ATMOSPHERIC SCIENCE LETTERS
Atmos. Sci. Let. (2014)
Published online in Wiley Online Library
(wileyonlinelibrary.com) **DOI:** 10.1002/asl2.507

A ranking of high-resolution daily precipitation extreme events for the Iberian Peninsula

Alexandre M. Ramos,[1]* Ricardo M. Trigo[1] and Margarida L. R. Liberato[1,2]
[1]*Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, 1749–016 Lisboa, Portugal*
[2]*Universidade de Trás-os-Montes e Alto Douro, UTAD, Quinta de Prados, 5000–801 Vila Real, Portugal*

**Correspondence to:*
A. M. Ramos, Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, Campo Grande, Edf. C8, Piso 3, Sala 8.3.1, 1749-016 Lisbon, Portugal.
E-mail: amramos@fc.ul.pt

Received: 5 August 2013
Revised: 21 February 2014
Accepted: 7 April 2014

Abstract

A method for ranking daily precipitation events is presented based on the most comprehensive database of daily gridded precipitation dataset available for the Iberian Peninsula spanning from 1950 to 2008. The magnitude of an event is obtained after considering the area affected as well as its intensity in every grid point and taking into account the daily normalized departure from climatology. Different precipitation rankings are presented considering the entire Iberian Peninsula, Portugal and also the six largest river basins in the Iberian Peninsula.

Keywords: Iberian Peninsula; extreme precipitation; ranking events; high-resolution dataset

1. Introduction

Extreme precipitation events in the Iberian Peninsula (hereafter IP) during winter months have been associated historically with major socioeconomic impacts such as flooding, landslides, extensive property damage and human casualties, and are usually associated to low-pressure systems with Atlantic origin (e.g. Fragoso *et al.*, 2010; Liberato *et al.*, 2013). Frequently, these events have been evaluated on a case-by-case approach, without a systematic assessment. Furthermore, the extent and magnitude evaluation has been performed with relatively few stations.

Fronts and associated depressions over the North Atlantic tend to develop in well-defined favourable areas. The main zones of frontal-wave development correspond to baroclinic prone areas (Barry and Chorley, 2003). This is the case of eastern North America and the eastern Greenland coast, especially in winter and over mid-latitudes, where the variability of the climate is strongly associated with travelling low-pressure systems (Trigo, 2006). In the extended winter (October–March), most cyclones travel along the North Atlantic or, secondarily, through the Azores-Mediterranean axis (Trigo, 2006). Interestingly, a large number of precipitation events in IP are associated with low-pressure systems that do not cross directly over IP. However, it should be noted that most well developed extratropical cyclones often reach up to 2000 km in diameter and that the frontal precipitation associated with extratropical cyclones typically occurs predominately south of the low-pressure centre. In the IP, extratropical cyclone precipitation represents between 65 and 75% of the total precipitation (Hawcroft *et al.*, 2012). This is confirmed by other works that have devised automated atmospheric classification procedures over IP (e.g. Trigo and DaCamara, 2000). These authors show that days classified as cyclonic, or with predominant flow from west or southwest account for ~65% of the precipitation although their frequency is just about 30% of the winter days.

Analysing precipitation events and rank them is not straightforward, as it depends not only on the precipitation dataset available, but also crucially on the criteria as well as on the purpose of the study. Some authors select extreme events based on socioeconomic impacts (e.g. Fragoso *et al.*, 2010; Liberato *et al.*, 2011), whereas others analyse precipitation extremes based on different selection criteria (e.g. Liberato *et al.*, 2013; Pinto *et al.*, 2013). Moreover, to the best of our knowledge, there is no study with a precipitation rank classification of top extreme events covering the entire IP with a high-resolution dataset.

In this study, the main objective is to develop several objective rankings of extreme precipitation events relative to the entire IP and some subregions, namely the six largest river basins. We use a seasonal-dependent definition for extreme event emphasizing that these must have large departures from climatology. Moreover, it should be stressed that the establishment of these rankings is independent from the occurrence of significant socioeconomic impacts. The events will be characterized by daily high-precipitation sums that influenced relatively large areas.

2. Datasets

In this work, the most comprehensive database of daily precipitation sum available for continental IP

© 2014 Royal Meteorological Society

(IB02) was used. It results from the combination of two national datasets recently made available, 'Spain02' for peninsular Spain and Balearic islands (Herrera *et al.*, 2012), and 'PT02' for mainland Portugal (Belo-Pereira *et al.*, 2011). The database spans from 1950 to 2008, with a spatial resolution of 0.2° latitude/longitude grid. These databases are based on a dense network of rain gauges, combining a total of more than 2000 stations over Spain and 800 stations over Portugal, all quality controlled and homogenized. This large number of stations is crucial to allow meaningful regional assessments of extreme precipitation over medium-size river basins.

It is important to mention that there are differences in the daily accumulation period considered for the Spanish and Portuguese datasets. Thus, daily precipitation records obtained in Portugal for any given day n correspond to the precipitation registered between 0900 UTC of day $n-1$ and 0900 UTC of day n. On the contrary precipitation records obtained in Spain for the same day n correspond to the precipitation registered between 0700 UTC of day n and 0700 UTC of day $n+1$ (notice the difference in both the hours and the days). Therefore in order to derive the most consistent common dataset, we have shifted the Portuguese daily precipitation by 1 day.

However, despite this adjustment when using the dataset one should keep in mind that the 2 h lag between the two original dataset which could be a limitation of the database especially for those precipitation events that can have their peak during this 2-h window. Despite this, in the original paper presenting the database, Belo-Pereira et al. (2011), the following is mentioned in the conclusions: 'Although IB02 is a combination of two different datasets, albeit with a common grid, there is no evidence of artificial features at the border between Portugal and Spain, neither at the monthly scale nor at finer scales, including daily results'. The largest concentration of rainfall in the IP is recorded between October and March (Trigo and DaCamara, 2000). In fact, over most sectors of IP the precipitation accumulated between October and March represents more than two-third of the total annual precipitation. Summer precipitation is not significant except in northern mountainous sectors such as Pyrenees and also close to the Mediterranean coast, where intense downpours can occur, often associated with Mesoscale Convective Systems (García-Herrera *et al.*, 2005). Therefore, the analysis presented here will be restricted to the extended winter (October–March).

3. Ranking precipitation anomalies

In the IP, winter large-scale precipitation hardly affects the entire IP simultaneously (Cortesi *et al.*, 2013). Thus, the method described below was applied to characterize and rank each extended winter day taking into account not only the severity of the precipitation but also its spatial extension.

The method applied in this work is partially adapted from the approach initially proposed by Hart and Grumm (2001) that have suggested some criteria to classify each day in terms of extremeness. For that, we use normalized precipitation departures from the seasonal climatology, where for each day and each grid point a measure of event rarity is given by:

$$N = \frac{\text{Prec} - \mu}{\sigma} \tag{1}$$

where Prec is the precipitation value for a particular day and grid point, μ is the Julian daily mean value for that grid point and σ is the standard deviation (std) from this daily mean. A 7-day running mean was applied in order to smooth the daily mean and the std noisy climatological time series. This was performed instead of a monthly mean climatology to avoid artefacts at monthly edges. The reference period for the computation of the daily mean and std was the entire period of analysis 1950–2008 where only the days with daily precipitation above 1 mm (wet days) were taken into account. This approach has been used with success in other applications where the authors assess heavy large-scale precipitation events in the Czech Republic (Kaspar and Müller, 2008) or the standardized anomaly fields to anticipate extreme rainfall in the mountains of Northern California (Junker *et al.*, 2008).

Thus for each day and for each grid point a normalized departure from climatology is attained. As we are only interested in the upper part of the distribution (intense precipitation events), a new computation was done where the magnitude or rarity of an event (hereafter R) is given daily by an index that is obtained after multiplying:

1. the area (hereafter A, in percentage) that has precipitation anomalies above two std (2std)
2. the mean value of these anomalies (hereafter M) for all the grid points that are characterized by precipitation anomalies above the two std.

The 2std threshold corresponds approximately to the 95% percentile of the daily precipitation distribution throughout the domain (in the extended winter months). It must be acknowledged that the normalization procedure applied to the daily gridded precipitation does not ensure a typical Gaussian distribution in each grid point. Nevertheless the 2std threshold ensures a robust limit that is similar to the 95th percentile threshold often used in similar studies.

We have also assessed the sensitivity of our ranking to the temporal length of the smoothing filter. It was found that using a 21-day running mean (instead of a 7-day) does not alter significantly the days included in the Top #50, although some days appear in different rank order.

We have applied the methodology to different domains in the IP (Figure 1). Results will be presented not only for continental IP but also for Portugal and to the most important river basins (Minho, Douro, Tagus, Guadiana, Guadalquivir and Ebro) of the IP.

© 2014 Royal Meteorological Society

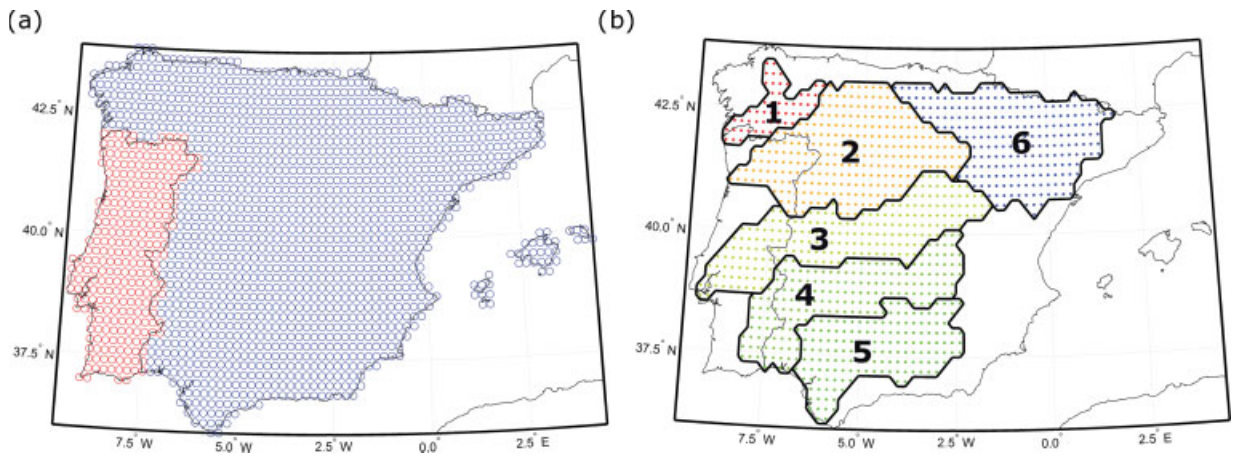

Figure 1. The 0.2° resolution precipitation dataset domain used in the computation of the anomalous precipitation rakings for the eight domains considered. (a) Iberian Peninsula (red and blue grid points) and Portugal (red grid points). (b) The six river basins correspond to (1) Minho; (2) Duero; (3) Tagus; (4) Guadiana; (5) Guadalquivir and (6) Ebro.

4. Results

The repeated application of the methodology described above allows us to derive a normalized ranking of events for each of the eight different domains considered (and therefore eight individual ranking lists) which can be used in different applications depending on the purpose of the study. In the present work, only a few examples of Top #10 events for different domains and the precipitation fields corresponding to the most anomalous days will be shown as example and to illustrate the relevance of the method. It should be stressed that not all days included in the top rank had necessarily severe impacts and the opposite is also true, i.e. some days characterized by fatalities or socioeconomic disruption may be ranked in relative modest places.

4.1. Iberian Peninsula and Portugal domains

In Table I, the Top #10 anomalous days for the whole IP (Table I(a)) and Portugal (Table I(b)) domains (Figure 1) are presented along with the area that has precipitation anomalies above two std (A) and the mean value of these anomalies over area A that is above two std (M). Moreover, the final index $R = A \times M$ used for ranking the days is also shown. The days that are coincident in the Top #10 of both domains are highlighted in bold. In particular, the cases in the Portuguese domain: #1 (12 March 1969), #3 (15 February 1963) and #5 (6 February 2001) correspond to the #3, #10 and #5, respectively, in the raking of the IP domain. The spatial variability of the IP precipitation regime and its links with the main precipitation synoptic patterns provide some contextual background for this result (Cortesi *et al.*, 2013). The authors show that days characterized by generalized precipitation over the whole IP are unusual and generally related to frontal systems associated with extratropical cyclones located north of IP. In fact, looking in detail to the percentage of the IP area holds the highest daily value of A corresponds to ~43% on 6 November 1982.

Table I. The ten most anomalous precipitation events for (a) Iberian Peninsula and (b) Portugal.

Year	Month	Day	A (%) = Area > 2std	M = Mean$_{std}$ > 2std	$R = A \times M$	#
(a) Iberian Peninsula						
1982	11	6	42.98	3.57	153.54	1
1997	11	5	32.88	4.45	146.18	2
1969	**3**	**12**	**34.01**	**4.07**	**138.40**	**3**
1997	12	17	37.18	3.55	132.08	4
2001	**2**	**6**	**29.77**	**4.34**	**129.33**	**5**
1979	2	10	36.88	3.39	125.14	6
2006	10	22	32.52	3.76	122.16	7
1972	2	2	28.21	4.20	118.49	8
2001	3	1	37.18	3.17	117.81	9
1963	**2**	**15**	**28.75**	**3.75**	**107.69**	**10**
(b) Portugal						
1969	**3**	**12**	**87.18**	**4.80**	**418.76**	**1**
1956	3	22	87.18	4.38	381.84	2
1963	**2**	**15**	**89.01**	**4.22**	**375.44**	**3**
2000	12	6	80.59	4.61	371.19	4
2001	**2**	**6**	**82.42**	**4.50**	**370.57**	**5**
1952	3	27	78.75	4.30	338.62	6
1951	11	4	79.85	4.14	330.85	7
1979	10	5	67.40	4.52	304.45	8
1958	1	27	74.73	3.80	283.74	9
1970	1	17	72.16	3.92	283.17	10

The first three columns correspond to the date of the event. Column A corresponds to the area (in %) of the domain that has precipitation anomalies above two standard deviation. Column M corresponds to mean value of these anomalies over area A that is above two standard deviation is also represented. Column R corresponds to the final rank index used for ranking the days. The final column corresponds to the ranking of the event.

The method was developed to take into consideration two factors, namely the area of influence of the precipitation (given by the anomalies above a certain threshold) and the intensity of the event (given by the mean values of the anomalies above a certain threshold), which is clearly evident when analysing in detail the top 3 values for the IP domain (Figure 2). The top ranking event (Figure 2(a)) corresponds to 6 November 1982 where generalized and intense precipitation

© 2014 Royal Meteorological Society

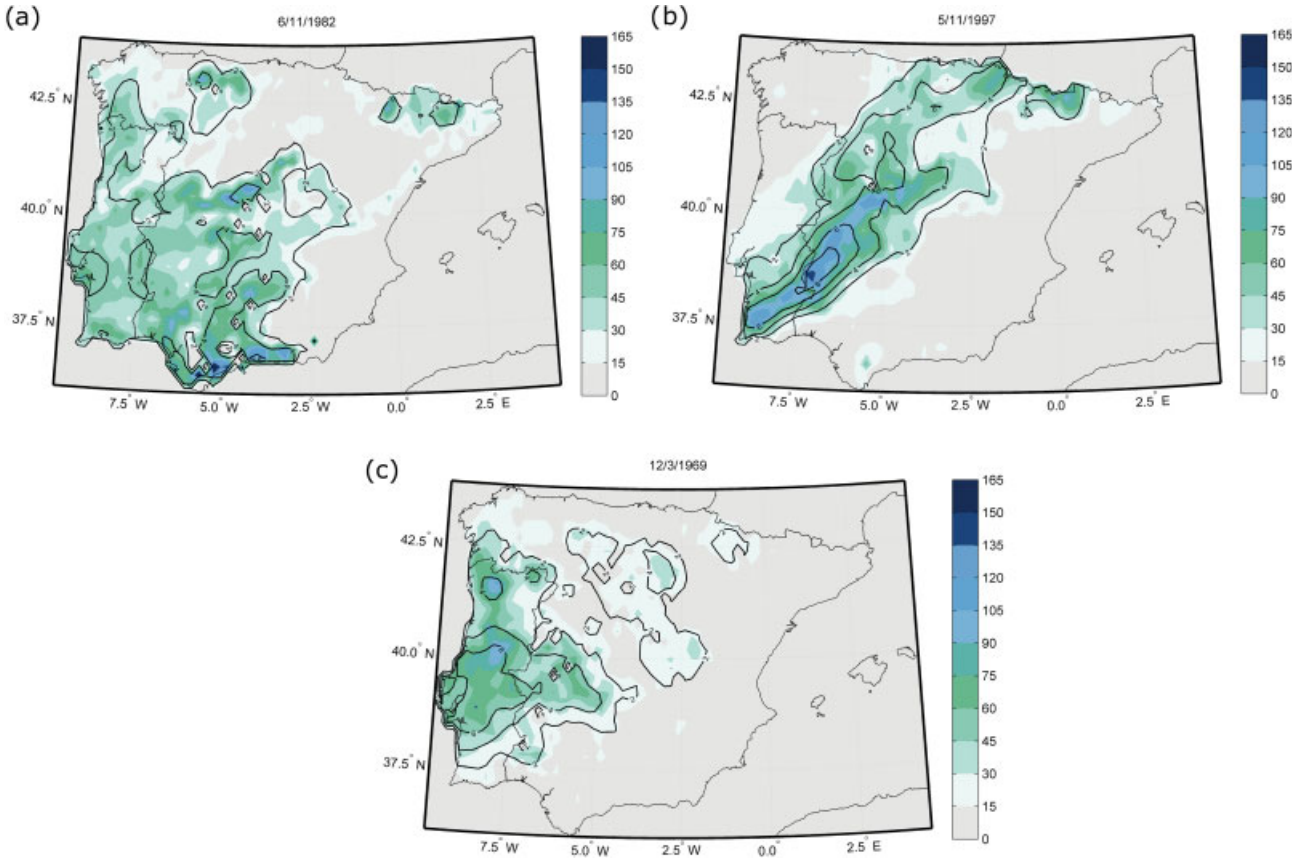

Figure 2. Daily accumulated precipitation (mm, shaded) and corresponding standard deviation anomalies (black contour) of the top three anomalous events in the Iberian Peninsula domain. (a) 6 November 1982; (b) 5 November 1997 and (c) 12 March 1969. The standard deviation anomalies were smoothed with the neighbour grid points.

occurs in the western part of the domain, along with some intense precipitation occurring in some parts of the Pyrenees. This event had been referenced by some authors due to its major socioeconomic impacts in Spain (Olcina-Cantos, 1994). It is important to stress that some important precipitation occurred also in the following day, namely on 7 November 1982 (ranking #14), where some intense precipitation occurred but more localized over Catalonia and in central and southern Spain. In terms of the synoptic pattern, these 2 days were characterized by a very deep low-pressure system with a cold core located over northwest Spain with its associated fronts crossing the Iberian Peninsula from the southwest headed for the northeast. This synoptic configuration led to an advection of warm and moist air from the Mediterranean basin towards the Pyrenees, which associated with the cold air aloft, triggered very deep convection and consequently heavy precipitation. The second top event in the IP ranking corresponds to 5 November 1997, a more localized event ($A = 32.9\%$ of the domain) and characterized by an extended band of precipitation with a SW-NE orientation (Figure 2(b)). However, it was more intense ($M = 4.5$) than the top rank event and produced major socioeconomic impacts with 11 deaths in Portugal and 21 in Spain (Ramos and Reis, 2001). According to Lorente *et al.* (2008), this event was due to a cut-off-low that deepened quickly and extended to lower levels just before leaving the Atlantic Ocean. This configuration implied a substantial increase of the large atmospheric instability and consequently triggered strong convection that played a fundamental role in the development of several Mesoscale Convective Systems.

The third top event in the ranking of the IP domain, 12 March 1969 (Figure 2(c)), corresponds to the first top rank event for the Portuguese domain. This day is characterized by intense precipitation mainly in Portugal and continuous 'Extremadura' region in Spain, where the A (M) index reaches around 87% (4.8) in the Portuguese domain and 34% (4.1) over the entire IP domain. Despite its top rank position for the Portuguese domain, there is scarce information on socioeconomic impacts in the newspapers and available literature.

As mentioned before, the method was developed to identify and characterize anomalous and widespread precipitation values over the Iberian Peninsula associated with large-scale synoptic events despite causing (or not) human fatalities or important socioeconomic impacts. Conversely, we would like to stress again that some of the extreme precipitation episodes that have caused significant damages and/or deaths are often associated with extreme precipitation at a more local scale. We now present two examples of such events that have affected the Lisbon area and are still remembered by a large fraction of the population, being often referred by the media as benchmark events.

© 2014 Royal Meteorological Society

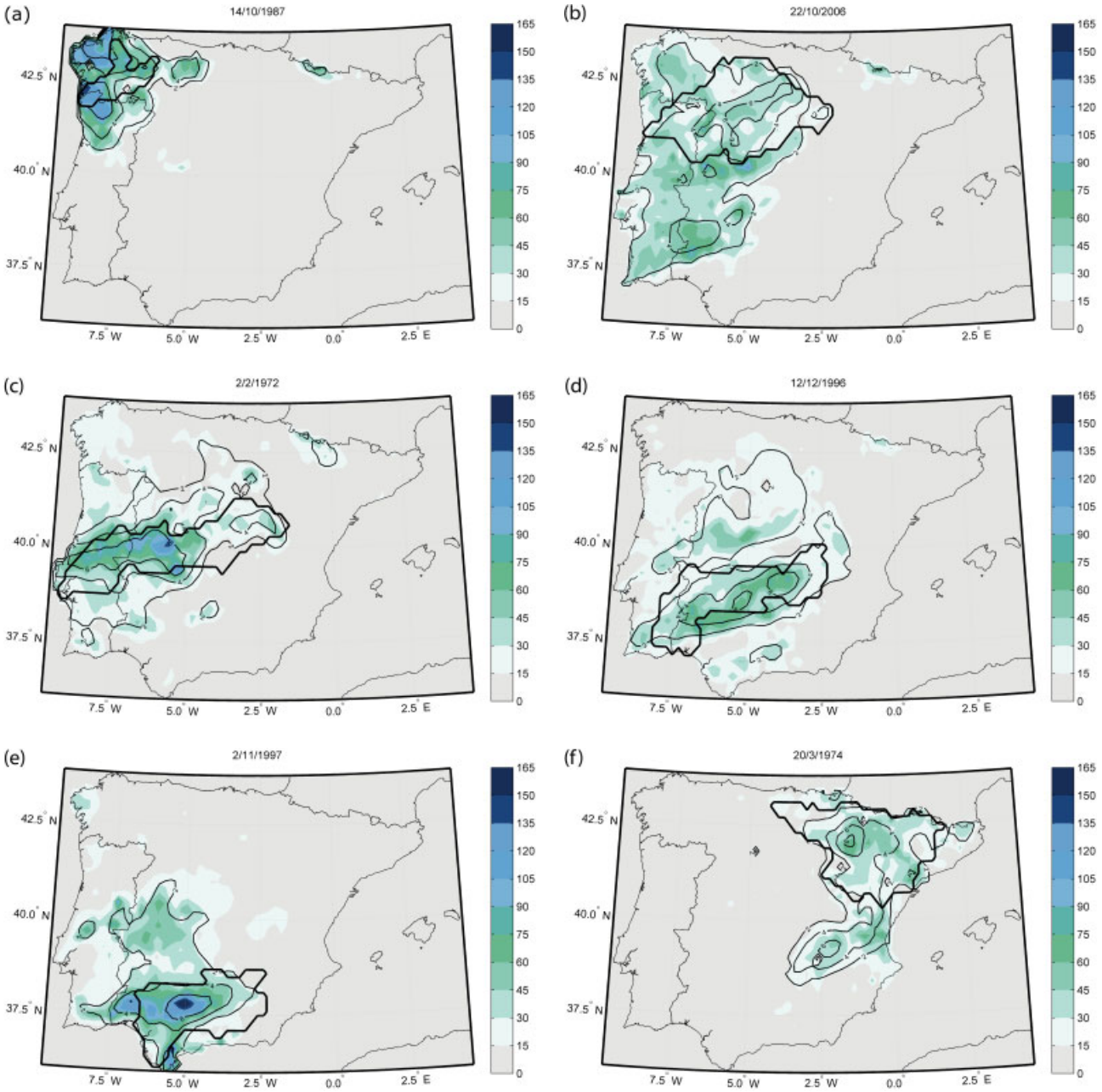

Figure 3. Daily accumulated precipitation (mm, shaded) and corresponding standard deviation anomalies (black contour) of the most anomalous event in each river basin. (a) Minho (14 October 1987); (b) Duero (22 October 2006); (c) Tagus (2 February 1972); (d) Guadiana (12 December 1996); (e) Guadalquivir (2 November 1997) and (f) Ebro (20 March 1974). The standard deviation anomalies were smoothed with the neighbour grid points. Each river basin domain is also highlighted with a thick black contour.

On 18–19 November 1983, Lisbon was struck by the heaviest precipitation event during the 20th century, immediately followed by widespread urban flash flooding and dozens of landslides around Lisbon (Zêzere *et al.*, 2005) and the human lives losses were estimated to be of ten fatalities (Liberato *et al.*, 2013). However, these 2 days (18 and 19 November 1983) do not stand high in our classification for Portugal because they affected a relatively small area (although very intensively). Thus, the 18 and the 19 November correspond to the #142 day ($A = 20.8\%$ and $M = 5.2$) and the #145 day ($A = 35.5\%$ and $M = 3.0$), respectively. It must be stressed that some of the impacts mentioned, namely floods and landslides, were also amplified by the fact that it had rained substantially in the weeks prior to this event (Zêzere *et al.*, 2005).

The second and more recent localized extreme event corresponds to the rainiest day on record since December 1863 at the Lisbon's Dom Luiz Observatory (118.4 mm), which took place, on 18 February 2008 (Fragoso *et al.*, 2010). According to the Portuguese official authorities there were a total of four deaths, 65 people dislodged and 121 evacuated in safety and rescue operations. Nevertheless, in terms of the Portuguese ranking, this day was characterized by indices even lower than those for the previous

© 2014 Royal Meteorological Society

case study with only the rank #242 ($A = 24.2\%$ and $M = 3.0$).

4.2. River basins

In order to study the important precipitation events that can have impact in different river catchments, the method was also applied to six important river basins located in the IP. Four of these basins correspond to the major international rivers located in the IP (Minho, Douro, Tagus and Guadiana) and the other two, Guadalquivir and Ebro, correspond to the two largest river basins located solely in Spain (Figure 1(b)). The results for the most anomalous day for each river basin are shown in Figure 3. Each river basin is also represented in maps with a 0.2° resolution (similar to the precipitation grid) and the method was applied taking into account only the grid points that fall inside the considered river basin. For the sake of simplicity, only one example for river Tagus basin (Figure 3(c)) will be analysed. This event occurred on 2 February 1972 and was characterized by generalized precipitation in the central region of the IP, being more intense and anomalous inside the river basin and along the 40°N parallel. In fact, the event presents very high indices ($A = 83.6\%$ and $M = 5.2$).

In the case of the river basins, the spatial precipitation variability assumes even more importance. For example, most of the Top #25 events in the Ebro basin (not shown) correspond to days with precipitation falling only in the N/NE and E quadrants of the IP (Llasat *et al.*, 2007). On the contrary, for the Tagus and Douro basins, these Top #25 events are generally characterized by widespread precipitation in the western and central IP. This result confirms the one found by Cortesi *et al.* (2013) about the spatial variability of precipitation in the IP and its dependence on the predominant direction of the atmospheric flow. In addition, the examples shown for the river basins prove that the method can also be useful when applied to smaller subregions.

5. Final remarks

In this study, we present a method for ranking of precipitation events in the Iberian Peninsula and some subregions, namely Portugal and several large river basins. The magnitude of an event is characterized not only by the area affected but also by its average intensity. Moreover, it should be stressed out that the establishment of these rankings is independent from the occurrence of significant socioeconomic impacts as shown for different examples presented. The apparent mismatch between top rank positions detected here and ranks of events that have caused large economic damage or human fatalities can be attributed to different issues: (1) the duration of the event is not taken into account in the ranking because we are using daily accumulated precipitation, (2) some of the hydrometeorological extreme events such as landslides or flash floods are dependent on previous weekly or monthly accumulated precipitation and soil moisture saturation, (3) generally speaking the risk is a function not only of the hazard but also of the values of the goods exposed and their vulnerability. In this regard, quite often the areas characterized by intense precipitation anomalies do not correspond to dense population, buildings and transport networks.

The authors would like to point out that the eight different daily rankings (IP, Portugal and the six river basins) will be available to the scientific community at the webpage of the author's research group (http://idlcc.fc.ul.pt/).

Finally, it should be stressed out that the method can be easily adapted to find cases that are more intense and/or more localized. For that the std threshold should be tuned to higher values (e.g. 3 or 4 std) in order to restrict the anomalous precipitation over localized areas. Future work will consider the hydrological responses to heavy precipitation events, using new rankings taking into account the sum of the normalized anomalies over different time periods. This information is currently being analysed in the context of river floods in the main river basins of the IP and as they are out of the scope of the present work they are not shown.

Acknowledgements

This work was partially supported by FEDER funds through the COMPETE (Programa Operacional Factores de Competitividade) Programme and by national funds through FCT (Fundação para a Ciência e a Tecnologia, Portugal) through project STORMEx FCOMP-01-0124-FEDER-019524 (PTDC/AAC-CLI/121339/2010). A. M. Ramos was also supported by a postdoctoral grant (FCT/DFRH/SFRH/BPD/84328/2012). The authors thank the Portuguese and Spanish Meteorology Institutes for gridded precipitation dataset used in this work (PT02 and SPAIN02, respectively).

References

Barry RG, Chorley RJ. 2003. *Atmosphere, Weather and Climate*, 8th ed. London: Routledge.

Belo-Pereira M, Dutra E, Viterbo P. 2011. Evaluation of global precipitation data sets over the Iberian Peninsula. *Journal of Geophysical Research* **116**: D20101.

Cortesi N, Gonzalez-Hidalgo JC, Trigo RM, Ramos AM. 2013. Weather types and spatial variability of precipitation in the Iberian Peninsula. *International Journal of Climatology* , DOI: 10.1002/joc.3866.

Fragoso M, Trigo RM, Zêzere L, Valente MA. 2010. The exceptional rainfall episode registered in Lisbon in 18 February. *Weather* **65**: 31–35.

García-Herrera R, Barriopedro D, Hernández E, Paredes D, Correoso JF, Prieto L. 2005. The 2001 Mesoscale Convective Systems over Iberia and the Balearic Islands. *Meteorology and Atmospheric Physics* **90**: 225–243.

Hart RE, Grumm RH. 2001. Using normalized climatological anomalies to rank synoptic-scale events objectively. *Monthly Weather Review* **129**: 2426–2442.

Hawcroft MK, Shaffrey LC, Hodges KI, Dacre HF. 2012. How much Northern Hemisphere precipitation is associated with extratropical cyclones? *Geophysical Research Letters* **39**: L24809.

Herrera S, Gutiérrez JM, Ancell R, Pons MR, Frías MD, Fernández J. 2012. Development and analysis of a 50-year high-resolution

© 2014 Royal Meteorological Society

daily gridded precipitation dataset over Spain (Spain02). *International Journal of Climatology* **32**: 74–85.

Junker NW, Grumm RH, Hart R, Bosart LF, Bell KM, Pereira FJ. 2008. Use of standardized anomaly fields to anticipate extreme rainfall in the mountains of Northern California. *Weather Forecasting* **23**: 336–356.

Kaspar M, Müller M. 2008. Selection of historic heavy large-scale rainfall events in the Czech Republic. *Natural Hazards and Earth System Sciences* **8**: 1359–1367.

Liberato MRL, Pinto JG, Trigo IF, Trigo RM. 2011. Klaus – an exceptional winter storm over Northern Iberia and Southern France. *Weather* **66**: 330–334.

Liberato MLR, Ramos AM, Trigo RM, Trigo IF, Durán-Quesada AM, Nieto R, Gimeno L. 2013. Moisture sources and large-scale dynamics associated with a flash flood event. In *Lagrangian Modeling of the Atmosphere*, Lin J, Brunner D, Gerbig C, Stohl A, Luhar A, Webley P (eds). American Geophysical Union: Washington, DC, DOI: 10.1029/2012GM001244.

Llasat MC, Martín F, Barrera A. 2007. From the concept of "kaltluftropfen" (cold air pool) to the cut-off low. The case of September 1971 in Spain as an example of their role in heavy rainfalls. *Meteorology and Atmospheric Physics* **96**: 43–60.

Lorente P, Hernández E, Queralt S, Ribera P. 2008. The flood event that affected Badajoz in November 1997. *Advances in Geosciences* **16**: 73–80.

Olcina-Cantos J. 1994. *Riesgos climáticos en la Peninsula Ibérica*. Penthalon: Madrid.

Pinto JG, Ulbrich S, Parodi A, Rudari R, Boni G, Ulbrich U. 2013. Identification and ranking of extraordinary rainfall events over Northwest Italy: the role of Atlantic moisture. *Journal of Geophysical Research: Atmospheres* **118**: 2085–2097.

Ramos C, Reis E. 2001. As Cheias no Sul de Portugal em Diferentes Tipos de Bacias Hidrográficas. *Finisterra* **71**: 61–82.

Trigo IF. 2006. Climatology and interannual variability of storm-tracks in the Euro-Atlantic sector: a comparison between ERA-40 and NCEP/NCAR reanalyses. *Climate Dynamics* **26**: 127–143.

Trigo RM, DaCamara CC. 2000. Circulation weather types and their influence on the precipitation regime in Portugal. *International Journal of Climatology* **20**: 1559–1581.

Zêzere JL, Trigo RM, Trigo IF. 2005. Shallow and deep landslides induced by rainfall in the Lisbon region (Portugal): assessment of relationships with the North Atlantic Oscillation. *Natural Hazards and Earth System Sciences* **5**: 331–344.

© 2014 Royal Meteorological Society