EXTREME POINT RAINFALL TEMPORAL SCALING: A LONG TERM (1805-2014) REGIONAL AND SEASONAL ANALYSIS IN SPAIN

Extreme point rainfall temporal scaling in Spain

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Abstract

This paper presents a regional and seasonal study of extreme point rainfall scaling from 10 minutes to 2 years. To do this, the highest point-based rainfall list for different temporal periods spanning from 10 minutes to 2 years was calculated from the Spanish Meteorological Service (AEMET) precipitation databases with more than 11000 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 2h (193 mm), 24h (817 mm) or 1 year (5503 mm). Rainfall extremes for 10 minute 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) vs 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). 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.

Keywords: extreme precipitation, rainfall depth duration scaling, rainfall ranking, heavy precipitation event, Spain

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 minutes and 24h 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 minute 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 Jenning's scaling law in some studies such as Galmarini *et al.* (2004), Zhang *et. al.* (2013a,b) or Breña-Naranjo *et al.* (2014) 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 o orographic factors. Substantial efforts have been devoted to study this scaling law, for example using multifractal theory (Hubert et al., 1993), statistical autocorrelation (Galmarini *et al.*, 2004) or stochastic truncated autoregressive models (Zhang *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 *et al.*, 2002; Peters & Christensen, 2002).

With a similar approach Moncho *et al.* (2009), Monjo (2016) and Monjo & Martin-Vide (2016) employed 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. This index has been tested with rain gauges around the world showing again a fractal behaviour as reported by Monjo (2016) and Monjo & Martin-Vide (2016).

Many other studies regarding extreme precipitation have been performed based on the analysis of long term rainfall data and the development of depth vs 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 & 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 analyze subsequent regional and seasonal variability. To achieve these targets a large data set of more than 11000 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 values of Spain for different scales from 10 minutes to 2 years. The extreme depth duration scaling for Spain is characterized in Section 4, comparing it with world records and analyzing seasonal and regional variability. Finally, we present a summary of findings and conclusions in Section 5.

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 minutes 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 precipitation for several durations in Table S1.

From 10 minutes to 1 hour, we used a daily database generated by 10-minutely database with the maximum amounts of precipitation in 10, 20, 30 and 60 minutes for each day. From 2 hours to 18 hours 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 1980 with a marginal number of rain gauge stations. Since then, the number of stations have been steadily increasing. By now there are more than 900 10-minutely automatic rain gauges distributed around Spain starting the oldest one in 1973. This is a relative small number if compared with the number of stations in the following database.

From 1 day to 31 days we used the daily (from 07:00 to 07:00 UTC) database detailed by Ramis *et al.* (2013) and from 2 months to 2 years we used a monthly database created from the daily data. We performed the rolling sums of the whole database in order to obtain the maximum amounts for different durations. These networks have more rain gauges (more than 9000 nowadays) and are much longer than sub-daily ones (the oldest one starting in early XIX century). Consequently, there is a large discontinuity between sub-daily and supra-daily temporal coverage. As a result of this discontinuity, we detected that greatest rainfall recorded in 9, 12 and 18 hours by sub-daily database are lower than the minimum possible in these durations estimated considering stationary rainfall rate in the greatest precipitation ever registered in 1 day (817 mm at Oliva), so we select the esimated values as the greatest values. For example, the proportional part of that event corresponding to 12 hours is 408.5 mm, exceeding the maximum amount found in the hourly database, that is 314.6 mm.

We grouped rain gauges stations in four domains showed in Figure 2. Mediterranean domain (MED) takes the pragmatic definition of Romero et al. (1998) and includes all stations in administrative regions which border the Mediterranean Sea. Similarly, Atlantic domain (ATL) has been chosen so that rain gauges located in the regions to the Atlantic. The remaining regions into peninsular Spain were classified as Continental rain gauges (CON) and none of them is close to the sea. Stations that cover Canary Islands are classified as Subtropical rain gauges (SBT).

2.2 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 to 9 days time spans, registered at Commerson crater in Reunion Island when the Tropical Cyclone Gamede crossed trough the island in 2007 (Quetelard, 2009). Most of the extremes are listed in Table 2. This list has been used in other studies related with the global extreme rainfalls (e.g. Galmarini *et al.*, 2004 and 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 minutes to 18 hours and 24 hours to 2 years. This separation corresponds approximately to microscale and mesoscale (10 minutes to 18 hours) and to synoptic and planetary scales (24 hours 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 midlatitudes 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 *et al.* (1999b).

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 midlatitude places (see Table 1), as discussed 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 minutes and 126 mm in 8 minutes, 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 correspond with the HyMEX Intensive Observation Period 8 (IOP8) (Jansà *et al.* 2014). This event has been well studied (Röhner *et al.* 2016; Khodayar *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 hours may be underestimated compared to longer periods, especially from 9 to 18 hours, as illustrated by the fact that the records obtained for those periods were estimated from the maximum 24 hours 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 WR.

Recently, it has been published a ranking of daily and multi-day precipitation extreme events for Iberian Peninsula (Ramos *et al.*, 2014 and Ramos *et al.*, 2016, hereafter Ram46) using a high-resolution (0.2º) 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 Ram46. For example, the highest precipitation for 1 day in Oliva corresponds to the 309th

extreme event in Ram46. 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) appear 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 westerlies predominate advecting moist air masses regularly. According to results in Table 2, the percentages of SE vs. WE vary from 44.8% (at 24 hours) 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 Neweel, 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 two years.

4. Extreme depth duration scaling

4.1. Data fit and upper envelope

Figure 3 shows a log-log plot of rainfall depth *P* [mm] vs. duration *D* [minutes] of Spanish rainfall extremes (SE) and the world extremes (WE). For both datasets, we computed the fitting line $\log(P) = \mathrm{a} + \mathrm{b}\log(D)$ (bold line in Figure 3) using least squares linear regression, which in power law format may be expressed as R = 43.6 $D^{0.507}$ (r^2 = 0.958) for WE and as R = 21.8 $D^{0.422}$ (r^2 = 0.978) for SE where *R* is rainfall depth in mm and *D* is duration in minutes.

Following the approach by Paulhus (1965), the upper envelope (dashed line) was plotted too, finding a parallel line to the data fit (i.e. with the same slope *b*) which was 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 was determined by finding the point with the maximum distance:

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

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

$$a_{env} = b * (-D_{sup}) + P_{sup}$$

Using this method and the most updated data, the WE envelope may be expressed as R = 60.5 $D^{0.507}$ and the SR envelope as R = 39.3 $D^{0.422}$.

In a first approximation, both WE and SE exhibit a close power-law scaling. A power-law goodness-of-fit test (Gaudoin *et al.*, 2003) shows that both data sets are compatible with a power-law scaling. 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 (Almeria, 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 hours) 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 a 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 from here on.

4.2. Regional variability

Figure 4 shows the amount of the most extreme precipitation for each location at different scales, while Figure 5a shows the scaling of the greatest rainfalls for each domain we divided Spanish territory in Section 2. From 10 minutes to 3 hours absolute rainfall extremes for each station at short scales are evenly distributed in Spain (Figure 4a 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 hours 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 Martín-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 4c) fits pretty well with the daily CI distribution defined by Martin-Vide (2004) that already divided peninsular Spain into two regions, the Mediterranean façade 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 façade (Figure 4d 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 provides 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 INT regions have an intermediate exponent close to the average Spanish exponent. 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 1). For these small regions, very dry provinces of southeastern Spain as Murcia or Almeria present a low exponent (~0.3) while the wetter provinces located in the northwest of Spain as Ourense or A Coruña have a higher index (~0.5).

4.3. Seasonal variability

Figure 5b shows depth vs. 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.

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.

5. 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 for example 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 minutes 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.

For short scales less than 3 hours, extreme rainfall events are widespread distributed through Spain while for scales from 4 hours 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 façade, where Atlantic westerlies provides 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 (Martín-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.

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Appendix

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 minutes to 2 years, showing the parameters *a* and *b* and correlation coefficient.

PROVINCE	a	b	r^2
BARCELONA	14.802	0.380	0.978
TARRAGONA	21.884	0.331	0.971
GIRONA	12.119	0.429	0.981
LLEIDA	10.844	0.407	0.982
CANTABRIA	11.487	0.414	0.982
CORDOBA	21.443	0.339	0.971
HUELVA	14.783	0.382	0.978
SEVILLA	9.896	0.431	0.984
JAEN	5.099	0.489	0.991
GRANADA	7.961	0.469	0.986
ALMERIA	31.088	0.313	0.963
CADIZ	10.018	0.484	0.987
MALAGA	19.041	0.407	0.978
ALICANTE	24.895	0.368	0.972
VALENCIA	26.845	0.349	0.969
CASTELLON	17.995	0.364	0.975
TERUEL	9.008	0.420	0.983
HUESCA	10.399	0.456	0.984
ZARAGOZA	9.175	0.392	0.983
GUADALAJARA	5.694	0.434	0.988
CUENCA	9.018	0.417	0.984
TOLEDO	8.976	0.410	0.985
ALBACETE	14.486	0.365	0.977
CIUDAD REAL	4.713	0.453	0.991
LEON	6.045	0.496	0.990
BURGOS	8.341	0.440	0.986
VALLADOLID	6.281	0.398	0.986
PALENCIA	6.061	0.459	0.989
ZAMORA	4.122	0.516	0.993
SORIA	7.987	0.414	0.985
SEGOVIA	6.287	0.425	0.988
AVILA	6.973	0.495	0.989
SALAMANCA	10.007	0.446	0.984
LUGO	5.986	0.497	0.990
PONTEVEDRA	6.699	0.496	0.990
A CORUNA	6.517	0.511	0.990
OURENSE	5.151	0.525	0.992
CACERES	6.447	0.488	0.990
BADAJOZ	8.622	0.410	0.985
NAVARRA	9.694	0.445	0.985
GIPUZKOA	18.090	0.382	0.976
BIZKAIA	13.814	0.385	0.979
ARABA/ALAVA	6.995	0.426	0.987
ASTURIAS	7.836	0.455	0.987
MURCIA	29.560	0.310	0.966
MADRID	9.616	0.410	0.984
LA RIOJA	7.297	0.428	0.985
BALEARES	18.964	0.404	0.978
LAS PALMAS	13.552	0.409	0.980
SANTA CRUZ DE TENERIFE	23.002	0.392	0.975

Supporting Information

This paper is complemented with supporting information listing the 10 highest point-based rainfall values recorded for 38 selected time periods in Spain from AEMET rain-gauge databases. Table S1 contains, for each time period, the following items: CODE (AEMET station code), STATION NAME (Name of the station), CMT (Three letter code of the AEMET regional office in charge of the station), PROVINCE (Spanish administrative province of the station), DATE (Date of the event or initial date for periods longer than 24 hours).

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Table 1. Metadata of the four databases used in this study.

Name	Number of rain gauges	Serie starting year	Median of starting years	Number of registers	
BD10Min	959	1973	2006	3052131	days
BDHour	959	1973	2006	7,5E+07	hours
BDDay	10681	1855	1968	9,2E+07	days
BDMonth	11063	1805	1966	3183192	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 Figure 2 and 3.

	Spanish Extremes				World Extremes		
Duration	Id	Location	Depth [mm]	Date	Location	Depth [mm]	Relation [%]
10 min	1	Cuevas de Nerja, Malaga	41,6	21 Set 2007	N/A	N/A	N/A
20 min	1	Cuevas de Nerja, Malaga	74,2	21 Set 2007	Romania	206	36,0
30 min	2	Sineu, Baleaic 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 hours	4	San Sebastian, Gipuzkoa	193,0	1 Jun 1997	China	489	39,5
3 hours	4	San Sebastian, Gipuzkoa	204,7	1 Jun 1997	USA	724	28,3
4 hours	5	Huercal-Overa, Almeria	216,3	28 Sep 2012	N/A	N/A	N/A
5 hours	5	Huercal-Overa, Almeria	248,3	28 Sep 2012	N/A	N/A	N/A
6 hours	5	Huercal-Overa, Almeria	275,0	28 Sep 2012	China	840	32,7
9 hours	6	Oliva, Valencia	306,4*	0 Nov 1987	La Réunion	1087	28,2
12 hours	6	Oliva, Valencia	408,5*	1 Nov 1987	N/A	N/A	N/A
18 hours	6	Oliva, Valencia	612,8*	2 Nov 1987	La Réunon	1589	38,6
1 day	6	Oliva, Valencia	817,0	3 Nov 1987	La Réunon	1825	44,8
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	24,9
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, Cadiz	1023,2	14-20 Dec 1958	La Réunion	5400	18,9
8 days	9	Grazalema, Cadiz	1099,2	14-21 Dec 1958	La Réunion	5510	19,9
9 days	9	Grazalema, Cadiz	1226,2	14-22 Dec 1958	La Réunion	5512	22,2
10 days	9	Grazalema, Cadiz	1273,6	13-22 Dec 1958	La Réunion	5678	22,4
11 days	9	Grazalema, Cadiz	1277,2	12-22 Dec 1958	La Réunion	5949	21,5
12 days	9	Grazalema, Cadiz	1280,0	12-23 Dec 1958	La Réunion	5949	21,5
13 days	9	Grazalema, Cadiz	1282,2	11-23 Dec 1958	La Réunion	6072	21,1
14 days	9	Grazalema, Cadiz	1282,2	11-23 Dec 1958	La Réunion	6082	21,1
15 days	9	Grazalema, Cadiz	1284,8	9-23 Dec 1958	La Réunion	6083	21,1
20 days	9	Grazalema, Cadiz	1454,1	3-23 Dec 1958	N/A	NA	N/A
31 days	10	Cortes de la Frontera, Malaga	1674,0	18 Nov – 18 Dec 1989	N/A	N/A	N/A
1 natural month		Caldera Taburiente, Santa Cruz de Tenerife	1626,1	1-31 Jan 1979	India	9300	17,5
2 months	10	Cortes de la Frontera, Malaga	2420,0	Dec 1995 – Jan 96	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	3835,8	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

Table 3. Depth – duration scaling properties for each season and geographical domain.

	DJF			MAM			JJA			SON		
	a	**b**	**R^2**	**a**	**b**	**R^2**	**a**	**b**	**R^2**	**a**	**b**	**R^2**
ATL	4,5	0,5	0,992	6,5	0,5	0,989	22,2	0,4	0,973	11,4	0,4	0,983
INT	3,6	0,6	0,993	11,4	0,4	0,982	15,4	0,4	0,977	12,5	0,4	0,981
MED	10,8	0,5	0,985	12,2	0,4	0,983	25,4	0,3	0,970	22,8	0,4	0,976
SBT	13,1	0,5	0,983	28,1	0,3	0,968	7,5	0,3	0,976	16,3	0,4	0,978
SPAIN	12,0	0,5	0,985	20,7	0,4	0,976	30,8	0,3	0,967	22,8	0,4	0,976

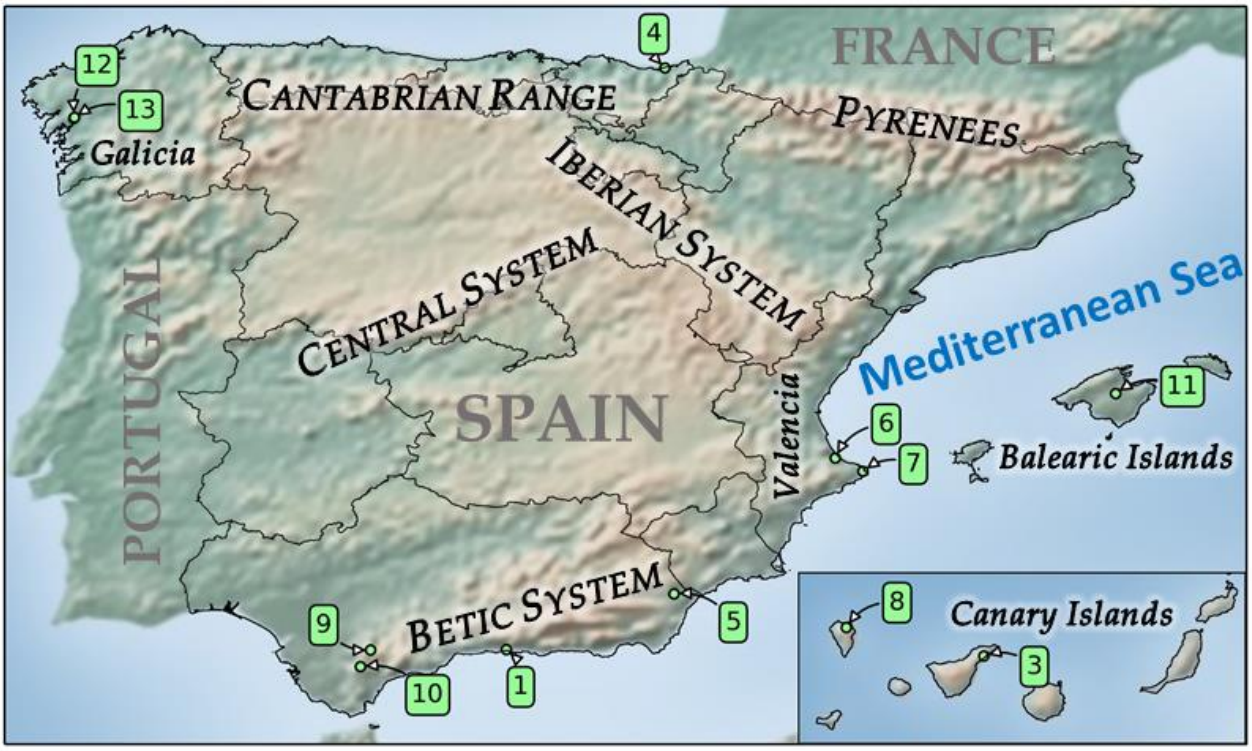

Figure 1. Geographic distribution of the SE and locations used in this study. Green numbers show the episode Id. which produced the extreme rainfall (see table 1). Lower (higher) numbers indicate shorter (larger) scales.

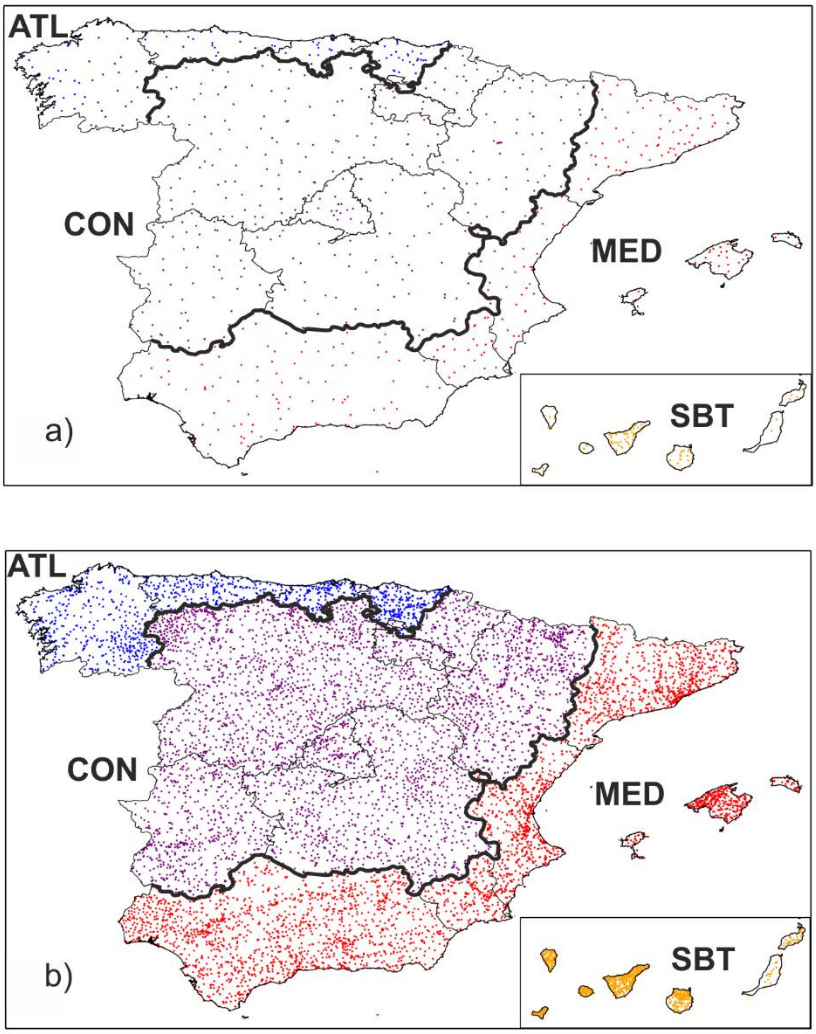

Figure 2. Sub-daily (top panel) and daily (bottom panel) database raingauge locations and regions considered in this study: Atlantic (blue), Mediterranean (red), Continental (purple) and Subtropical (orange).

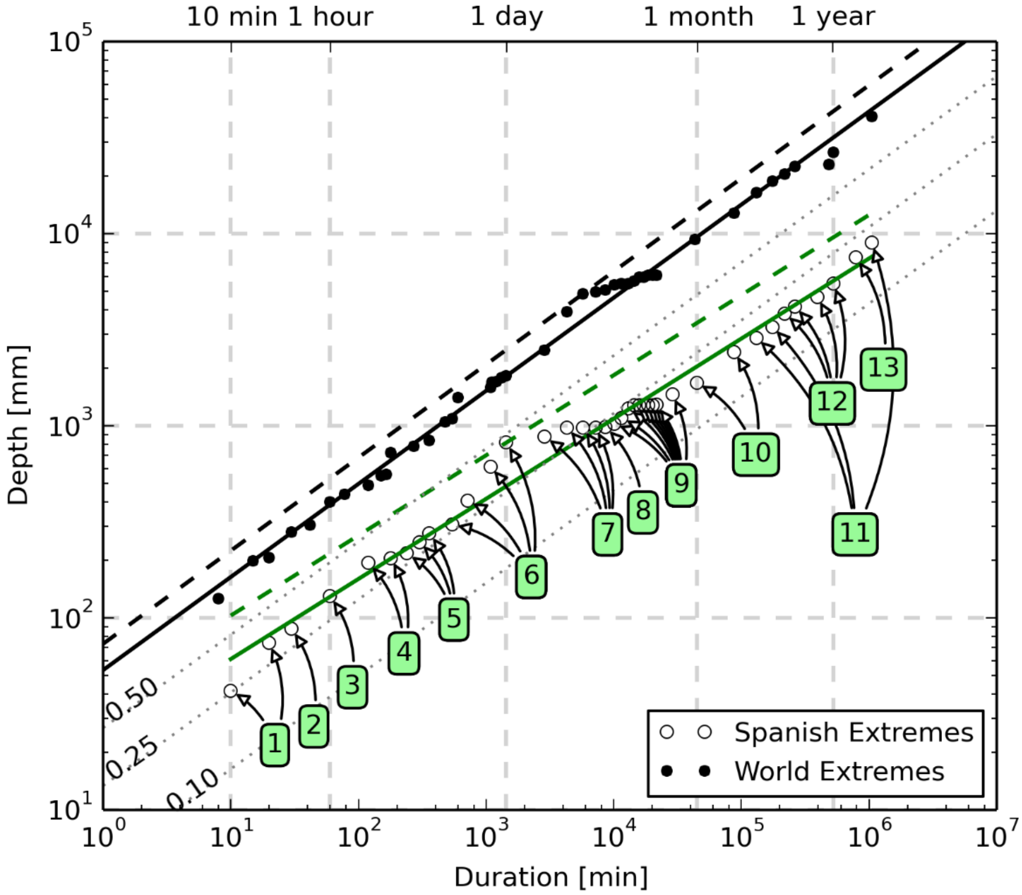

Figure 3. Observed point-based rainfall extremes for different durations for World (black dots) and Spain (green dots). Bold lines correspond to a power law fitting and dashed lines to the data upper envelope scaling. Black dotted lines show the proportion with respect to the WE fitting line as reference (i.e., 0.50 corresponds to 50%). Numbers in green labels show the episode Id which produced the extreme rainfall (see table 1).

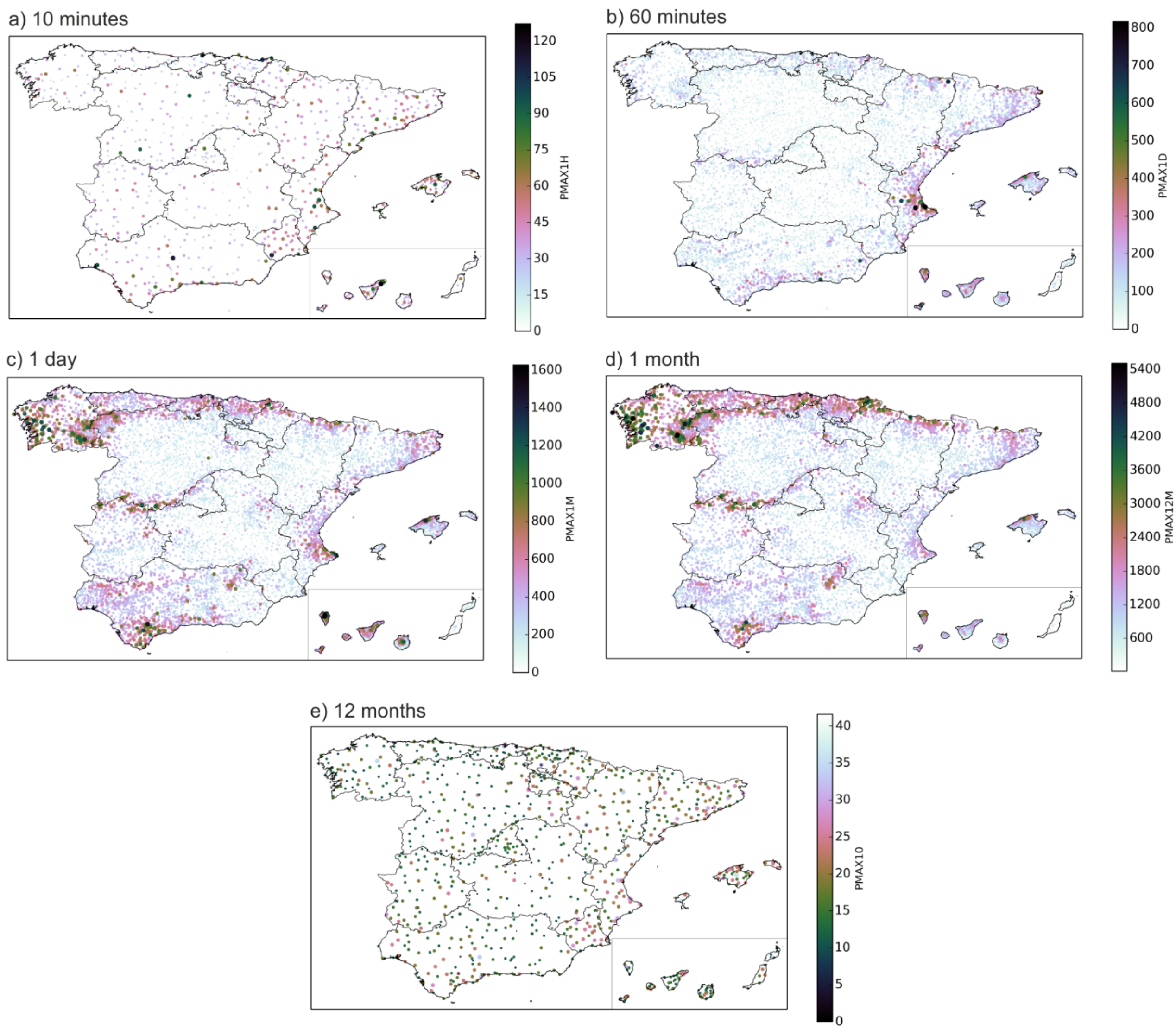

Figure 4. Extreme precipitation [mm] record maps for point-based rain gauge in Spain. Coloured points show the maximum precipitation amount recorded at each location for a) 10 minutes, b) 1 hour, c) 1 day, d) 1 month and e) 1 year.

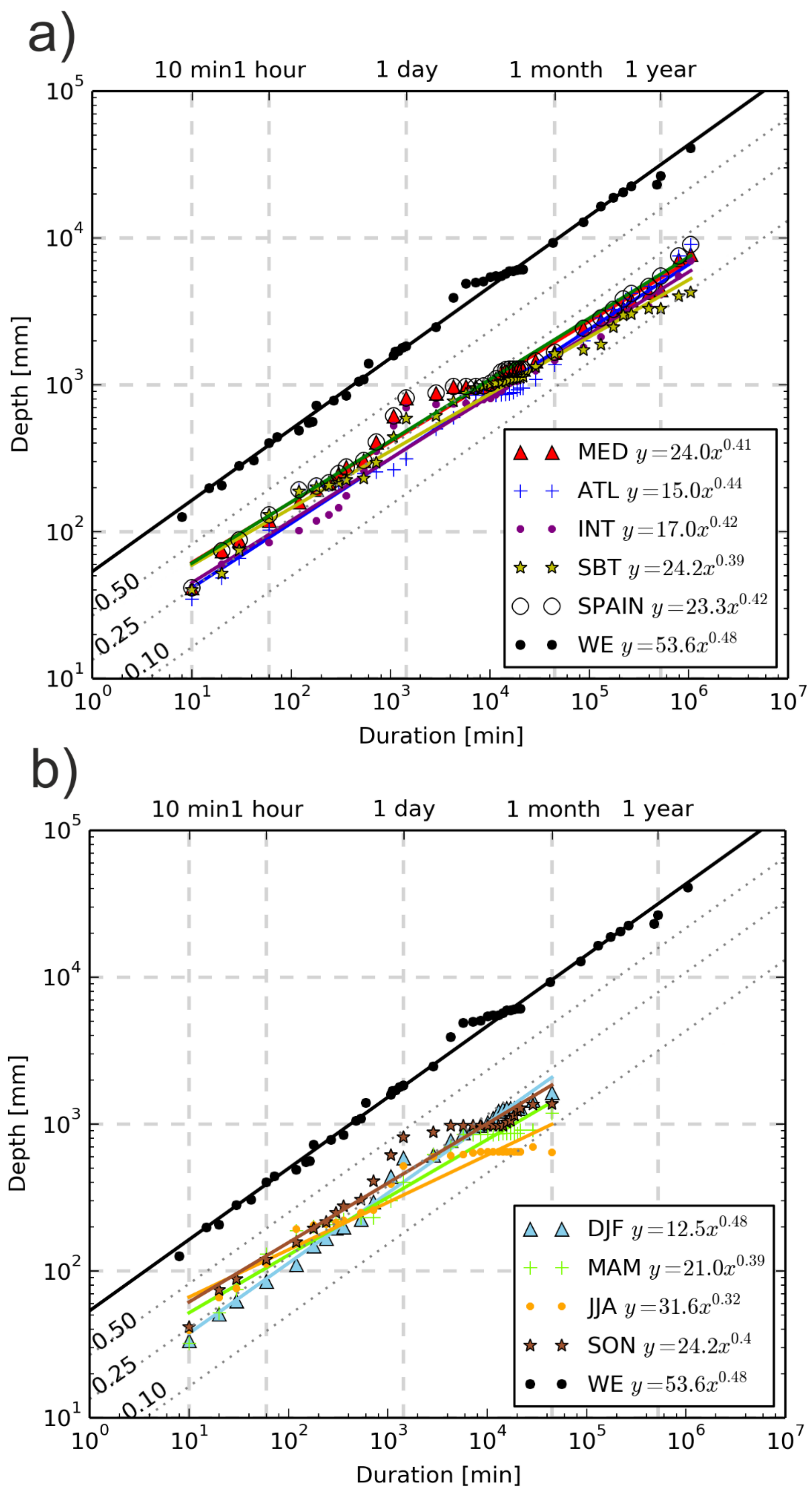

Figure 5. As Figure but showing specific records and scaling for a) each regional domain (coloured circles for each region and empty circles for all-regions record) and b) for each season for

all-regions data. World extremes and scaling are also included for reference.