations per 100 km^2. If the pluviometric stations were uniformly distributed, the mean distance between them (r) could be calculated from the equation,[19]

$$r = \sqrt{A}\left[(1+\sqrt{n})/(n-1)\right], \qquad (3)$$

where A is the area where the n-pluviometers network is installed. As the Catalonian surface is close to $A = 32{,}000$ km^2 and $n = 145$, the mean distance r between pluviometric stations in our case is approximately 16 km.

Following Hershfield's procedure, statistical parameters $\bar{X}_n$, $\bar{X}_{n-1}$, σ_n, and σ_{n-1} have been calculated for each of the selected series, as well as the coefficient of variation $(\mathrm{CV}) = \sigma_n/\bar{X}_n$ and the frequency factors k_m using Equation (2). Since the frequency factor is the number of standard deviations σ_{n-1} to be added to the mean $\bar{X}_{n-1}$ to achieve the maximum X_M, its value is higher for series including an extraordinarily extreme rainfall event (or *outlier*).[20] The inclusion of an *outlier,* with a recurrence period much longer than the length of the series, could cause an anomalous effect in the calculated mean and standard deviation values.[6] One of the employed methods to compensate this effect consists in the analysis and adjustment of the CV of the annual maximum rainfall series.[21] When in a certain area the CV value for a station differs too much from neighboring stations within a range of 50 km (for example), it has to be adjusted to the nearest value from the neighboring stations. With the revised CV and the original mean value, the standard deviation value can be recalculated. In this work, only 4% of the stations had to be revised in order to modify an anomalous standard deviation value: La Pobla de Lillet (b0079), with a CV of 58% reduced to 40%; Cherta (t9979e), from 62% to 50%; Cornellà de Llobregat (b0200), from 56% to 45%; Cadaqués (g0433), from 90% to 75%; Vimbodí *Riudavella* (t0019), from 56% to 40%; and Puigcerdà (g9584), from 87% to 50%.

Based on the 145 stations, the highest value of k_m for the 1-day duration was found to be 8.7. Following Hershfield,[7] since the frequency factor varies inversely with the mean of the series, the k_m values of the 145 stations were plotted against $\bar{X}_n$ in order to consider an appropriate enveloping curve that would give reliable estimates of 1-day PMP rather than using the observed highest value.[21] Figure 2 shows the enveloped curve drawn with the help of four upper points relating to the stations of Puigcerdà (g9584, $k_m = 8.7$), La Pobla de Lillet (b0079, $k_m = 7.3$), Capdella (l9689, $k_m = 6.1$), and Cadaqués (g0433, $k_m = 5.1$), having maximum k_m versus $\bar{X}_n$ values shown in Figure 2 as thick dots. The equation fitted to these four points, represented as a dashed line in this figure, is:

$$k_m = -7.56 \ln \bar{X}_n + 40.2. \qquad (4)$$

To get the 145 points below the enveloping curve, a +0.3 value had to be added, resulting in the following equation:

$$k_m = -7.56 \ln \bar{X}_n + 40.5, \qquad (5)$$

represented as a solid line in Figure 2.

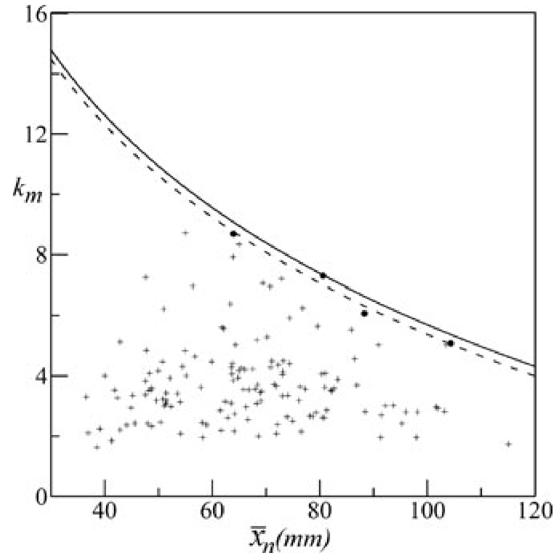

Figure 2. Enveloping frequency factor curve for Catalonia, fitted to the four upper ($\bar{X}_n$, k_m) points (thick dots).

This enveloping curve has been used to obtain maximized k_m values for the corresponding mean values of every station. From these calculated frequency factors, X_n and σ_n, the 1-day PMP value for every station has been calculated using Equation (1). The obtained PMP values have been adjusted to correct for the use of a fixed observational time interval of 24 h. The World Meteorological Association[1] recommends multiplying the results of a frequency analysis of annual maximum rainfall amounts for a single fixed time interval of 24 h by a factor of 1.13 to yield values closely approximating those based on true maxima.[6] More recent research resulted in a slightly higher value of this correcting factor (1.16) for daily rainfall in Catalonia[22] and a value of 1.167 in the U.K.[23] The corrected 1-day PMP values using Hershfield's factor 1.13 are shown in Table 1.

In order to determine the return period of the PMP values obtained, the data of the series has been fitted to the extreme-value type I distribution function (Gumbel).[24] Since some of the maximum rainfall annual series used are relatively short (15–20 years) and sometimes *outliers* have been observed, the use of the

TABLE 1. Estimated 1-Day PMP Values

Station	PMP (mm)	Station	PMP (mm)	Station	PMP (mm)	Station	PMP (mm)
b0072	307	b0332	291	l0135	292	l9921	192
b0079	357	b0333	262	l9619	305	l9952	251
b0086	331	g0265	403	l9621	350	l9990	265
b0092	305	g0275	481	l9638	246	l9991	319
b0097	245	g0281	344	l9647	269	t0001	428
b0106	242	g0282a	399	l9650	324	t0002	434
b0111	365	g0283a	415	l9651u	261	t0008	389
b0114	266	g0283u	431	l9669	245	t0013	394
b0120	282	g0287	404	l9675	228	t0016	304
b0144	271	g0290	412	l9684	214	t0016a	302
b0150	268	g0292a	443	l9688	393	t0017	316
b0158o	347	g0311	439	l9689	370	t0019	354
b0161	336	g0316	326	l9695	319	t0020	281
b0166	243	g0320	297	l9696a	268	t0024	277
b0180	309	g0321	328	l9701e	333	t0025	284
b0181	263	g0328	319	l9704	269	t0034a	238
b0185	291	g0357	398	l9710	253	t0038	280
b0190	299	g0360	383	l9713	235	t0042	296
b0200	380	g0365e	449	l9720o	226	t9947	324
b0201	357	g0370a	438	l9726	290	t9948	273
b0202	276	g0383	318	l9727i	230	t9951	300
b0203	349	g0384	386	l9729	297	t9951a	305
b0204	308	g0385i	290	l9734	307	t9953	345
b0212a	318	g0387	383	l9736	369	t9961	312
b0213	328	g0395	376	l9741	299	t9967	398
b0220	420	g0417	364	l9745	320	t9968	404
b0222	297	g0429	541	l9766	237	t9972	394
b0229e	392	g0430	400	l9766e	244	t9973	354
b0229i	391	g0431	511	l9767	329	t9975	389
b0240	343	g0432a	375	l9768	284	t9979	333
b0241	321	g0433	567	l9768e	198	t9979e	416
b0242	345	g0433e	537	l9769i	210	t9981a	396
b0246	346	g9582	245	l9770e	312	t9985	409
b0248	361	g9584	386	l9772	290	t9987	339
b0259	347	g9585	286	l9773	229		
b0263	478	g9635	291	l9777	204		
b0280	379	l0134e	320	l9920	181		

traditional fitting method with the conventional moments mean and standard deviation could result in return periods shorter than the ones corresponding to a longer sample containing a larger number of years. In order to minimize this effect, the L-moments fitting method has been used.[24,25] This method was preferred because of its robustness, i.e., because unlike other methods, it does not overemphasize an occasional extreme event as it does not involve squaring of the data. For the same reason, the use of the L moments also acts to reduce the effect of the variability of the sample, giving a more certain parameters estimation in the case of short series.[26]

According to the Gumbel functions fitted, 90% of the obtained PMP values show a return period between 10^4 and 10^8 years. Specifically, the estimated 1-day PMP for the station b0201 corresponding to the Barcelona center

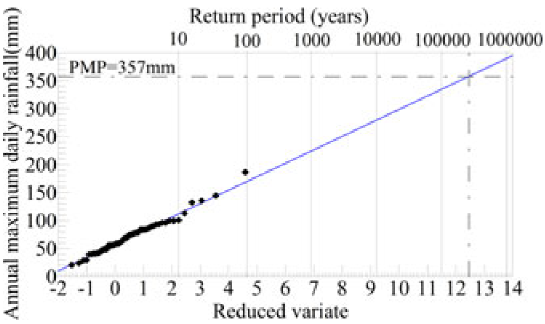

Figure 3. Annual maximum precipitation in 24 h registered in the center of Barcelona (b0201, 1931–1985), fitted by a Gumbel distribution using the L-moments method. The 1-day PMP value of 357 mm estimated for Barcelona corresponds to a 250,000-year return period. (In color in *Annals* online.)

is 357 mm (Table 1) with a return period of 250,000 years (according to the Gumbel function fitted to its 55 annual maximum rainfall data using the L moments) (Fig. 3).

Applying the objective analysis shown in the next section, the calculated PMP amounts for the 145 stations have been used to estimate the 1-day PMP at any other point of Catalonia and to obtain the 1-day PMP distribution map.

Spatial Analysis of the 1-day PMP over Catalonia

The objective spatial analysis of the 1-day PMP over Catalonia has been carried out using the Cressman method.[27,28] This technique consists of the recurrent application of a calculation algorithm as follows,

$$X^{a(k+1)} = X^{a(k)} + \sum h_j \left(X_j^o - X_j^{a(k)}\right), \quad (6)$$

$X^{a(k+1)}$ being the analyzed value at the grid points in the $k+1$ iteration step, $X^{a(k)}$ is the calculated value in the former k step, while h_j represents the weights used to weight differences between the analyzed values ($X_j^{a(k)}$) at points where pluviometric stations are located and observed data at these stations (X_j^o). Applying the Cressman method, weights are calculated by

$$h_j = \begin{cases} \frac{R^2-d^2}{R^2-d^2}, & d \leq R \\ 0, & d > R \end{cases}, \quad (7)$$

where d is the distance between the j observatory (or pluviometric station in our case) and the grid point where the analyzed field has been calculated. R is the radius of influence, which determines the size of the circle containing the observations that influence the analysis at the grid point. This area of influence has to be chosen depending on the kind of the meteorological variable to be analyzed and the characteristics of the terrain where the analysis is being done. The radius of influence R can vary in every iteration step and is usually reduced on each successive scan in order to build smaller scale information into the analysis where the data density supports this.

The analysis corresponding to the first step of the iterative process, $X^{a(0)}$, can be established following the same procedure used in a previous paper to determine the maximum daily precipitation in Catalonia for several return periods.[29] The maximum daily rainfall with 100,000-year return period at every point of a 1-km × 1-km grid covering Catalonia has been considered as the initial field for the analysis. To estimate these maximum daily rainfall amounts, the mean monthly precipitation corresponding to the rainiest month at every grid point has been determined first, using the multiple regression with residual correction interpolation method employed by Ninyerola *et al.*[30] This methodology of climatic interpolation uses Geographic Information Systems techniques applied to geographical variables as altitude (calculated using a digital elevation model with 180 m of resolution), latitude, continentality, solar radiation, and cloudiness, as well as the meteorological stations data. The obtained mean monthly precipitation map shows a high level of detail and differentiated structures with a very short wavelength compared to the station density of the network, which is a consequence of the high resolution of the determined grid (1 km × 1 km).

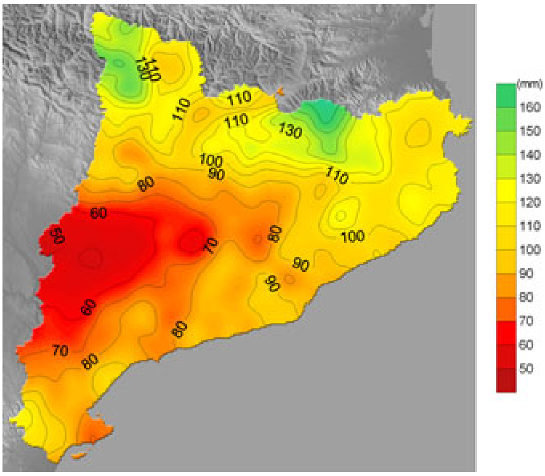

Figure 4. Smoothed map showing mean monthly precipitation of the rainiest month obtained using the multiple regression analysis results of Ninyerola *et al.*[30] (In color in *Annals* online.)

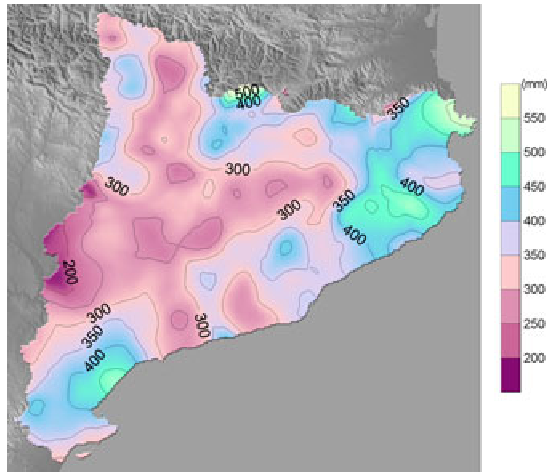

Figure 5. Spatial distribution of the 1-day PMP (mm) over Catalonia. (In color in *Annals* online.)

As it is known, when the mean distance between observatories is r, field structures with wavelength $\lambda \leq 2r$ cannot be correctly represented and have to be eliminated using an appropriate filtering or smoothing technique.[19] In order to smooth this map and to get an initial field containing only structures that can be correctly represented by the observation network used, a bidimensional filter[31] has been applied:

$$\bar{X}^a_{ij} = X^a_{ij} + \tfrac{S}{4}\big(X^a_{i-1j} + X^a_{i+1j} + X^a_{ij-1} + X^a_{ij+1} - 4X^a_{ij}\big), \quad (8)$$

where $\bar{X}^a_{ij}$ is the smoothed analysis value at the grid point (i, j), calculated from the field value at this grid point and at its four surrounding grid points. In essence, the method consists of substituting one part (S) of the field value at every point by its mean value at the four nearest grid points. Figure 4 shows the map obtained after the smoothing. To get an appropriate initial rainfall field for the analysis, these monthly rainfall values have been normalized, dividing them by the highest monthly precipitation corresponding to the grid point nearest to the Fabra Observatory of Barcelona, then multiplied by the maximum daily precipitation corresponding to a 100,000-year return period estimated from the Intensity-Duration-Frequency curves obtained by Casas *et al.*[32] for this observatory.

Applying Equation (6) and using weighting factors defined by Equation (7), this first analysis has been modified. To assure the contribution of at least two pluviometric stations to calculate the analysis correction at every grid point applying Equation (6), a decreasing radius of influence with every iteration step until the minimum value of 31 km has been chosen. Figure 5 shows the obtained 1-day PMP spatial distribution after 12 iterations (with radius of influence 100, 80, 60, 50, and 40 km for the five first steps and 31 km for the remaining 7), which achieve convergence between the analyzed values and observed data.

In order to check the 1-km × 1-km grid results for the 1-day PMP spatial distribution, the maximum daily rainfall annual series from a group of 24 new meteorological stations all over Catalonia (Fig. 1) have been used. Table 2 shows their length, altitude, and relative differences between the obtained PMP by the Cressman analysis at grid points where the test stations are located (X^a) and the estimated values using the statistical approach (X^o). Discrepancies between the grid value and the observed rainfall data do not exceed 15% for 15 of the

TABLE 2. Length (L), Altitude (H), and Relative Differences ($|X^o - X^a|/X^o$) between the PMP Obtained by the Cressman Analysis at Gridpoints where Test Stations are Located (X^a) and the Estimated Values Using a Statistical Approach (X^o)

	Station	L (years)	H(m)	Relative differences (%)
b0067	Castellví de la Marca	30	190	2.7
b0069	Pantà de Foix	64	104	12.4
b0099	Borredà	27	790	6.7
b0163	Esparreguera	21	169	13.0
b0175	Santa Maria de Miralles	28	640	23.6
b0194	La Palma de Cervelló	25	140	9.9
b0225	Sabadell	33	168	8.0
b0249	Mataró	23	90	13.0
b0254	Calella	44	6	13.2
b0261	Santa Maria de Palautordera	34	229	8.2
b0348	Gurb de la Plana	21	440	11.6
g0366	Santa Coloma de Farners	23	135	25.0
g0388	Bas	22	479	20.5
l0132	Solsona	26	677	31.8
l9690	Mont-Ros – Molinos	46	1020	26.7
l9703e	Abella de la Conca	32	797	13.3
l9712n	Guissona	22	484	17.6
l9726o	Ciutadilla	26	510	6.8
l9762	Alfarràs	24	280	6.5
l9780	Utxesa embassament	27	170	36.3
l9995	Les Cledes	20	760	26.7
t0002l	Vandellós – Central Nuclear	27	34	23.0
t0022	Montblanc	24	340	14.8
t9974	Miravet	25	25	4.0

24 test stations, being between 15% and 25% for five other stations and between 25% and 36% for the remaining four. The greatest differences (over 25%, see Table 2 and Fig. 1) have been observed in high mountain stations (l9690, Mont-Ros-Molinos and l9995, Les Cledes) in zones with low observatory density (l0132, Solsona), and in boundary zones (l9780, Utxesa embassament), with two of these factors concurring at the station Les Cledes in the western Pyrenees.

Discussion of the Results

The isohyets of the PMP range from less than 200 mm to over 550 mm, with relative differences up to 150%. The higher values are expected in the eastern half of Catalonia, in the highest zones of the Pyrenees, and in the southern area of Catalonia, whereas areas where the lowest PMP is expected are found within a large area in the Central Basin, extending from the western extreme to the Vic Plain.

In the eastern half of Catalonia, places where the highest PMP is expected are Guilleries and Cape Creus areas (see Figs. 5 and 6). In the Pyrenees, the most notable area with high PMP values is located to the north of Cerdanya, between the Perafita and the Puigpedrós peaks. In the southern area of Catalonia, an area of high PMP is defined around the Gulf of Sant Jordi. The main minima are distributed with a great concordance in the driest areas of Catalonia, specifically the western end of the Central Basin as shown in the mean annual precipitation map (Fig. 7).[33]

Figure 6. Main orographic features of Catalonia. (In color in *Annals* online.)

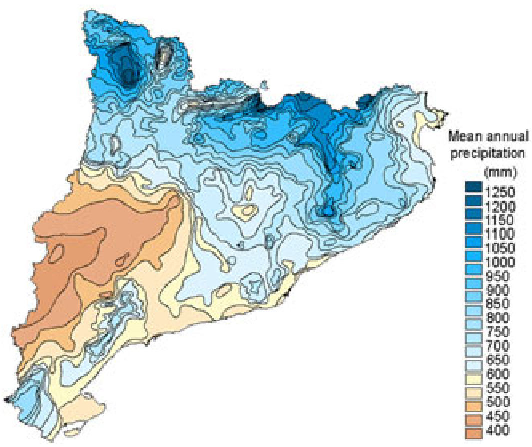

Figure 7. Mean annual precipitation over Catalonia.[33] (In color in *Annals* online.)

Despite the general concordance between the spatial distribution of the obtained highest values of PMP and the rainiest areas of Catalonia, remarkable differences have been found. For example, high PMP values have also been obtained in areas considered dry, such as Cape Creus and the Gulf of Sant Jordi, where the registered mean annual precipitation is within the range of 500–600 mm. The Aran Valley and the Vic Plain are, on the other hand, areas located inside rainy Catalonia but have minimum values for the 1-day PMP. The discrepancy between both distributions could be explained as a consequence of the different meteorological scales involved in each case. In Catalonia, the meteorological situations contributing to high rainfall for monthly or annual periods are very different from those producing the highest rainfall in 1-day time intervals. Thus, whereas the synoptic-scale organizations have a greater influence on the annual precipitation distribution, the local and mesoscale factors (e.g., orographical and geographical characteristics, temperature differences between sea and land, distance to sea, and humidity and temperature advections at low levels) have a greater influence on the 1-day PMP map.

Conclusions

Using Hershfield's[6,7] frequency analysis of registered annual maximum rainfall series in Catalonia, the statistical estimation of the 1-day PMP in the region has been possible. An appropriate enveloping k_m curve showing the relationship between the frequency factor k_m and the mean annual maximum rainfall $\bar{X}_n$ for a duration of 24 h ($k_m = -7.56 \ln \bar{X}_n + 40.5$) has been developed. The calculated 1-day PMP values for 90% of the series show a return period between 10^4 and 10^8 years, almost matching the PMP range established by the National Research Council.

To analyze the spatial distribution of the 1-day PMP over all Catalonia from the estimated values in every station, a method using the Cressman analysis algorithm[28] on an initial rain field calculated from the multiple regression equation obtained by Ninyerola *et al.*[30] has been used. This initial field presents an acceptable correlation with the analyzed variable and has been very useful in order to improve the analysis resolution, especially in areas where the station density is not high enough (as the Pyrenees and Transversal Mountain Range) to appropriately represent the great variations associated with terrain irregularity.[34] A numerical filter applied to the initial rain field has eliminated those structures with a wavelength shorter than the double of the mean distance between the pluviometric stations, adjusting its variability to the observatory network density.

This technique has been useful for assigning a numeric value objectively calculated every km^2 using a mathematical algorithm, providing a high spatial resolution of the 1-day PMP distribution, and notably improving the estimation that can be made from a map analyzed by hand. In order to test the goodness of the spatial analysis made, 24 new test stations not used in the initial analysis have been selected. Differences between the assigned 1-day PMP precipitation values at the grid points corresponding to the test stations and those calculated from the new data series do not exceed 15% for 15 of the 24 test stations, are between 15% and 25% for five stations, and are between 25% and 36% for the remaining four. The greatest differences seem to be associated with orographic factors (high mountain zones), with the observation network density, and with a possible boundary effect in border zones of the analyzed area.

Acknowledgments

This work was sponsored by the Spanish Ministry of Science and Technology under Grant REN2002-04558-C04-04.

Conflicts of Interest

The authors declare no conflicts of interest.

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