Extreme point rainfall temporal scaling: a long term (1805–2014) regional and seasonal analysis in Spain

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ABSTRACT: This paper presents a regional and seasonal study of extreme point rainfall scaling from 10 min to 2 years. To do this, the highest point-based rainfall list based on these temporal periods was calculated from the Spanish Meteorological Service (AEMET) precipitation databases with more than 11,000 rain-gauge stations, with the longest series ranging from 1805 to 2014 (209 years). This list constitutes the register of single station largest amounts of precipitation in Spain ever recorded for selected periods, including for example the values for 2 h (193 mm), 24 h (817 mm) or 1 year (5503 mm). Rainfall extremes for 10 min periods are evenly distributed in coastal and inland areas. Daily precipitation extremes are mostly concentrated over the Mediterranean coast while from durations from one month to two years, extremes are located in southern and northwest Spain. Extreme data obtained were compared with existing worldwide rainfall records for equivalent periods. Results indicate that Spanish extreme rainfall scaling relating R depth (in mm) against D duration (in minutes) may be expressed as a potential law $R = 21.8 D^{0.422}$ ($R = 43.6 D^{0.507}$ for worldwide data). We propose the upper envelope line (greater or equal to extreme rainfall values) parallel to the potential fit law as a simple method to estimate possible extreme records for different time scales. Using this method, worldwide envelope may be expressed as $R = 60.5 D^{0.507}$ and the Spanish envelope as $R = 39.3 D^{0.422}$. Further analysis stratifying results by season and region show that seasonal scaling has more variability than regional scaling. The methodology described can be readily applied to other regions for which detailed rainfall databases exist. Applications of the results include using the scaling found as a reference for classification of heavy precipitation events for temporal scales.

KEY WORDS extreme precipitation; rainfall depth duration scaling; rainfall ranking; heavy precipitation event; Spain

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1. Introduction

The study of extreme rainfall point records, i.e. absolute maximum precipitation amounts registered at specific stations, has been a relevant research topic for decades given the implications for water cycle management purposes, meteorological processes involved, hydraulic design, flood early warning systems or climatological analysis, more recently, in a context of climate change. Wussow (1922) studied point heavy rainfall events in Germany for aggregation periods between 30 min and 24 h and found that maximum rainfall records $R$, expressed in mm, increased with duration $D$, in minutes, according to $R = \sqrt{20D}$, i.e. showing a power-law dependence between depth and duration with exponent 0.5. Jennings (1950) presented a collection of the world greatest observed point rainfalls for 39 different time periods spanning from 1 min to 2 years, plotting them in a log–log graph which showed an approximately linear dependence, consistent with a power-law behaviour. Paulhus (1965) updated the record list of Jennings with some new values and, considering 29 records, fitted an envelope curve to the data using a power law, obtaining 0.475 for the exponent. This relationship has been quoted as Jennings’s scaling law in some studies such as Galmarini \textit{et al.} (2004), Zhang \textit{et al.} (2013a,2013b) or Breña-Naranjo \textit{et al.} (2015) and represents the maximum rainfall amount possible in a given time period limited by physical factors such as moisture availability, atmospheric instability, large scale dynamics or orographic factors. Substantial efforts have been devoted to study this scaling law, for example using multifractal theory (Hubert \textit{et al.}, 1993), statistical autocorrelation (Galmarini \textit{et al.}, 2004) or stochastic truncated autoregressive models (Zhang \textit{et al.}, 2013b). In a framework of physical complex systems, the precipitation process has been described formally as a self-organized critical process, like other natural phenomena such as earthquakes (Peters and Christensen, 2002; Peters \textit{et al.}, 2002).

With a similar approach Monjo (2016) defined a dimensionless $n$-index, which was the exponent of the power function fitting the greatest rainfall for different time periods at a given location to analyse individual rain events and Moncho \textit{et al.} (2009, 2011) applied it for analysing extreme rainfall and intensity–duration–frequency curves. In fact, the exponent of the power-law scaling function of Jenning’s law is 1 minus the $n$-index. Monjo and Martin-Vide (2016) used an ordered version of $n$-index to measure the climate concentration of the daily rainfall around the world showing its fractal behaviour.

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Many other studies regarding extreme precipitation have been performed based on the analysis of long term rainfall data and the development of depth against duration relations which allowed deriving probable depth amounts for specific return periods – see for example Bell (1969) or other approaches based on scaling properties of the rainfall at different scales such as those described in Burlando and Rosso (1996), Casas et al. (2010) or Pérez-Zanón et al. (2015).

The objectives of this paper are (1) to determine absolute extreme point rainfall records in Spain for different durations, (2) to examine possible power-law scalings of the extreme values found and, (3) to analyse subsequent regional and seasonal variability. To achieve these targets a large data set of more than 11 000 rain-gauge stations ranging from 1805 to 2014 has been used, which is described in detail in Section 2. In Section 3, we discuss the extreme rainfall values of Spain for different scales from 10 min to 2 years. The extreme depth duration scaling for Spain is characterized in Section 4, and a simple method to estimate extreme rainfalls is proposed. Seasonal and regional variability of extreme rainfall is analysed in Section 5. Finally, we present a summary of findings and conclusions in Section 6.

2. Data sources and extreme rainfall records

2.1. Spanish extreme precipitation data

In order to obtain precipitation extreme amounts with different durations we did a comprehensive survey of all Spanish Meteorological Service (AEMET) precipitation databases that cover all temporal ranges and the entire Spanish territory, including mainland Iberian Peninsula, Balearic Islands and subtropical Canary Islands (Figure 1). The most important features of each of the four databases used are listed in Table 1. Data passed through several quality controls by AEMET Climatological Department (AEMET, 2009) and each checked record was flagged with two possible status: valid and suspicious (not valid records were not available in the databases used). From these two sets, only valid data were used in this analysis.

A list of maximum rainfall data for different time periods spanning from 10 min to 2 years was calculated from AEMET databases. The time periods selected are based on those given by Galmarini et al. (2004) and NWS (2014). The rainfall extreme values were calculated using rolling sums applied over moving windows. Note that records in a given time period may include non-rainfall data, i.e. extreme records obtained do not necessarily imply continuous precipitation for the period considered. Maximum rainfall extremes calculated with this method are listed in Table 2. We provide as well, the ranking of the 10 highest point-based precipitations for several durations in Table S1 (Supporting information).

From 10 min to 1 h, we used a daily database generated by 10-min database with the maximum amounts of precipitation in 10, 20, 30 and 60 minutes for each day. From 2 to 18 h we used an hourly database. We computed maximum extremes for several durations using rolling sums. Hourly database is derived from the 10-minutely database so, time series contained have the same temporal coverage. Both, 10-minutely and hourly databases, started in

| Table 1. Metadata of the four databases used in this study. |
|----------------|----------------|----------------|----------------|----------------|
| Name           | Number of rain gauges | Series starting year | Median of starting years | Number of registers | Unit   |
| BD10Min        | 959               | 1973            | 2006            | 3.1E+06          | days   |
| BDHour         | 959               | 1973            | 2006            | 7.5E+07          | hours  |
| BDDay          | 10681             | 1855            | 1968            | 9.2E+07          | days   |
| BDMonth        | 11063             | 1805            | 1966            | 3.2E+06          | months |
Table 2. Observed point-based rainfall extremes for different temporal durations for the WE and SE. The ratio between each SE with their respective WE is also showed. Each SE has an Id number to relate itself with Figures 2 and 3.

| Duration | Id | Location          | Depth (mm) | Date          | Location          | Depth (mm) | Relation (%) |
|----------|----|-------------------|------------|---------------|-------------------|------------|--------------|
| 10 min   | 1  | Cuevas de Nerja, Málaga | 41.6       | 21 Sep 2007   | N/A               | N/A        | N/A          |
| 20 min   | 1  | Cuevas de Nerja, Málaga | 74.2       | 21 Sep 2007   | Romania           | 206        | 36.0         |
| 30 min   | 2  | Sineu, Balearic Islands | 87.8       | 12 Oct 2012   | China             | 280        | 31.4         |
| 60 min   | 3  | Santa Cruz de Tenerife | 129.9      | 31 Mar 2002   | China             | 401        | 32.4         |
| 2 h      | 4  | San Sebastian, Gipuzkoa | 193.0      | 1 Jun 1997    | China             | 489        | 39.5         |
| 3 h      | 4  | San Sebastian, Gipuzkoa | 204.7      | 1 Jun 1997    | USA               | 724        | 28.3         |
| 4 h      | 5  | Huercal-Overa, Almería | 216.3      | 28 Sep 2012   | N/A               | N/A        | N/A          |
| 5 h      | 5  | Huercal-Overa, Almería | 248.3      | 28 Sep 2012   | N/A               | N/A        | N/A          |
| 6 h      | 5  | Huercal-Overa, Almería | 275.0      | 28 Sep 2012   | China             | 840        | 32.7         |
| 9 h      | 6  | Oliva, Valencia      | 306.4*     | 3 Nov 1987    | La Réunion        | 1087       | 28.2         |
| 12 h     | 6  | Oliva, Valencia      | 408.5*     | 3 Nov 1987    | La Réunion        | 1589       | 38.6         |
| 18 h     | 6  | Oliva, Valencia      | 612.8*     | 3 Nov 1987    | La Réunion        | 1825       | 44.8         |
| 1 day    | 6  | Oliva, Valencia      | 817.0      | 3 Nov 1987    | La Réunion        | 2282       | 53.6         |
| 2 days   | 7  | Javea, Alicante      | 878.0      | 1–2 Oct 1957  | India             | 2493       | 35.2         |
| 3 days   | 7  | Javea, Alicante      | 978.0      | 1–3 Oct 1957  | La Réunion        | 3929       | 25.0         |
| 4 days   | 7  | Javea, Alicante      | 978.0      | 1–3 Oct 1957  | La Réunion        | 4869       | 20.1         |
| 5 days   | 7  | Javea, Alicante      | 978.0      | 1–3 Oct 1957  | La Réunion        | 4979       | 19.6         |
| 6 days   | 8  | Sauces, Santa Cruz de Tenerife | 984.8 | 24–29 Feb 1988 | La Réunion        | 5075       | 19.4         |
| 7 days   | 9  | Grazalema, Cádiz     | 1023.2     | 14–20 Dec 1958| La Réunion        | 5400       | 18.9         |
| 8 days   | 9  | Grazalema, Cádiz     | 1099.2     | 14–21 Dec 1958| La Réunion        | 5510       | 19.9         |
| 9 days   | 9  | Grazalema, Cádiz     | 1226.2     | 14–22 Dec 1958| La Réunion        | 5512       | 22.2         |
| 10 days  | 9  | Grazalema, Cádiz     | 1273.6     | 13–22 Dec 1958| La Réunion        | 5678       | 22.4         |
| 11 days  | 9  | Grazalema, Cádiz     | 1277.2     | 12–22 Dec 1958| La Réunion        | 5949       | 21.5         |
| 12 days  | 9  | Grazalema, Cádiz     | 1280.0     | 12–23 Dec 1958| La Réunion        | 5949       | 21.5         |
| 13 days  | 9  | Grazalema, Cádiz     | 1282.2     | 11–23 Dec 1958| La Réunion        | 6072       | 21.1         |
| 14 days  | 9  | Grazalema, Cádiz     | 1282.2     | 11–23 Dec 1958| La Réunion        | 6082       | 21.1         |
| 15 days  | 9  | Grazalema, Cádiz     | 1284.8     | 9–23 Dec 1958  | La Réunion        | 6083       | 21.1         |
| 20 days  | 9  | Grazalema, Cádiz     | 1454.1     | 3–23 Dec 1958  | N/A                | N/A        | N/A          |
| 31 days  | 10 | Cortes de la Frontera, Málaga | 1674.0 | 18 Nov–1 Nov 1989 | N/A                | N/A        | N/A          |
| 1 natural month | 10 | Cortes de la Frontera, Málaga | 1626.1 | 1–31 Jan 1979 | India              | 9300       | 17.5         |
| 2 months | 10 | Cortes de la Frontera, Málaga | 2420.0 | Dec 1995–Jan 1996 | India              | 12767      | 19.0         |
| 3 months | 11 | Casteloais, Ourense   | 2866.8     | Nov 1959–Jan 60 | India              | 16369      | 17.5         |
| 4 months | 11 | Casteloais, Ourense   | 3269.9     | Nov 1959–Feb 60 | India              | 18738      | 17.5         |
| 5 months | 12 | Casas do Porto, A Coruña | 3858.5     | Nov 2000–Mar 01 | India              | 20412      | 18.8         |
| 6 months | 12 | Casas do Porto, A Coruña | 4176.1     | Oct 2000–Mar 01 | India              | 22454      | 18.6         |
| 9 months | 12 | Casas do Porto, A Coruña | 4680.1     | Aug 2000–Apr 01 | N/A                | N/A        | N/A          |
| 12 months| 12 | Casas do Porto, A Coruña | 5503.4     | Apr 2000–Mar 01 | India              | 26461      | 20.8         |
| 18 months| 13 | Dodro, A Coruña       | 7523.6     | Oct 1984–Mar 86 | N/A                | N/A        | N/A          |
| 24 months| 11 | Casteloais, Ourense   | 8991.5     | Feb 1958–Jan 60 | India              | 40768      | 22.1         |

Spanish rainfall records for 9, 12 and 18 hours are estimated from the 24 hours record and are marked with an asterisk (*).
2.2. Limitation of data

As previously described, sub-daily databases contain \(\sim 900\) rain gauges with data from 1973 while supra-daily databases use \(\sim 9000\) rain gauges with data from early 19th century. This difference in amount of gauges and length of records of the different databases entails a discontinuity between sub-daily and supra-daily temporal scales coverage. An example of the effect of this discontinuity is given by the Oliva one day record (817 mm). The corresponding proportional sub-daily extremes for 9, 12 and 18 h (306, 409, 613 mm, respectively) exceeded the records found in the sub-daily database so those proportional values were selected as records for the temporal scales given. Therefore, the approach followed in this study implies evaluating all possible extreme records for any valid station and temporal scale available. Considering a period where temporal scales were homogeneously covered would limit drastically the possibility of capturing absolute records as volume data would be much smaller.

2.3. World extreme precipitation data

We obtained the world extreme point-based rainfall measurement from NOAA National Weather Service (NWS, 2014). These measurements represent the current extreme rainfall ever recorded for each scale. NOAA National Weather Service first retrieved the data from WMO (1994) and nowadays maintains the most updated extreme rainfall data available. The latest update were several records broken between the 3 and 9 days time spans, registered at Commerson crater in La Réunion Island when the Tropical Cyclone Gamede crossed trough the island in 2007 (Quetelard et al., 2009). Most of the extremes are listed in Table 2. Previous versions of this list has been used in other studies related with the global extreme rainfalls (e.g. Galmarini et al., 2004; Zhang et al., 2013a).

3. Discussion of extreme rainfall values

Specific values of Spanish rainfall extremes (SE), and their corresponding World extremes (WE), as well as...
their proportion (%) are listed in Table 2. This table is obtained after examining the AEMET rainfall databases as described in Section 2. In this section are discussed the values obtained considering two groups: 10 min to 18 h and 24 h to 2 years. This separation corresponds approximately to microscale and mesoscale (10 min to 18 h) and to synoptic and planetary scales (24 h to 2 years) according to the classical classification given by Orlanski (1975).

3.1. From 10 min to 18 h

Total point-based rainfall is the product of the precipitation rate (which depends on the air vertical motion, moisture supply and precipitation efficiency) and event duration (Doswell et al., 1996). As noted Trenberth et al. (2003), moisture availability from the atmosphere is very limited since the precipitable water in mid-latitudes hardly exceeds 40 mm, and precipitation efficiency is rarely greater than 70%, being sometimes even lower (Ferrier et al., 1996; Anip and Market, 2007). So, in an extreme precipitation event, part of the moisture supply typically must come from moisture advection, and the other part through surface evaporation. The recycling ratio shows the relation between these two sources being higher as much rainfall comes from local surface evaporation. Recycling ratio is greater in summer than in winter according to Trenberth (1999).

At very short scales, typically from a few minutes to one hour, most of the local atmospheric moisture must be released to produce extreme precipitation events typically associated to deep moist convection. Such events need a large amount of precipitable water over a wide area and mechanisms that trigger strong vertical air motions like those present in organized convective storms. This kind of process can occur over most of Spain as well as other tropical and mid-latitude places (see Table 1), as discussed by Galmarini et al. (2004). Therefore, it is reasonable to think that Spain has the same potential to develop, for short temporal periods of the order of few minutes, extreme rainfalls as great as any other country that holds short scale precipitation records such as Romania or Germany – 206 mm in 20 min and 126 mm in 8 min, respectively, according to NWS (2014). The probability of capturing those events depends on the spatial and temporal density of observations and the temporal length of the datasets. For these reasons, and because of the temporal and spatial limitations of the 10-minutely database explained in Section 2, SE at those scales might be underestimated compared to longer scales duration present in daily and monthly databases, and consequently short scales extremes may quickly increase with a wider and longer database.

For scales between some tens of minutes until a few hours, besides organized air vertical currents to maintain the precipitation intensity, it is needed a constant transport of moisture from nearest sources for a few hours or even from further sources for a few days. This situation may be exemplified by the event #5, that corresponds with the HyMEX Intensive Observation Period 8 (IOP8) (Jansà et al., 2014). This event has been well studied (Khodayar et al., 2016; Röhner et al., 2016) and it is demonstrated the importance of the feeding moisture (Röhner et al., 2016). Furthermore, it has been observed for some heavy precipitation events (HPEs) in the Western Mediterranean region that moisture can be transported from the Mediterranean Sea as well as from further sources such as the North Atlantic Ocean (Duffourg and Ducrocq, 2011; Trapero et al., 2013; Röhner et al., 2016).

It seems likely that extreme rainfall records in Spain obtained for periods until 18 h may be underestimated compared to longer periods, especially from 9 to 18 h, as illustrated by the fact that the records obtained for those periods were estimated from the maximum 24 h case (817 mm, event #6) as explained in Section 2.

3.2. From 1 day to 2 years

So far we discussed sub-daily data scales that seems to be underestimated since the spatial and temporal resolution is limited. For scales over a day, this argument is not valid since our database has more than 10000 rain gauges that last almost two centuries for the longer station series. Highest SE compared with WE is for 1-day duration, when at 3 November 1987 was recorded in Oliva (Valencia) 817 mm (episode #6) (Riosalido et al., 1988; Romero et al. 2000), which represents a 44.8 % of the 1-day WE.

Recently, it has been published a ranking of daily and multi-day precipitation extreme events for Iberian Peninsula (Ramos et al., 2014; Ramos et al., 2017, hereafter Ram47) using a high-resolution (0.2°) gridded daily database, considering both the intensity of the grid point and the area affected. It is remarkable the difference between point-based extreme precipitations and those in Ram47. For example, the highest precipitation for 1 day in Oliva corresponds to the 309th extreme event in Ram47. Similarly, the extreme precipitation records of episode #7 (the most extreme point-based precipitation for periods spanning between 2 and 5 days) do not appear in any of the top 100 events for 3-day and 5-day period. The episode #9 (the most extreme point-based precipitation for time spans between 7 and 20 days) appears as the 24th and the 20th most extreme events for 7-day and 10-day period, respectively. Those examples show that the point-based extreme precipitation events generally do not correspond to events affecting large areas, especially for shorter time durations.

From 3 days to 7 days there is a noteworthy period where precipitation does not increase due to the exceptional nature of one single event (event #7, 978 mm in 3 days); this episode is not overtaken until the 6-day period of subtropical rainfall in Canary Islands exceeds it. Events #2 and #3 occurred in the coastal region of Valencia (E Spain), which has the highest rainfall variability in Spain (Martin-Vide, 2004) and relatively few precipitation days per year compared with other areas in the Iberian Peninsula (IM-AEMET, 2011). Interestingly, from periods of 7-day onward, the extreme precipitation regions move to Grazalema mountain range (S Spain) and Galicia (NW Spain), two of the wettest regions in Spain.

For scales longer than a few days it is not needed a large amount of moisture transport in a short time but a constant input of moisture along the time with many
consecutive days (Casanueva et al., 2014). This is why at longer scales the geographical distribution changes from the Mediterranean to the Atlantic region of Galicia (from event #11 to #13), where westeers predominate advecting moist air masses regularly. According to results in Table 2, the percentages of SE against WE vary from 44.8% (at 24 h) to 17.5% (for 1, 3 and 4 months). Remarkably from 4-day periods, percentages do not exceed 23%. A possible explanation for this, is that moisture at middle latitudes is distributed as transient, relatively narrow areas or strings known as atmospheric rivers (Zhu and Newell, 1998), and presence or absence of these moisture belts precipitating over a point, acts as a limiting factor for large scale extreme rainfall. Hence, in mid-latitudes moisture input is irregular compared with that in the WE in the tropics, where large scale tropical circulations as the monsoons over the Indian subcontinent provides a constant input of moisture. Therefore, SE heavy rains for several days or months cannot last long, being SE around 20% with respect to WE from 4 days onwards. This approximate relation holds at least until a duration of 2 years.

4. Extreme depth duration scaling

4.1. Data fit

Figure 3 shows a log–log plot of rainfall depth \( P \) (mm) against duration \( D \) (minutes) of Spanish rainfall extremes (SE) and the world extremes (WE). For both datasets, we computed the fitting line \( \log(P) = a + b \log(D) \) (bold line in Figure 3) using least squares linear regression, which in power-law format may be expressed as \( R = 43.6 \ D^{0.51} \) \( (r^2 = 0.958) \) for WE and as \( R = 21.8 \ D^{0.42} \) \( (r^2 = 0.978) \) for SE where \( R \) is rainfall depth in mm and \( D \) is duration in minutes.

In a first approximation, both WE and SE exhibit a close power-law scaling. A power-law goodness-of-fit test (Gau- doin et al., 2003) shows that both data sets are compatible with a power-law scaling (for \( P < 0.05 \) and \( n = 40 \) the power law is rejected when \( r^2 < 0.887 \)). In both cases, only few rain events contribute to most of the registered extremes. The locations of SE episodes are showed at Figure 1. It is remarkable that all SE are located near the sea, even for large time spans. Locations are clustered in the Mediterranean and Canary Islands for mid and short scales and near the Galician coast for longer scales. It is also worth to notice that except Sineu (Balearic Islands, extreme #2 in Table 1) and Huercal-Overa (Almería, extreme #5), all other maximum amounts are located in areas of complex terrain. This suggests that both, sea proximity and a complex orography (the last one, especially for scales longer than 6 h) are critical ingredients to develop extreme rainfall amounts. This is consistent with previous climatological studies such as Romero et al. (1998) and Ramis et al. (2013).

As discussed above, extreme rainfalls shorter than a day might be underestimated and may disturb the scaling. However, we have seen that the event fitting line is compatible with a power-law scaling. This means that some discontinuities have very little effect in the scaling goodness-of-fit. Therefore, we can assume that the discussion of the extremes precipitation may be hardly affected by this discontinuity. This applies too for the discussion in Section 5.

4.2. Upper envelope as a method to estimate possible extreme records

Instead of using a fit of the extreme data to characterize extreme world rainfall records, Paulhus (1965) employed the upper envelope, i.e. greater or equal to all data, with a power-law scaling line. However the specific method to derive the envelope line was not described. To find the envelope curve we suggest using a parallel line to the data fit (i.e. with the same slope \( b \)) which is moved upwards to reach the furthest depth duration point so all rainfall record amounts are equal or below the envelope line. Specifically, from all possible data points \((D_i, P_i)\), the furthest point \((D_{sup}, P_{sup})\) to the fit line is determined by finding the point with the maximum distance:

\[
(D_{sup}, P_{sup}) = \left( D_i, P_i \right) \mid \text{Max} \left\{ \frac{|b \cdot D_i - P_i + a|}{\sqrt{b^2 + 1}} \right\}
\]

We get the envelope line \( \log(P) = a_{env} + b \log(D) \), obtaining a new intercept \( a_{env} \) calculated as:

\[
a_{env} = b \ast (-D_{sup}) + P_{sup}.
\]

Using this method and the most updated data available, the WE upper envelope may be expressed as \( R = 60.5 \ D^{0.507} \) and the SE envelope as \( R = 39.3 \ D^{0.422} \). The envelope curve is plotted in Figure 3 (dashed line) for both WE and SE.
5. Regional and seasonal variability of extreme rainfall

5.1. Regional variability

Figure 4 shows the amount of the most extreme precipitation for each location at different scales, while Figure 5(a) shows the scaling of the greatest rainfalls for each domain we divided Spanish territory in Section 2. From 10 min to 3 h absolute rainfall extremes for each station at short scales are evenly distributed in Spain (Figures 4(a) and (b)). In fact, among the records for these time spans, there are absolute extremes (i.e. the maximum for a given time duration) from three different regions (MED, ATL and SBT). This agrees with Galmarini et al. (2004) statement that short scales extremes can occur indistinctly both in mid-latitudes and tropics.

For scales from 4 h to 5 days, extreme precipitation in MED clearly dominates over the other regions. MED region has all the ingredients that permit to have the heaviest rainfalls at daily scales: a warm sea that supplies moisture and potential instability that may release all this moisture, small scale shallow cyclones that can mobilize the moisture and provide constant transport to the storm (Jansà, 1997), and complex terrain that can locally lift the moisture, concentrating moisture and rainfall in a small territory.

Daily variability has been studied by Martin-Vide (2004) who elaborated a Concentration Index (CI) that evaluated the contribution of the days with greatest rainfall to the total amount. SE distribution for 1 day (Figure 4(c)) fits pretty well with the daily CI distribution defined by Martin-Vide (2004) that already divided peninsular Spain into two regions, the Mediterranean coast and the rest of the country. The main difference between CI and SE distribution is that the last one is more concentrated near the coast.

As already commented by Ramis et al. (2013), when they characterized the daily greatest point-based
precipitations in mainland Spain, most of the extreme daily precipitations (over 500 mm) occur near the Mediterranean coastline except one single event at the Pyrenees (700.5 mm at Benasque station in 1923). This point is the only one that exceeds 500 mm outside the MED region and the event was likely influenced by orographic factors.

For scales longer than a month, SE tend to concentrate at mountain ranges of the western coast (Figures 4(d) and (e)). The longer the time span the larger are the amounts near the Atlantic compared with the Mediterranean region. This may be explained because the Atlantic Ocean and, specially, the atmospheric rivers provide a constant moisture supply in ATL region that can be released by mechanical ascent favoured by the mountains. No other place in Spain has such a constant input of moisture during the whole year (Casanueva et al., 2014) and therefore, a succession of fronts during several months may produce a considerable amount of rainfall.

Notice that although the five regions are climatically different, they do not show large differences in the scaling, especially in the exponent that is comprised between 0.39 and 0.44. Since rainfall at short scales is not much different between regions, exponent is well related with the wetness of the region and the variability of the moisture transport rate through the year. As we explained above, ATL has a constant moisture input (Fernández et al., 2003; Gimeno et al., 2010) that implies longer rainy periods for large scales and therefore a greater exponent. On the contrary, SBT region has a clear seasonal drought that produces lower extremes at large scales, and therefore a lower exponent. MED and CON regions have an intermediate exponent close to the average Spanish exponent.

In general, single station exponents (Figure 6) have higher values in ATL region stations and lower values in SBT region stations, consistently with results shown in Figure 5(a). It is worth to note that most stations of MED and CON regions also show very low exponents, especially in southeast Spain, the driest region in Spain. In fact, there is an east–west gradient of exponent in Spain also well related with the CI previously discussed. This coincidence in the spatial distribution between CI and the scaling exponent may be noteworthy considering that the exponent is built with information from many more temporal scales and CI is based only on daily rainfall.

The general pattern of single station exponents is distorted by stations located in mountains: Pyrenees, Central System or even in Serra Tramuntana in north of Majorca Island (the biggest of Balearic Islands) are well defined by a higher exponent in their meteorological stations. It is well-known that annual rainfall is usually larger and more regular in mountains due to orographic effects therefore is no surprise they exhibit larger exponents in those regions.

These results extend to most extreme rainfalls, those obtained by Meseguer-Ruiz et al. (2016) who linked the fractal dimension of the precipitation to the regular recurrence of precipitation through the scales. Regional variability comes out when we diminish the area of the regions using Spanish provinces (see Appendix). For these small regions, very dry provinces of southeastern Spain as Murcia or Almería present a low exponent (approximately 0.3) while the wetter provinces located in the northwest of Spain as Ourense or A Coruña have a higher index (approximately 0.5).

5.2. Seasonal variability

Figure 5(b) shows depth against duration scaling plot in Spain for each season. Differences in the exponent between seasons are larger than between regions. In winter, moisture content in the atmosphere is relatively small so, when it is released and produces heavy rainfall, greatest values at short scales are typically lower than in warm season convective events. Nevertheless, on winter, moisture fluxes in Spain can be more stable during all season since polar jet circulates at lower latitudes. This means that in comparison, greatest rainfalls at large temporal scales are higher than at short scales and therefore exponent values become high, close to 0.5.

Figure 5. As Figure 3 but showing specific records and scaling for (a) each regional domain (empty circles identify all-regions records) and (b) for each season for all-regions data. World extremes and scaling are also included for reference. [Colour figure can be viewed at wileyonlinelibrary.com].
By contrast, moisture content of the atmosphere may reach maximum values in summer, and elevated instability is able to release it in a few hours, especially near the Mediterranean Sea that offers a great source of moisture. For this reason, it is not difficult to find events where more than 100 mm are registered in one or few hours. However, during the warm season transport of moisture is more intermittent and Canary and Iberian summer climate is characterized by high pressure systems that do not permit to have large rainfalls over long temporal scales (Esteban et al., 2006). This explains the lower exponent (0.3) that characterizes summer for Spain.

Spring and autumn have intermedium exponents (0.4) and are seasons of transition between the winter and summer regimes. Even so, most of the extremes in almost all scales occur in autumn.

In Table 3, we examined seasonal differences for each region. Results show that these features (lower exponents in summer and larger exponents in winter) are common for all regions, even those ones with very different climates as ATL and SBT.

6. Summary and concluding remarks

After a comprehensive analysis of the Spanish precipitation databases, this paper has documented the most extreme rainfall amounts in Spain for a large range of temporal scales. Despite there are studies documenting sets of extreme rainfall events for a given country or area at selected time periods (see e.g. Hand et al., 2004; Cerveny et al., 2007; or Shein et al., 2013), as far as the authors know, this is the most complete survey of absolute extreme rainfalls made in a country providing records from 10 min to 2 years. We complemented this data with a ranking of the 10th highest rainfall for each time span in Spain and the highest precipitation for each domain and province as well (see Appendix and Supporting information).

For short scales less than 3 h, extreme rainfall events are widespread distributed through Spain while for scales from 4 h to 20 days rainfalls are concentrated in the Mediterranean and sometimes in Canary Islands. For scales larger than a month rainfalls are mainly concentrated at the Atlantic coast, where Atlantic westerlies provide a constant moisture input.

Power scaling of the extreme rainfalls in Spain has been compared with the extreme rainfalls in the World. This relation largely varies with the scale, from 45% in 1 day to 18% at large scales. Both data sets are compatible with a scaling law, even though Spanish data below a day seems to be clearly underestimated with the amount of data available.

We characterized the spatial distribution and the regional and seasonal scaling of extreme precipitation showing that main features that characterize the scaling and the extremes rainfalls in Spain are (1) moisture content of the atmosphere for short scales, (2) constant moisture transport supply for larger scales, (3) orography and (4) proximity to the sea.

For different regions, the scaling is characterized for larger scales more than shorter scales, since the extreme precipitation for shorter scales is similar for all regions. Nevertheless, the scaling factor does not change so much between regions. Conversely, scaling is very different between seasons, being the scaling factor much greater for winter than for summer. Our results qualitatively agree with other indices calculated for the Iberian Peninsula as CI (Martin-Vide, 2004) or fractal dimension (Meseguer-Ruiz et al., 2016).

The resulting lists of precipitation extremes may be used as a reference framework to characterize the amount of precipitation of HPEs in function of its distance to the record, thus providing a classification method useful both for case studies or more exhaustive climatological analysis. This study should be extended to larger regions.
Table 3. Depth – duration scaling properties for each season and geographical domain.

| Season | ATL | INT | MED | SBT | SPAIN |
|--------|-----|-----|-----|-----|-------|
| DJF    | 4.5 | 3.6 | 10.8 | 13.1 | 12.0  |
|        | 0.53| 0.58| 0.46 | 0.46| 0.48  |
|        | 0.992| 0.993| 0.985| 0.983| 0.985 |
|        | 6.5 | 11.4| 12.2 | 28.1| 20.7  |
|        | 0.51| 0.41| 0.44 | 0.32| 0.39  |
|        | 0.989| 0.972| 0.983| 0.968| 0.976 |

Table A1. Extreme rainfall scaling fit for each Spanish province, $R = aD^b$, with $R$ in mm and $D$ in minutes, adjusted with records from 10 min to 2 years, showing the parameters $a$ and $b$ and correlation coefficient.

| Province | $a$  | $b$  | $r^2$ |
|----------|------|------|-------|
| Barcelona | 14.8 | 0.38 | 0.978 |
| Tarragona | 21.9 | 0.33 | 0.971 |
| Girona    | 12.1 | 0.43 | 0.981 |
| Lleida    | 10.8 | 0.41 | 0.982 |
| Cantabria | 11.5 | 0.41 | 0.982 |
| Cordoba   | 21.4 | 0.34 | 0.971 |
| Huelva    | 14.8 | 0.38 | 0.978 |
| Sevilla   | 9.9  | 0.43 | 0.984 |
| Jaen      | 5.1  | 0.49 | 0.991 |
| Granada   | 8.0  | 0.47 | 0.986 |
| Almería   | 31.1 | 0.31 | 0.963 |
| Cádiz     | 10.0 | 0.48 | 0.987 |
| Málaga    | 19.0 | 0.41 | 0.978 |
| Alicante | 24.9 | 0.37 | 0.972 |
| Valencia | 26.8 | 0.35 | 0.969 |
| Castellon | 17.0 | 0.36 | 0.975 |
| Teruel    | 9.0  | 0.42 | 0.983 |
| Huesca    | 10.4 | 0.46 | 0.984 |
| Zaragoza  | 9.2  | 0.39 | 0.983 |
| Guadalajara | 5.7 | 0.44 | 0.988 |
| Cuenca    | 9.0  | 0.42 | 0.984 |
| Toledo    | 9.0  | 0.41 | 0.985 |
| Albacete  | 14.5 | 0.37 | 0.977 |
| Ciudad Real | 4.7 | 0.45 | 0.991 |
| Leon      | 6.0  | 0.50 | 0.990 |
| Burgos    | 8.3  | 0.44 | 0.986 |

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Appendix

Table A1. Continued

| Province | $a$  | $b$  | $r^2$ |
|----------|------|------|-------|
| Valladolid | 6.3  | 0.40 | 0.986 |
| Palencia | 6.1  | 0.46 | 0.989 |
| Zamora   | 4.1  | 0.52 | 0.993 |
| Soria    | 8.0  | 0.41 | 0.985 |
| Segovia  | 6.3  | 0.43 | 0.988 |
| Avila    | 7.0  | 0.50 | 0.989 |
| Salamanca | 10.0 | 0.45 | 0.984 |
| Lugo     | 6.0  | 0.50 | 0.990 |
| Pontevedra | 6.7 | 0.50 | 0.990 |
| A Coruña | 6.5  | 0.51 | 0.990 |
| Ourense  | 5.2  | 0.53 | 0.992 |
| Cáceres  | 6.4  | 0.49 | 0.990 |
| Badajoz  | 8.6  | 0.41 | 0.985 |
| Navarra  | 9.7  | 0.45 | 0.985 |
| Gipuzkoa | 18.1 | 0.38 | 0.976 |
| Bizkaia  | 13.8 | 0.39 | 0.979 |
| Araba/Alava | 7.0 | 0.43 | 0.987 |
| Asturias | 7.8  | 0.46 | 0.987 |
| Murcia   | 29.6 | 0.31 | 0.986 |
| Madrid   | 9.6  | 0.41 | 0.984 |
| La Rioja | 7.3  | 0.43 | 0.985 |
| Baleares | 19.0 | 0.40 | 0.978 |
| Las Palmas | 13.6 | 0.41 | 0.980 |
| Santa Cruz de Tenerife | 23.0 | 0.39 | 0.975 |

Supporting information

The following supporting information is available as part of the online article:

Table S1. Ranking of the top ten precipitation amounts recorded in Spain from AEMET rain-gauge databases for selected time periods. There are 38 tables for periods spanning from 10 min to 2 years. See Gonzalez and Bech (2017) for details.

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