A study of the scaling properties of rainfall in Spain and its appropriateness to generate intensity-duration-frequency curves from daily records

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ABSTRACT: A methodology based on the fractal properties of rainfall has been applied to obtain the intensity-duration-frequency, IDF, curves for 100 pluviometric Spanish stations over the Iberian Peninsula and the Balearic Islands from their daily precipitation series. The scaling behaviour of maximum rainfall intensities has been investigated and simple scaling has resulted suitable. This methodology has been verified in three emblematic observatories with available sub-daily registers and current known generalized IDF relationships: the Fabra Observatory of Barcelona, the Ebre Observatory near Tortosa (Tarragona) and the Retiro Observatory of Madrid. Despite some general concordance with the mean annual rainfall distribution over Spain, the spatial distribution of the scaling parameter found for the 100 stations shows some discrepancies in diverse areas probably due to the influence of other features, as the inter-annual rainfall variability and the contribution of convective rainfall to total precipitation, on the characteristic rainfall pattern in these areas.

KEY WORDS: simple scaling; fractal analysis; rainfall intensity; intensity-duration-frequency curves

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1. Introduction

The calculation of the intensity-duration-frequency curves (IDF curves), which remains as an important tool for the risk analysis of natural hazards and hydrological design, usually requires a historical series of the maximum rainfall intensities at a sub-daily durations. Such in most locations rainfall data are usually available only from totaliser rain gauges registering 1-day precipitation, a method to infer intensity-frequency values for short durations from daily rainfall data can be very useful. There is a methodology based on the fractal properties of rainfall, or more specifically on the characteristic scale invariance of the fractal processes (Bendjoudi et al., 1997; De Michele et al., 2002; Yu et al., 2004), to obtain the disaggregation or down-scaling of low resolution precipitation data (daily) to high resolution (sub-daily) (Menabde et al., 1999; Desramaut, 2008; Bara et al., 2010). Many atmospheric processes produced by complex dynamic mechanisms acting in a wide temporal range, as rainfall generation, give rise to phenomena that look the same regardless the scale they are contemplated (self-similarity). These processes can be considered of fractal type and their properties exhibit power laws of the scale parameter $\lambda$, which is the ratio $I_2/I_1$ between any two durations $t_2$ and $t_1$ within the scaling regime. The fractal self-similarity of natural processes, such as rainfall generation, has a statistical nature, as opposed to mathematical fractals in which the parties are an exact copy of the whole. Therefore the scaling properties of phenomena like rain can be expressed by statistical relationships describing their fractal behaviour (Scherter and Lovejoy, 1987; Schertzer and Lovejoy, 2011). Several studies analysed the rainfall process in Spain from a fractal point of view: Oñate Rubalcaba (1997) obtained a mean fractal dimension of 1.32 ± 0.01 for annual rainfall series recorded by 10 stations in the Iberian Peninsula, whereas Meseguer-Ruiz et al. (2014) compared the fractal dimension of 10-min rainfall data from 20 Spanish observatories with a concentration index (CI) expressing the relative weight of the rainiest days of a series on the total accumulated rainfall of that series. Other studies investigated the multifractal character of rainfall records in Spanish stations (Valencia et al., 2010, 2015; García-Marín et al., 2008, 2013, 2015; Rodríguez et al., 2013).

It has been widely observed that the probability distribution of the annual maximum precipitation intensities satisfies scale relationships (Koutsosyannis and Foufoula-Georgiou, 1993; Burlando and Rosso, 1996; Menabde et al. 1999), which means that the probability distribution of the annual maximum daily intensity $I_{24}$ ($t_0 = 24$ h) and the distribution at other scale $I_t$ can be related by a factor that is a power function of the scale parameter $\lambda$. In terms of the moments of order $q$, $I_t^q$, of the intensity...
for duration $t$, this scaling relationship can be expressed as Equation (1).

$$ I(t, T) = I(24, T) \left( \frac{t}{24} \right) ^{\beta} $$

If the scaling exponent in Equation (1) is a linear function, $K(q) = \beta q$, the process is considered as simple scale monofractal, and multiscale or multifractal if it is not.

In the monofractal case, the application of the scaling relationship to extreme rainfall intensities with a return period $T$ and a duration $t$ (IDF curves) leads to the Equation (2), useful to estimate IDF values for sub-daily durations $t$ from daily values $I(24, T)$, once the scaling exponent $\beta$ is determined.

The reliability of this methodology has been verified in this work for three emblematic Spanish observatories: the Fabra Observatory of Barcelona, the Ebre Observatory near Tortosa (Tarragona) and the Central Meteorological Observatory located in the Parque del Retiro of Madrid (Figure 1), with well known generalized IDF equations (Casas et al., 2004; Rodríguez et al., 2014; Pérez-Zanón et al., 2015). This methodology has also been applied to 100 other Spanish stations distributed throughout the Iberian Peninsula and the Balearic Islands with the purpose of: (1) testing the downsampling technique on reproducing the IDF values of 36 of them, previously published by the Meteorological Agency of Spain AEMET (INM AEMET, 2003), and (2) to obtain a spatial distribution of the scaling parameter $\beta$ and its relationship with the characteristic rainfall pattern over the diverse regions of the studied area.

Despite its clear hydrological application, the general purpose of this work is the analysis of the structure of rainfall in the Mediterranean area, taking into account geographical and climate characteristics also. This knowledge could be very useful for consideration in studying variability of the structure of the precipitation under climate change conditions, since changes over years might be different for shorter durations than for longer ones, resulting for instance in different projections for convective and torrential rainfall than for the total of the precipitation. This issue was explored for Europe and Germany by Zolina et al. (2010), Zolina (2014) and for Barcelona (Spain) by Rodríguez et al. (2014).

2. Data and methods

For the Fabra Observatory of Barcelona, the Ebre Observatory near Tortosa (Tarragona) and the Retiro Observatory of Madrid, sub-daily records from the digitalization of long registers of pluviograph strip charts were available, as well as daily records registered simultaneously by totalizer gauges located at the same observatories. Thus, rainfall data from the Fabra Observatory of Barcelona were obtained, on one hand, from the digitalized records of a Jardí gauge (Burgués et al., 1994) between 1927 and 1992, and on the other hand from the simultaneous daily record of a totalizer Hellman gauge (code 200E) located in the same observatory. Rainfall data of the Ebre Observatory were the digitized records of a Lambrecht siphon rain gauge between 1905 and 2003 (with a gap of approximately 1 year due to the Spanish civil war, from 4 April 1938 to 1 May 1939), and the simultaneous daily record of another totalizer Hellmann gauge (code 9981A). In the case of Madrid, the records between 1940 and 2012 of a tipping bucket rain gauge located in the Retiro Observatory were available, as well as data from a totalizer gauge (code 3195) recording simultaneously at the same observatory, as in the two former cases. Daily rainfall registers until 2012 were available also for other 100 Spanish stations distributed throughout the Iberian Peninsula and the Balearic Islands (Figure 1). These registers began in different dates, the earliest in 1920, so their length range from 21 to 91 years (Figure 2).

2.1. Identification of scaling rainfall regimes in Barcelona, Ebre and Madrid

To identify the scaling behaviour of rainfall in Barcelona, Ebre and Madrid, an analysis of the statistical moments of their rainfall series has been done. Series of annual maximum rainfall for durations $t$ between 5 min and several days were obtained from the digitalized records of the three pluviographs: the Jardí gauge at the Fabra Observatory of Barcelona, the Lambrecht siphon at the Ebre Observatory and the tipping bucket gauge at the Retiro Observatory of Madrid, as well as their corresponding q-order moments $I(q)$, shown in Figures 3(a), 4(a) and 5(a). Simple scaling regimes can be identified in the three cases; the straight lines fitted to the q-order moments indicate scale invariance over a certain range, which resulted different for the three stations suggesting some dependence on the measuring instrument. The range of the scaling regimes found for Barcelona and Madrid start from 20 min whereas it does from 2 h for the Ebre Observatory. The
slopes of these straight lines determine the scaling function $K(q)$. Figures 3(b), 4(b) and 5(b) show the linear relationship found between $K(q)$ and the order $q$ of the statistical moments for Jardí, Ebre and Retiro series, so one can assume simple scaling for these series with a scaling exponent $\beta$ that can be estimated from the slope of the linear regression: $-0.78$ for Barcelona, $-0.75$ for Ebre and $-0.72$ for Madrid.

This scaling analysis has been extended to rainfall data from records of the totalizer gauges 200E (Barcelona), 9981A (Ebre) and 3195 (Madrid) registering daily precipitation simultaneously to pluviographs. A process of aggregation has been done to the annual maximum daily rainfall series from the three totalizer gauges records to generate series with durations from 2 to 20 days. These series had previously been corrected by the factor of Weiss (1964) to correct the discrepancy between the daily amounts registered by the totalizer gauges using fixed intervals and the true maximum rainfall amounts for the considered durations calculated with sliding intervals from the pluviographs records. In the case of Barcelona, the analysis of the aggregated series corresponding to 200E gauge shows a scaling regime with an exponent value of $-0.78$, the same exponent obtained for Jardí records, in a range from 1 to 11 days (see Figure 6(a)). The annual maximum daily series registered by the totalizer gauge 9981A of the Ebre Observatory has been aggregated also to obtain series with durations from 2 to 20 days. In this case, a scaling behaviour for a range of durations between 1 and 6 days has been observed (Figure 6(b)), with a scaling exponent of $-0.78$, similar to that found for the sub-daily range in the same location using the pluviograph data ($-0.75$). This slight discrepancy, not observed in the case of Barcelona, can be related to the inaccuracy of the instrument, a siphon gauge in the Ebre Observatory, measuring rainfall for short durations. The possible influence of the kind of measurement instrument on the obtained results will be discussed later. The same process of aggregation was performed to the daily 3195 gauge record of Madrid-Retiro. In this case, a scaling regime with exponent $\beta = -0.71$ for a range from 1 to 9 days has been observed for the aggregated series, almost the same than that found for the pluviograph series, $\beta = -0.72$. Both scaling regimes for Madrid have been represented jointly in Figure 7.

The values of the upper limit of the scaling ranges found are between 6 and 11 days. This result is compatible with many studies of scaling properties of rainfall reporting a scaling temporal break at scales between 1 and 3 weeks.
days in case of Olsson (1995) and De Lima and Grasman (1999), 16 days for Ladoy et al. (1998), Tessier et al. (1996), Royer et al. (2008) and De Lima & De Lima (2009), and 21 days for García-Marín et al. (2013). This scaling break can be related to lifetime associated with the strongest synoptic scale activities (Fraedrich and Larndner, 1993). The fact that the upper limit of the scaling ranges resulted a little lower than those reported by multifractal studies analysing larger samples can be explained by the smaller size of annual maximum samples compared to total series usually used in multifractal studies (De Lima & De Lima, 2009). In fact, Rodriguez et al. (2013) obtained a limit of the scaling range of 22 days in Barcelona applying multifractal analysis techniques to larger series of rainfall data.

2.2. Reproduction of the IDF curves in Barcelona, Ebre and Madrid

The purpose in this section is to reproduce the current known IDF curves of the three locations, Barcelona, Ebre and Madrid, by the application of Equation (2) to infer sub-daily values \( I(t, T) \) from daily intensity-frequency points \( I(24, T) \) calculated using the totalizer gauges series, taking into account the scaling exponents found in Section 2.1. To that end, the Weiss corrected annual maximum daily series from the 200E, 9981A and 3195 gauges were fitted to the extreme value Gumbel distribution using L-moments to obtain the \( I(24, T) \) values required in Equation (2) for several return periods between 2 and 100 years.

Figure 8 shows the IDF curves obtained, i.e. \( I(t, T) \) values for durations between 5 min and 24 h and several return periods, compared to the current IDF curves for the three locations. In the case of the Fabra Observatory of Barcelona, considering the scaling exponent \( \beta = -0.78 \) found in Section 2.1 for both pluviograph and aggregated series, the \( I(t, T) \) values obtained by downscaling the 200E daily records differ notably to the current IDF curves of the city (Casas et al., 2004; Rodríguez et al., 2014) for durations shorter than 20 min (Figure 8(a)), whereas in the...
range from 1 to 24 h relative differences between them are below 13% for all return periods, with an average value of 7%. For the Ebre Observatory, Equation (2) has been applied using the scaling exponent $\beta = -0.78$ found for the aggregated series from the 9981A totalizer gauge. As in the case of Barcelona, the IDF values obtained by downscaling the 9981A daily records differ notably to the current IDF curves (Pérez-Zanón et al., 2015) for short durations (Figure 8(b)). Relative differences between them in the range from 1 to 24 h have resulted below 17% for all return periods, with an average value of 6%. In the case of the Retiro Observatory of Madrid, the scaling exponent of $\beta = -0.71$ found for the aggregated series from the 3195 records was considered. Figure 8(c) shows the IDF values obtained by downscaling the daily 3195 records compared to the current IDF curves of the city (INM (AEMET), 2003). For Madrid-Retiro, the generated IDF curves have resulted closer to the current ones comparing to the two previous cases, with a mean value of the relative differences of 5% and below 16% for all return periods, possibly due to the different measurement instrument as it will be discussed later in Section 3.

2.3. Application of the downscaling technique to daily rainfall series from 100 Spanish stations over the Iberian Peninsula and the Balearic Islands

The downscaling methodology described in the previous sections has been applied to 100 pluviometric stations managed by the AEMET, for which daily rainfall registers were available until 2012 (Figures 1 and 2). The AEMET (INM (AEMET), 2003) published IDF curves for 36 of these 100 stations, so they have been useful to test the reliability of the applied methodology. Since pluviographs of the AEMET stations are siphon gauges, the error of the IDF values obtained by downscaling is expected to be similar to that found for the Ebre Observatory. From the daily registers of these 36 stations (shown in Table 1), annual maximum series were fitted to the extreme value Gumbel distribution using L-moments to obtain the daily rainfall intensity with return periods between 2 and 100
years, i.e. \( I(24, T) \) points. These \( I(24, T) \) values match those published by the AEMET, with relative differences lower than 20%. Sub-daily values \( I(t, T) \) have been calculated for these test stations applying the downscaling technique. For 26 of the test stations (almost 75%) the downscaled \( I(t, T) \) values match the published ones for durations longer than 2 h, whereas 20 of the test stations (57%) does for 1 h. This satisfactory result, with relative differences lower than 20% for durations higher than 60 min, suggests the usefulness of this downscaling technique to obtain suitable sub-daily intensity values above 1 h in places where only daily data are available, which is the most common situation. The value of the scaling exponent found for the 100 stations ranges from \(-0.52\) to \(-0.92\), with a general east–west gradient over the Iberian Peninsula. Figure 9 shows the linear correlation between the scaling exponents found and the longitude of the stations, probably due to the presence of the Atlantic Ocean to the west of the Iberian Peninsula and the Mediterranean Sea to the east, along with the influence of the atmospheric general circulation in these latitudes.

The spatial distribution of this scaling exponent over the Iberian Peninsula shows a general concordance with the mean annual precipitation distribution, with low absolute values in rainy areas and high for the dry ones, even though some remarkably exceptions can be observed in several zones. Figure 10 shows this general distribution where, grouping the values of beta in four categories covering approximately its range of variation (0.4), four areas with similar exponent ranges indicating similar rainfall behaviour can be identified: two of them are areas with an Atlantic influence (zones I and II) whereas the other two have Mediterranean influence (zones III and IV). The lowest absolute values of the exponent have been found in the northwest (Galicia, zone I in Figure 10, Table 1), over a rainy area where the annual mean precipitation ranges from 700 mm to values higher than 2.200 mm (AEMET, 2011). In this zone exponents between \(-0.52\) and \(-0.67\) were found. Whereas the highest absolute values correspond to a semi-arid area in the southeast (zone IV), with less than 300 mm of annual mean precipitation. In zone IV, exponents between \(-0.84\) and \(-0.92\) were found. Despite of this, in other similar rainy areas than zone I as the northeastern coast bordering the Bay of Biscay (Cantabric coast, into zone II) the absolute value of the exponent has resulted higher (\( \beta \) from \(-0.68\) to \(-0.73\) approximately); whereas in the driest areas of the Ebro basin, except in two cases, absolute values lower than 0.83 have been observed and they have been included in zone III. Zone II covers the largest area of the Iberian Peninsula, with a general range of exponent values between \(-0.67\) and \(-0.76\) [with some exceptions shown in Figure 10, as Navacerrada (code 2462) at 1894 m altitude]. In the eastern zone III, which in addition to the Ebro River basin it includes Catalonia in the north-east and the Balearic Islands Mallorca and Menorca, there is a general range between \(-0.77\) and \(-0.83\). The Balearic Island Ibiza has shown an exponent of \(-0.89\) and has been included in zone IV.

3. Discussion

The applied methodology reproduced satisfactorily the current IDF curves of the three locations considered in Sections 2.1 and 2.2 (Fabra Observatory of Barcelona, Ebre Observatory and Retiro Observatory of Madrid) for durations higher than approximately 1 h, since differences between rainfall intensity measured by the pluviographs of these locations and that calculated by downscaling daily records from their totalizer gauges resulted very small for all return periods. For shorter durations this discrepancy is slightly higher and seems to depend on the measuring instrument. Figure 11 compares results obtained for the three locations for return periods of 10 and 100 years, where symbols represent the intensity-duration values with the three cases, even though differences are much smaller for the Jardí (Barcelona) and the tipping bucket (Madrid) than for the siphon gauge (Ebre). In addition, the intensity values obtained by the two methods are practically the same for durations higher than 30 min for these two instruments, while for the siphon gauge differences persist until 1 h. This result seem to show that the differences observed...
of the three observatories. Thus, the hypothetical use always higher than those measured by the pluviographs downscaling technique assigns to every return period are rainfall intensities that the IDF curves obtained by the 100 years and the same duration. For short durations, the a duration of 60 min, and of 13% for a return period of observed and downscaled values resulted 4% for the a duration of 20 min (Figure 11), the difference between the worst result observed for the siphon pluviograph of the Ebre Observatory can be explained by its very slow response to changes in the rainfall intensity. All three instruments suffer the inconvenience of the lack of temporal resolution in the band record, since rainfall intensity is recorded on a strip of paper rotating one turn per day, making, for instance, 11 mm of band per hour in Jardí gauge. However, their response time differs significantly, especially for high intensity values when the dump mechanism of stored water of the siphon gauge is working more often, introducing a large error in the evaluation of the collected water. Instead, the Jardí gauge improves response time to intensity changes and takes approximately 10 s to go from 10 to 90% of signal change (Burgueño et al., 1987). The tipping bucket gauge has even a shorter response time, inversely proportional to rainfall intensity in addition, which makes this instrument rainfall type at each observatory contribute to these differences and should be mentioned. It is true that the tipping bucket in Madrid measures better and the syphon recording in Ebre is the worst, but short-time results are in fact just worse for the two seaside locations, maybe due to the contribution of eastern advections and higher convective activity in these areas. In any case, the value of the scaling exponent \( \beta \) obtained for long durations can be related also to the rainfall type in the corresponding location, as is discussed below.

The spatial distribution over the Iberian Peninsula of the scaling exponent found in Section 2.3 and its main discrepancies with the general concordance to the annual mean rainfall distribution seem to be related to the high rainfall variability depending on the considered temporal scale, and could be explained in terms of the kind of precipitation contributing to high rainfall amounts in the area and eventually of the proportion of convective rainfall in total precipitation. As known, the temporal variability of precipitation on yearly, seasonal, monthly, even daily resolution is high in a large part of Spain. Episodes of heavy rain affecting the Iberian Peninsula are produced mainly by the action of frontal systems associated with Atlantic depressions moving from west to east across the peninsula, and also by Mediterranean depressions originating mesoscale convective systems which cause torrential rainfall. Atlantic depressions affect mainly the western part of the Peninsula, and the heaviest rainfall episodes are associated with the cold front frontal system and usually arrive weakened to the Mediterranean basin. Instead, episodes of heavy rainfall affecting the eastern part of the Peninsula are caused by mesoscale convective
Table 1. Simple scaling exponent $\beta$ found for the 36 test stations and assigned pluviometric zone.

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<th>Station Code</th>
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<th>Latitude</th>
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<th>Zone</th>
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The absolute values of the scaling exponent $\beta$ obtained in locations where multifractal analysis was performed resulted similar to the values of the multifractal parameter $\gamma$, expressing the maximum probable singularity in rainfall distribution. In the multifractal framework, a scaling exponent $\gamma$ known as the order of singularity or

systems associated with Mediterranean depressions. These systems can cause much intense torrential rainfall than in the western part of the Peninsula, due to the advection of warm and humid air from the Mediterranean, especially in late summer and autumn. Martín-Vide (2004) found a spatial pattern of daily precipitation showing a region with highly aggressive rainfall clearly discriminated from the rest: an eastern façade where the Mediterranean depressions produce highly contrasting daily amounts comparing to the rest of the territory, where the stronger influence of Atlantic disturbances produces more regular daily rainfall values. Zones III and IV of Figure 10 almost match that eastern façade. In any way, the spatial distribution of scaling exponents shows that the highly variability of precipitation extends to sub-daily temporal resolution in the eastern area.
4. Conclusions

The time scale invariance of rainfall intensity has been studied using records of three emblematic Spanish observatories with available sub-daily registers and current known generalized IDF relationships: the Fabra Observatory of Barcelona, the Ebre Observatory near Tortosa (Tarragona) and the Central Meteorological Observatory located in the Buen Retiro Park of Madrid. Simple scaling behaviours have been identified for rainfall series obtained in the previous Section 2.1. In the same subsection, an absolute value of $\beta$ of 0.78 for the Fabra Observatory of Barcelona has been presented, whereas Rodríguez et al. (2006) found a value of $\gamma_s$ of 0.77 for Barcelona.
from registers of the pluviographs of the three observatories, as well as for aggregated series calculated from daily records of their totalizer gauges. The simple scaling exponents found for the three locations have been −0.78 for Barcelona and the Ebre Observatory, and −0.71 for Madrid. These exponents have been used to infer sub-daily intensity values from daily data. The IDF curves of the three locations have been very satisfactorily reproduced by downscaling these daily records for durations above 1 h: the mean value of the relative differences between the downscaled IDF values and the current IDF curves for all return periods have resulted 7% for Barcelona, 6% for the Ebre Observatory and 5% for Madrid. For shorter durations than 1 h, this discrepancy has resulted slightly higher and seems to depend on the measuring instrument. Despite the three pluviographs suffer the inconvenience of the lack of temporal resolution in the band record the response time of the siphon gauge of the Ebre Observatory is worse than those of the Jardí gauge of Barcelona and the tipping bucket gauge of Madrid. This last with the shorter response time resulted the best for measuring high intensities in short periods of time.

Even though the limitation of the measurement instruments to determine rainfall intensity for short durations seems to be a relevant factor to explain the differences observed between the IDF calculated from the pluviographs and those obtained by downscaling daily records, other effects related to the rainfall type at each observatory could be involved. In fact, short-time results are just worse for the two seaside locations, Ebre and Barcelona, maybe due to the contribution of eastern advections and higher convective activity in these areas. In any case, the value of the scaling exponent β obtained for long durations can be related also to the rainfall type in the corresponding location.

The simple scaling methodology has been applied on daily rainfall registers of 100 AEMET stations over the Iberian Peninsula and the Balearic Islands, 36 of them selected as test stations with known IDF curves. For almost the 75% of the test stations the IDF curves obtained by downscaling match, with relative differences lower than 20%, their current IDF for durations longer than 2 h, whereas the 57% do for 1 h. These results suggest this downscaling technique can be very useful and practical to infer suitable sub-daily data above 1 h, with a margin of error lower than 20%, in places where only daily data are available, which is the most common situation. The scaling exponents found for the 100 stations show some linear correlation with the longitude of the stations, probably due to the presence of the Atlantic Ocean to the west of the Iberian Peninsula and the Mediterranean Sea to the east, along with the influence of the atmospheric general circulation in these latitudes. The spatial distribution of this scaling exponent, with two areas with a clear Atlantic influence and other two Mediterranean, can be explained in terms of the meteorological situations contributing to high rainfall amounts in the area and the occurrence of convective rainfall in relation to the total rainfall. Thus, in rainy areas with high annual mean rainfall and where synoptic rain is predominant as the northwest and west of the Iberian Peninsula, the lowest absolute values of the exponents, between 0.52 and 0.67, have been obtained. Instead, in dry zones as the southeast, there is a higher proportion of convective rainfall due to local and mesoscale factors (temperature differences between sea and land, distance to sea, humidity and temperature advections at low levels, etc.) which resulted in the exponents with highest absolute value, above 0.84.

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