Daily Precipitation Extreme Events in the Iberian Peninsula and Its Association with Atmospheric Rivers*

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ABSTRACT

An automated atmospheric rivers (ARs) detection algorithm is used for the North Atlantic Ocean basin that allows the identification and a comprehensive characterization of the major AR events that affected the Iberian Peninsula over the 1948–2012 period. The extreme precipitation days in the Iberian Peninsula and their association (or not) with the occurrence of ARs is analyzed in detail. The extreme precipitation days are ranked by their magnitude and are obtained after considering 1) the area affected and 2) the precipitation intensity. Different rankings are presented for the entire Iberian Peninsula, for Portugal, and for the six largest Iberian river basins (Minho, Duero, Tagus, Guadiana, Guadalquivir, and Ebro) covering the 1950–2008 period. Results show that the association between ARs and extreme precipitation days in the western domains (Portugal, Minho, Tagus, and Duero) is noteworthy, while for the eastern and southern basins (Ebro, Guadiana, and Guadalquivir) the impact of ARs is reduced. In addition, the contribution from ARs toward the extreme precipitation ranking list is not homogenous, playing an overwhelming role for the most extreme precipitation days but decreasing significantly with the less extreme precipitation days. Moreover, and given the narrow nature of the ARs, the location of the ARs over each subdomain is closely related to the occurrence (or not) of extreme precipitation days.

1. Introduction

Understanding the complexity of the water cycle (sources, sinks, and transport) in the atmosphere continues to be an important topic within the meteorological and hydrological communities (Gimeno et al. 2012). Within this context, particular attention has been devoted in the last decade to the important role played by

atmospheric rivers (ARs; e.g., Ralph and Dettinger 2011; Gimeno et al. 2014). ARs are relatively narrow regions of concentrated water vapor (WV) and strong wind responsible for intense horizontal moisture transport in the lower atmosphere (Newell et al. 1992; Ralph et al. 2006). It was shown that more than 90% of the meridional WV transport in the midlatitudes occurs in these ARs, although they cover less than 10% of the area of the globe (Zhu and Newell 1998).

The analysis of the contribution of ARs to extreme precipitation events has been restricted to a few areas of the world, with a strong focus on the eastern North Pacific and their associated impacts on the contiguous North American west coast (Neiman et al. 2008; Ralph and Dettinger 2012). Over Europe, the large amount of WV that is transported by the ARs can also lead to extreme precipitation events and flooding, as described for

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a few specific extreme events (Liberato et al. 2012; Trigo et al. 2014; Stohl et al. 2008; Lavers et al. 2011) but also in a climatological context (e.g., Lavers et al. 2012). Lavers and Villarini (2013) have shown a strong relationship between ARs and the occurrence of annual maxima precipitation days in western Europe. This relationship is especially strong along the western European seaboard, with some areas having 8 of their top 10 annual maxima precipitation days related to ARs. The effects of ARs are also seen as far inland as Germany and Poland.

ARs are capable of transporting large amounts of moisture from other tropical reservoir source regions of the globe, particularly in the Northern Hemisphere (Knippertz and Wernli 2010; Zhu and Newell 1998; Sodemann and Stohl 2013). Bao et al. (2006) point out the dominant role of moisture convergence for forming AR-like bands of high integrated water vapor. More recently, Sodemann and Stohl (2013) studied the moisture origin and meridional transport in ARs and their association with cyclones affecting Norway for a short period (December 2006). The prevalence of ARs in the water cycle and their role in continental weather has become more evident with the arrival of microwave remote sensing from satellites, notably the Special Sensor Microwave Imager (SSM/I). This sensor has allowed frequent global measurements of the atmospheric column's total water vapor [integrated water vapor (IWV)] over the oceans, particularly from 1998 onward, where its spatiotemporal coverage became adequate (Wentz and Spencer 1998). In addition, several field experiments (focused on the eastern Pacific and western North America) have explored the physical characteristics of ARs (e.g., Ralph et al. 2005). In recent years, the use of reanalysis data allowed for the study of ARs prior to 1998 (e.g., Lavers et al. 2012; Rutz et al. 2014).

In summary, the detection of the ARs is usually achieved through the implementation of two different main approaches. The first methodology considers the use of the IWV, acquired mainly from the SSM/I (e.g., Ralph et al. 2004; Guan et al. 2010; Ralph and Dettinger 2011). The second approach is based on the use of the vertically integrated horizontal water vapor transport (IVT) between 1000 and 300 hPa, computed from different reanalysis datasets, or from general circulation models (e.g., Zhu and Newell 1998; Lavers et al. 2013). A review of the different methods to identify atmospheric rivers can be seen in Gimeno et al. (2014).

In the Iberian Peninsula (IP), extreme precipitation events during the winter months have been associated historically with major socioeconomic impacts such as flooding, landslides, extensive property damage, and human casualties and are usually associated with low

pressure systems of Atlantic origin (e.g., Fragoso et al. 2010; Zêzere et al. 2014; Liberato et al. 2012; Liberato 2014). In addition, the timing of hydrometeorological hazards in Iberia is region dependent, being concentrated in late autumn and winter over western and central Iberia (Cortesi et al. 2013; Zêzere et al. 2014) and during summer and early autumn over the eastern sector (Cortesi et al. 2013). However, as stated before, we are mostly interested in the extended winter season and therefore on the role played by Atlantic low pressure systems as they move into the region (Ulbrich and Christoph 1999; Trigo et al. 2004; Liberato and Trigo 2014).

The message given when discussing extreme precipitation events is often dependent on the precipitation dataset analyzed, particularly in what concerns its spatial and temporal resolution and total length. Similarly to other regions of the world, extreme precipitation analysis for Iberia is also dependent on the nature of the study undertaken. While some authors analyze extreme events by taking into account their associated socioeconomic impacts (e.g., Fragoso et al. 2010; Liberato et al. 2011; Trigo et al. 2014), others tend to assess precipitation extremes based exclusively on objective selection criteria (e.g., Liberato et al. 2012; Pinto et al. 2013). Ramos et al. (2014) developed a method to rank precipitation events for the entire IP and several subdomains, which takes into account the intensity of the precipitation but also its spatial extent over the IP (please see section 2a for additional details). However, that preliminary study on precipitation extremes is a pure statistical estimation and is thus lacking any assessment of the physical mechanisms responsible for such extreme episodes. Therefore, one of the main aims for this work is to investigate systematically to what extent ARs have contributed to just a few (or most) precipitation extreme events ranked previously in Ramos et al. (2014). To the best of our knowledge, only a few specific case studies of extreme precipitation in the IP have been clearly linked with ARs (Liberato et al. 2012; Liberato and Trigo 2014; Trigo et al. 2014; Lavers and Villarini 2013).

Thus, the main objective of this work is twofold: 1) to identify the ARs that affected the IP over the 1948–2012 period during the extended winter months [October–March (ONDJFM)] and 2) to provide a comprehensive analysis of the extreme precipitation days in the IP and to evaluate if these days are associated (or not) with the occurrence of ARs. To do so, we have applied an automated ARs detection algorithm (Lavers et al. 2012) to western Iberia using two different reanalysis datasets: NCEP–NCAR (1948–2012) and ERA-Interim (1979–2012). In addition, the top-ranking tables of extreme precipitation days developed by Ramos et al. (2014) for

IP and for the major Iberian river basins for the 1950–2008 period are used. Since the precipitation days are only available for the 1950–2008 period, the association between the extreme precipitation days and the ARs will be restricted to this common period.

Section 2 presents the datasets and the different methodologies while section 3 provides a climatological assessment of the ARs over the Iberian Peninsula. An example of an extreme precipitation episode on 4–5 November 1997 is studied in more detail in section 4. The relationship between the occurrence of ARs and large-scale modes of variability is assessed in section 5, while the association between the ARs and the extreme precipitation events in the different domains on the IP is shown in section 6. Finally, the conclusions are outlined in section 7.

2. Datasets and methodology

a. Extreme precipitation events

Here, we have used the ranking of extreme precipitation events recently developed by the authors for the IP (Ramos et al. 2014). It is based on the daily precipitation sum available for continental IP (IB02). The IB02 dataset results from the combination of two national precipitation datasets: Spain02 for peninsular Spain and the Balearic Islands (Herrera et al. 2012) and PT02 for mainland Portugal (Belo-Pereira et al. 2011). The dataset spans from 1950 to 2008, with a high spatial resolution of 0.2° latitude–longitude grid, and it is based on a dense network of rain gauges that are all quality controlled and homogenized.

The ranking of extreme precipitation (Ramos et al. 2014) takes into account that large-scale precipitation events during the extended winter months (ONDJFM) can hardly affect the entire IP simultaneously, as shown in Cortesi et al. (2013). Over most sectors of the Iberian Peninsula, the accumulated precipitation between October and March represents more than two-thirds of the annual total that is usually associated with low pressure systems of Atlantic origin, while summer precipitation is more often related with northerly or easterly flows in the Iberian Peninsula (Cortesi et al. 2013). Moreover, it should be noted that summer precipitation is not significant, except in northern mountainous sectors such the Pyrenees, and also close to the Mediterranean coast, where intense downpours can occur in small areas, often associated with mesoscale convective systems.

Therefore, the method applied to characterize and rank each extended winter day takes into account the severity of the precipitation anomaly and also its spatial extent. This was achieved through the use of the normalized precipitation departures from the daily

climatology, computed for each day and each grid point. Since we are only interested in the intense precipitation events, the next step was to compute the magnitude R of an event derived on a daily basis with an index that is obtained after multiplying 1) the area A (%) that has precipitation anomalies above two standard deviations by 2) the mean value M of these anomalies for all the grid points that are characterized by precipitation anomalies (mm) above two standard deviations.

The highest value of R (percent times millimeters of rain) corresponds to the first day of the ranking and so on. 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 (Fig. 1). These eight individual ranking lists include the entire Iberian Peninsula, Portugal, and the six major river basins of Iberia (Minho, Duero, Tagus, Guadiana, Guadalquivir, and Ebro). It is important to mention that the domains Iberian Peninsula and Portugal overlap with the six river basins domains. The main characteristics of each river basin can be found in the supplemental material as Table S2.

b. Reanalyses datasets

In this work, we have used two different reanalyses datasets: the NCEP–NCAR reanalysis (Kalnay et al. 1996) for the 1948–2012 period and the ERA-Interim (Dee et al. 2011) for the shorter 1979–2012 period. The NCEP–NCAR reanalysis dataset has a spatial resolution of 2.5° latitude–longitude grid while ERA-Interim was retrieved at a 0.75° latitude–longitude grid. The variables retrieved for both reanalyses with a 6-h temporal resolution were the specific humidity q and zonal u and meridional v winds at 1000, 925, 850, 700, 600, 500, 400, and 300 hPa. Additionally, the mean sea level pressure (SLP) was also retrieved.

c. AR identification

The identification of the ARs that affected the IP was done by means of the IVT computed with both the NCEP–NCAR and ERA-Interim datasets following the methodology used by Lavers et al. (2012) and Lavers and Villarini (2013).

The IVT was computed between the 1000 to 300 hPa levels in an Eulerian framework (e.g., Neiman et al. 2008; Lavers et al. 2012):

$$\text{IVT} = \sqrt{\left(\frac{1}{g} \int_{1000 \text{ hPa}}^{300 \text{ hPa}} qu \, dp\right)^2 + \left(\frac{1}{g} \int_{1000 \text{ hPa}}^{300 \text{ hPa}} qv \, dp\right)^2},$$

where q is the layer-averaged specific humidity (kg kg^{-1}); u and v are the layer-averaged zonal and

FIG. 1. The 0.2° gridded precipitation dataset used in the computation of the ranking of anomalous precipitation days and the eight different domains considered: IP, Portugal, and the six river basins: 1) Minho, 2) Duero, 3) Tagus, 4) Guadiana, 5) Guadalquivir, and 6) Ebro.

meridional winds (m s^{-1}), respectively; g is the acceleration due to gravity; and dp is the pressure difference between two adjacent pressure levels.

Following [Lavers and Villarini \(2013\)](#), we have identified those ARs that affect the IP ($35^\circ\text{--}45^\circ\text{N}$, 10°W) using the following set of criteria:

- 1) An IVT threshold was computed taking into account the maximum IVT at 1200 UTC for each day from 1948 to 2012 using NCEP–NCAR and from 1979 to 2012 using ERA–Interim between 35° and 45°N along 10°W . In view of the work by previous authors, we have computed the 85th percentile of the maximum IVT distribution ($451 \text{ kg m}^{-1} \text{ s}^{-1}$ for NCEP–NCAR and $486 \text{ kg m}^{-1} \text{ s}^{-1}$ for ERA–Interim) and used it as the threshold value for the identification of the ARs. This 85th percentile was adopted here following the work of [Lavers et al. \(2012\)](#) for the Atlantic, where the authors have shown the reliability of this threshold to detect the most intense ARs, using satellite versus reanalyses datasets.
- 2) At each 6-h time step between 1948 (or 1979 for ERA–Interim) and 2012, we have searched the IVT values at grid points between 35° and 45°N along 10°W and extracted the maximum IVT value and location.
- 3) If the maximum IVT exceeded the IVT threshold ($451 \text{ kg m}^{-1} \text{ s}^{-1}$ for NCEP–NCAR and $486 \text{ kg m}^{-1} \text{ s}^{-1}$ for ERA–Interim), this particular grid point was flagged. We then performed a backward/forward search to identify the maximum IVT at each

longitude and tracked the location for the grid points where the IVT threshold (as derived for 10°W) was exceeded. However, ARs must extend over many degrees of longitude. This condition is checked every 6 h, and we considered it an AR time step when it is fulfilled. For NCEP–NCAR this corresponds to eight contiguous longitude points ($8 \times 2.5^\circ = 20^\circ \sim 1700 \text{ km}$) above $451 \text{ kg m}^{-1} \text{ s}^{-1}$, and for the ERA–Interim it corresponds to 27 contiguous longitude points ($27 \times 0.75^\circ = 20.25^\circ \sim 1721 \text{ km}$) above $486 \text{ kg m}^{-1} \text{ s}^{-1}$. Taking into account that at 40°N the length of a degree of longitude is $\sim 85 \text{ km}$, then the minimum required length for the NCEP–NCAR (ERA–Interim) is approximately 1700 km (1721 km).

The methodological steps described above allow for the detection of many potential ARs close to Iberia. In terms of climatology analysis (section 3a), only persistent AR events will be considered. For a persistent AR event to occur ([Lavers et al. 2012](#); [Lavers and Villarini 2013](#)), the following additional temporal criteria must be fulfilled: 1) it must have at least three uninterrupted time steps, which is at least 18 h persistence, and 2) to have independent events, two persistent ARs were considered distinct only if they were separated by more than 1 day. Regarding the analysis of the relationship between the ARs and intense precipitation days (section 3b), all the AR events will be used (regardless of fulfilling the persistence criteria or not).

FIG. 2. (a) Interannual variability of the number of ARs per extended winter (ONDJFM) computed with NCEP–NCAR (black line) and with ERA–Interim (dotted light-gray line), and (b) intra-annual variability of the number of ARs from 1979 to 2012 over the IP with NCEP–NCAR (dark gray) and with ERA–Interim (light gray).

We acknowledge the fact that the NCEP–NCAR reanalysis prior to the inclusion of satellite data assimilation (1979) must be used with caution (Mo et al. 1995), especially in this particular case of the ARs where the atmospheric WV plays a critical role. Therefore, two sensitivity analyses were performed in order to assess differences between the two reanalyses and also to see if results from the NCEP–NCAR reanalysis are sensitive to the length of the period considered (i.e., 1948–2012 versus 1979–2012).

The comparison between the number of ARs computed with the NCEP–NCAR reanalysis and ERA–Interim for the extended winter season is shown in Fig. 2a. The number of ARs in ERA–Interim (298 persistent ARs) is lower than in the NCEP–NCAR reanalysis (406 persistent ARs) for the same period from 1979 to 2012. Despite this 30% difference in average, a close look on the interannual variability (Fig. 2a) reveals that the variability of the ARs is in good agreement

in both reanalyses. In fact, the correlation coefficient between the number of ARs per extended winter in both datasets is 0.9 (significant at the 1% level). We believe that the difference in the average of ARs may be related to the finer resolution of ERA-Interim, which will have implications in the criteria of the number of contiguous grid points above the threshold, but also to different data assimilation techniques employed by the different models used to create the reanalyses datasets.

The second sensitivity analysis was done in order to assess if there are important differences in the 85th percentile of the maximum IVT distribution (see the first criterion above) in two different subperiods (1948–78 and 1979–2012). Results show that the 85th percentile of the maximum IVT distribution between 35° and 45°N along 10°W does not differ significantly between the two subperiods ($440 \text{ kg m}^{-1} \text{ s}^{-1}$ in the first subperiod versus $462 \text{ kg m}^{-1} \text{ s}^{-1}$ in the second subperiod), with a value of $451 \text{ kg m}^{-1} \text{ s}^{-1}$ when the entire period (1948–2012) is considered. Nevertheless, when looking at the interannual variability of AR frequency (Fig. 2a), it seems that there is an increase of variability since the early 1980s. We acknowledge that a more in-depth comparison of AR climatology obtained with different reanalyses datasets is necessary, but it is beyond the scope of the present work.

d. Large-scale atmospheric circulation pattern indices

The standard modes of low-frequency variability indices were obtained from the Climate Prediction Center (CPC) of the National Oceanic and Atmospheric Administration (NOAA) for the years 1950–2012. These modes of low-frequency variability indices were computed from the 500-hPa geopotential height field for the entire Northern Hemisphere (20°–90°N), using rotated principal component analysis (PCA; Barnston and Livezey 1987) at the monthly scale. In this work, we have used the North Atlantic Oscillation (NAO), east Atlantic (EA), west Pacific (WP), east Atlantic/western Russia (EA/WR), Scandinavia (SCAND), and polar/Eurasia (POL). The extended winter mean indices for year N were computed taking into account the monthly means of the October–December (OND) $N - 1$ and January–March (JFM) N , so the first extended winter (1951) corresponds to the monthly means of the OND 1950 and JFM 1951, while the last extended winter (2012) corresponds to OND 2011 and JFM 2012.

The spatial patterns of the main teleconnections over the Atlantic Northern Hemisphere are shown in Fig. 7 (section 5). These patterns represent the amplitude of the temporal correlation between the monthly 500-hPa geopotential height standardized anomalies and the

monthly teleconnection pattern time series from 1950 to 2012.

3. AR climatology

A climatological assessment of ARs was undertaken using only the persistent AR events (i.e., restricting the ARs to those that have at least three uninterrupted time steps) that make landfall upon the IP (35°–45°N, 10°W) for both datasets. For the NCEP–NCAR reanalysis, during the 1948–2012 period (extended winter months ONDJFM) there was a total of 679 persistent AR events recorded corresponding to a mean value of $\sim 10.5 \text{ yr}^{-1}$ (standard deviation = $\sim 4.5 \text{ yr}^{-1}$). Comparing ERA-Interim with the NCEP–NCAR reanalysis results, for the 1979–2012 period, the number of ARs in ERA-Interim (total of 298 persistent ARs with 8.2 yr^{-1}) is lower than the number found for the NCEP–NCAR reanalysis (total of 406 persistent ARs with 11.9 yr^{-1}).

In addition, the interannual variability is shown in Fig. 2a. As mentioned before, the extended winter mean year N was computed taking into account the monthly means of the OND $N - 1$ and JFM N . Looking at the interannual variability of AR frequency computed with the NCEP–NCAR reanalysis, there is an increment of variability since the early 1980s. In fact, before 1979 the standard deviation is around 3.6 yr^{-1} , while in the most recent subperiod (after 1979) this increases to about 4.8 yr^{-1} . Moreover, it is important to stress that the maximum of both series, 25 ARs for the NCEP–NCAR reanalysis and 18 ARs for ERA-Interim, occurred in the extended winter of 2010, a winter characterized by extreme precipitation in Iberia (Vicente-Serrano et al. 2011).

The intra-annual variability for the 1979–2012 period was also analyzed (Fig. 2b), which allows us to compare the monthly mean AR value computed with different reanalysis datasets. This figure suggests that the intra-annual variability is very similar for both AR climatologies (NCEP–NCAR reanalysis versus ERA-Interim) with a distinctive decrease in the number of ARs per month after December for both datasets. This decrease in the number of ARs at the end of the winter could be related with the weakening of the storm track in the North Atlantic (Trigo 2006) and therefore the reduction of the moisture transport.

From this point forward, the analyses will be restricted to the results obtained with the NCEP–NCAR reanalysis for the entire period of analysis (1948–2012), unless otherwise stated.

We have also computed some additional features that help to characterize the ARs that strike the IP, such as the length of the ARs (Fig. 3a) or the number of time

FIG. 3. Distribution of the (a) length of the ARs (km) and (b) number of time steps (h) per each persistent AR.

steps for a particular AR (Fig. 3b). In terms of the spatial extension of the ARs, more than half of the considered ARs (384 out of 679) are between ~ 2300 and ~ 2500 km, with 85% of the ARs spatial extension presenting between ~ 2100 and ~ 3000 km. These long structures are in line with the current understanding of the AR that can extend for thousands of kilometers and sometimes across the entire ocean basin (Ralph and Dettinger

2011). Regarding the duration of the ARs, the number of time steps decays very quickly, with 85% of the cases falling between 18 (three consecutive time steps) and 48 h (eight time steps). Ralph et al. (2013) showed, when analyzing 91 well-observed events for California's Russian River region during the 2004–10 period, that the passage of ARs over a coastal site lasted 20 h on average and that 12% of the AR events

exceeded 30 h. For the ARs that passed over the IP, about 20% of events exceeded 30 h.

The narrowness of the ARs was assessed as the number of grid points between 35° and 45°N and along 10°W that were above the threshold at the initial time step of the detection of the AR. The results show that roughly 80% of the persistent ARs have a narrowness below or equal to 5° (equivalent to 550 km), which is in line with previous knowledge regarding the average width of the ARs (400–600 km; [Ralph and Dettinger 2011](#)).

To conclude the climatological assessment, two additional characteristics are also presented. For each of the persistent ARs, the latitude of the initial maximum IVT location and its maximum IVT value are recorded and their distribution is analyzed in [Fig. 4](#). The majority of the persistent ARs that were found between 35° and 45°N and along 10°W have their initial maximum IVT located at 45°N ([Fig. 4a](#); 424 out of 679) with the remaining one-third of the distribution being registered between 35° and 42.5°N. Along with its maximum location, the distribution of the maximum IVT values is also shown ([Fig. 4b](#)) using $50 \text{ kg m}^{-1} \text{ s}^{-1}$ interval bins (starting at $450 \text{ kg m}^{-1} \text{ s}^{-1}$). More than 80% of the cases have a maximum initial IVT value between 450 and $650 \text{ kg m}^{-1} \text{ s}^{-1}$, while there are only five cases above $900 \text{ kg m}^{-1} \text{ s}^{-1}$.

As mentioned before, the number of persistent ARs for the 1948–2012 period corresponds to 679, which, in terms of 6-h time steps and taking into account the duration of each AR, corresponds to 3837 time steps ([Fig. 3b](#)). We have computed the averages for the SLP and the IVT (intensity and components) using the 3837 AR time steps that affect the IP and compared them with the extended winter long-term mean ([Fig. 5](#)). The average pattern for the extended winter months is characterized by the well-known configuration with low pressure near Iceland (below 1004 hPa) and the Azores anticyclone high pressure (above 1020 hPa) located between the Azores archipelago and the IP ([Fig. 5a](#)). Simultaneously, the corresponding IVT mean values obtained range between 200 and $325 \text{ kg m}^{-1} \text{ s}^{-1}$ for a large band crossing the entire North Atlantic Ocean basin (67.5°–25°N, 80°–10°W) being advected from west-southwest to east-northeast. When analyzing the composite average for those time steps when the ARs are present, an intensified pattern emerges ([Fig. 5b](#)), with an intensified low pressure system (994 hPa) displaced toward the British Isles and also a stronger high pressure system (also displaced to the east). The corresponding IVT presents an increase of advection of moisture with values ranging from 200 to a maximum close to $500 \text{ kg m}^{-1} \text{ s}^{-1}$ (located northwest of the IP). The

anomalies between the extended winter (ONDJFM) long-term mean and the composite for the AR time steps were also computed ([Fig. 5c](#)), where all the differences represented (i.e., above and below $25 \text{ kg m}^{-1} \text{ s}^{-1}$) are significant at the 5% level. Negative SLP anomalies are found centered over Ireland, with greater anomalies around –18 hPa and with slight positive anomalies of SLP located over northern Africa. Overall, this configuration is in line with the results obtained by [Lavers and Villarini \(2013\)](#). In terms of the IVT anomalies over the IP, they range from 75 (in the south near the Mediterranean) to $275 \text{ kg m}^{-1} \text{ s}^{-1}$ (in the northwestern sector of Iberia).

4. Case study: Extreme precipitation episode on 5 November 1997

In this section, we analyze an example of an extreme precipitation day (number 2 in the ranking in the IP) that occurred on 5 November 1997. We analyze this example in more detail because it serves the purpose of considering some specifics of the AR detection method, and additionally, this case study was associated with strong socioeconomic impacts in Portugal ([Ramos and Reis 2002](#)) and Spain ([Lorente et al. 2008](#)).

To achieve this high-ranking spot, it necessarily implies that the higher-than-usual precipitation was generalized over a large fraction of the entire IP, in this case oriented from the southwestern sector to the north-eastern sector of the IP [see [Ramos et al. \(2014\)](#) for a detailed precipitation map for this particular day]. On this day, one may observe precipitation anomalies above two standard deviations in 32.88% of the grid points, and the mean of anomalies (in standard deviations) over this 32.88% area was 4.45 mm, with the magnitude of the event for this day being 146.18% (mm). This event produced major socioeconomic impacts, with 11 deaths in Portugal and 21 in Spain ([Ramos and Reis 2002](#); [Lorente et al. 2008](#)), mainly due to flash flood events in small stream basins. According to [Lorente et al. \(2008\)](#), this event was due to a cutoff low that deepened quickly and extended to lower levels, forming a strong and compact low pressure system on the afternoon of 5 November 1997. This configuration led to a substantial increase of the large atmospheric vertical instability and consequently triggered strong convection that played a fundamental role in the development of several mesoscale convective systems that crossed the IP in a southwest to northeast direction.

To show an example of a detected AR, in [Table 1](#), the detailed characteristics (length in grid points, maximum IVT along 10°W and its locations) of the AR during each time step are shown. In addition, the IVT field on

FIG. 4. (a) Distribution of the location of the initial max IVT between 35° and 45°N and along 10°W when a persistent AR is recorded and (b) the respective initial max IVT ($\text{kg m}^{-1} \text{s}^{-1}$) value distribution.

5 November 1997 (here represented at 0000, 0600, 1200, and the 1800 UTC) and the respective SLP field are shown in Fig. 6. As mentioned in section 2c, the AR detection starts if a maximum of IVT above the

451 $\text{kg m}^{-1} \text{s}^{-1}$ threshold between 45° and 35°N along 10°W is detected, and to be considered an AR time step, it must have at least eight contiguous grid points ($\sim 1700 \text{ km}$) above the threshold. This particular AR

FIG. 5. (a) Extended winter (ONDJFM) long-term mean (1950–2012) of the IVT direction (vectors) and intensity ($\text{kg m}^{-1} \text{s}^{-1}$; color shading) and SLP (hPa; contours) fields. (b) Mean composites of IVT direction (vectors) and intensity ($\text{kg m}^{-1} \text{s}^{-1}$; color shading) and SLP (hPa; contours) fields during the occurrence of the persistent ARs that affect the IP (679 persistent cases corresponding to 3837 time steps). (c) The anomalies between the long-term mean and the composites.

was first recorded at 1800 UTC 4 November 1997 at 35°N with a maximum IVT of $553.62 \text{ kg m}^{-1} \text{s}^{-1}$ along 10°W, and it had a length of 11 contiguous points ($\sim 2300 \text{ km}$) above the $451 \text{ kg m}^{-1} \text{s}^{-1}$ threshold (Fig. 6a). This AR had a duration of five time steps ending at 1800 UTC 5 November in which the maximum IVT along

the 10°W was recorded ($1094.85 \text{ kg m}^{-1} \text{s}^{-1}$ at 35°N; Fig. 6d). Since in this case the AR was detected in more than three consecutive time steps, it is considered a persistent AR.

The analysis of the IVT and SLP field on 5 November 1997 (Fig. 6) shows a strong advection of WV from the

TABLE 1. Detailed characteristics of the ARs that affected the IP during 4–5 Nov 1997. The length (grid points) of the ARs, the max IVT along 10°W, and its latitudinal location are shown. In addition, the characteristics of the precipitation event (Ramos et al. 2014) are also shown, including the area that has precipitation anomalies above two std dev, the mean values of these anomalies, and the magnitude of the event.

Year	Month	Day	Time (UTC)	Length	Max IVT ($\text{kg m}^{-1} \text{s}^{-1}$)	Max location (°N)	A (%)	M (mm)	R = AM [% (mm)]
1997	Nov	4	1800	12	553.6	35	1.37	2.43	3.34
1997	Nov	5	0000	11	809.5	35	32.88	4.45	146.18
1997	Nov	5	6000	13	1091.2	35	32.88	4.45	146.18
1997	Nov	5	1200	15	934.5	35	32.88	4.45	146.18
1997	Nov	5	1800	17	1094.6	35	32.88	4.45	146.18

FIG. 6. IVT direction (vectors) and intensity ($\text{kg m}^{-1} \text{s}^{-1}$; color shading) and SLP (hPa; contours) fields at (a) 0000, (b) 0600, (c) 1200, and (d) 1800 UTC 5 Nov 1997.

Atlantic Ocean toward the IP at 0000 UTC and associated low pressure system located over the British Isles. For the other time steps, the deepening of the low pressure system located over the British Isles and the intense IVT (above $700 \text{ kg m}^{-1} \text{s}^{-1}$) over the Atlantic Ocean directed toward the southwestern IP are clearly visible. At 1800 UTC, a secondary low pressure system developed over southwestern IP because of a rapid deepening of a cutoff low system (Lorente et al. (2008)). This synoptic configuration led to an advection of moist air from the Atlantic basin toward the IP, which, associated with the cold air aloft and instability at surface, triggered deep convection and subsequent heavy precipitation.

This extreme precipitation episode in the IP is in good agreement with the results from Liberato et al. (2012), which showed how long-range transport of water vapor from the subtropics associated with the occurrence of an AR was crucial in setting up the large-scale conditions required for a particular extreme precipitation event. In

fact, other case studies previously analyzed (Liberato et al. 2012; Liberato and Trigo 2014) also showed that the large-scale atmospheric flow associated with those extreme rainfall and flash flood episodes on the IP resulted from the simultaneous occurrence of favorable thermodynamical conditions, including 1) the presence of an AR structure, 2) a lower-than-usual latitudinal location of the jet stream related to the presence of strong meridional temperature gradient, and 3) intense vertical instability in an area of upper-level divergence in this case due to the presence of a cutoff low system.

5. Relationship between Iberian ARs and large-scale atmospheric circulation patterns

To evaluate the role played by atmospheric circulation variability, we have also computed the correlation coefficient between the number of persistent ARs per extended winter season (ONDJFM) and the various large-scale atmospheric circulation pattern indices

TABLE 2. Correlation analysis during the 1951–2011 extended winter months between the number of ARs and the large-scale atmospheric circulation pattern. Statistically significant correlations are highlighted in boldface.

	NAO	EA	EA/WR	SCAND	POL
Correlation	−0.135	0.697	−0.019	0.198	−0.278
<i>p</i> value	0.295	0.000	0.886	0.124	0.029

(NAO, EA, WP, EA/WR, SCAND, and POL) for the 1951–2011 period. Results are summarized in Table 2, and statistically significant correlation values (at the 5% significance level) are only found for the EA pattern (positive) and POL pattern (negative). These two patterns (EA and POL) are represented in Fig. 7, together with the two most important large-scale modes related to Iberian precipitation, that is, the NAO and SCAND (Trigo et al. 2008).

Regarding the EA mode, it is characterized by a pattern similar to the NAO, that is, consisting of a north–south dipole of anomaly centers spanning the North

Atlantic from east to west (Barnston and Livezey 1987), but with the anomalous centers displaced southeastward. In addition, the lower-latitude center contains a strong subtropical link in association with modulations in the subtropical ridge intensity and location. As mentioned before, the correlation between the number of ARs and the EA pattern is positive (0.697) and significant at the 1% level. Lavers et al. (2012) analyzed the relationship between large-scale circulation and ARs affecting the British Isles and showed that the most prominent mode (anticorrelated with the ARs) was the SCAND pattern. A closer analysis of Fig. 4 in Lavers and Villarini (2013) reveals the presence of positive anomalies of SLP south of the British Isles and negative anomalies slightly north of the British Isles on the ARs recorded between 50° and 60°N. This configuration resembles the SCAND patterns on its negative phase. In the case of the persistent ARs that affect the IP, the SLP anomalies (Fig. 5c) show negative anomalies centered over Ireland while positive SLP anomalies are present over northern Africa, a pattern that resembles the EA

FIG. 7. The large-scale atmospheric circulation patterns over the Northern Hemisphere Atlantic: (a) NAO, (b) POL, (c) SCAND, and (d) EA.

TABLE 3. Top 20 extreme precipitation days for the IP domain. The AR column indicates if a particular day is associated with persistent ARs despite having (or not) at least three AR time steps in that particular day.

Year	Month	Day	A (%)	M (mm)	$R = AM$ [% (mm)]	Ranking No.	No. of AR time steps per day	AR
1982	Nov	6	42.98	3.57	153.54	1	4	Yes
1997	Nov	5	32.88	4.45	146.18	2	3	Yes
1969	Mar	12	34.01	4.07	138.40	3	3	Yes
1997	Dec	17	37.18	3.55	132.08	4	4	Yes
2001	Feb	6	29.77	4.34	129.33	5	1	Yes
1979	Feb	10	36.88	3.39	125.14	6	4	Yes
2006	Oct	22	32.52	3.76	122.16	7	4	Yes
1972	Feb	2	28.21	4.20	118.49	8	3	Yes
2001	Mar	1	37.18	3.17	117.81	9	2	Yes
1963	Feb	15	28.75	3.75	107.69	10	4	Yes
1995	Dec	25	28.21	3.65	103.00	11	3	Yes
1966	Oct	3	27.38	3.72	101.89	12	3	Yes
2000	Dec	6	23.79	4.04	96.20	13	3	Yes
1982	Nov	7	25.10	3.81	95.69	14	4	Yes
1958	Dec	18	28.75	3.30	94.93	15	4	Yes
1967	Mar	8	28.27	3.25	91.95	16	3	Yes
1956	Mar	23	28.21	3.25	91.65	17	2	Yes
1977	Dec	7	24.03	3.69	88.59	18	1	Yes
1996	Dec	12	25.58	3.44	88.10	19	0	No
1969	Mar	16	27.56	3.18	87.57	20	4	Yes

pattern in its positive phase (Fig. 7d). Taking into account the information mentioned before, the occurrence of persistent ARs is closely related with negative anomalies of SLP north of the impact area and positive anomalies located south of the impact area. In addition, the NAO pattern is not correlated with the number of ARs. This confirms the importance of the positive SLP anomalies over northern Africa that was found in Fig. 5c, which is not found when the NAO pattern is dominant.

It is well known that the NAO and SCAND are better related to the average Iberian precipitation on monthly and seasonal scales (Trigo et al. 2008). However, the influence of ARs in the Iberian Peninsula requires a large-scale atmospheric pattern that is different from either NAO and SCAND, with a deep low system located just southwest of the British Isles and a positive SLP anomaly in northern Africa, necessary to increase the pressure gradient and thus increase the low tropospheric movement that is associated with all ARs (Fig. 5). In other words, if one just analyzes the well-known large-scale patterns for all four major Atlantic–European modes (Fig. 7), it becomes obvious that EA fits better with the SLP and IVT anomalous fields associated with persistent ARs (Fig. 5). We have shown that the AR pattern resembles the EA mode more than the NAO. However, that in itself does not warrant a clear added impact in extreme precipitation for two reasons: 1) the ARs will cross closer to the northern edge of the Peninsula (as clearly depicted in the anomalous IVT and SLP in Fig. 5c) and 2) increasing the frequency

of ARs at lower latitudes, that is, entering western Iberia, may be reflected in some additional precipitation, but not necessarily an extreme precipitation event (as defined through the ranking criteria).

The second mode associated with ARs corresponds to the POL pattern with a negative correlation of -0.278 (significant at the 5% level). The POL pattern takes into account the strength of the circumpolar vortex and affects the Mediterranean region through its southern European anomaly center, which extends up to the northern and western parts of the Mediterranean area. In fact, with a correlation value between both time series of -0.278 , this link, although statistically significant, only explains about 8% of the AR variability, and its importance is relative.

6. Iberian Peninsula extreme precipitation and ARs

With the identification of the ARs during the 1948–2012 period performed, the association between the extreme precipitation days and the ARs will be analyzed during the 1950–2008 period (common period available to both datasets). As mentioned before, we have used the precipitation ranking days derived by the authors in a previous work (Ramos et al. 2014). Because extreme precipitation is highly dependent on the region studied, we considered different ranking tables of precipitation (example for the IP in Table 3) for each domain assessed (IP, Portugal, Tagus, Duero, Minho, Guadiana, Guadalquivir, and Ebro). In addition, the total number

TABLE 4. Number of absolute days of the ranking for each different domain and the number of days (%) in the ranking according to the number of time steps of ARs per day.

	No. of days ranking	Zero time steps (%)	One time step (%)	Two time steps (%)	Three time steps (%)	Four time steps (%)	At least two time steps (%)
IP	6091	78.5	7.3	5.0	4.8	4.4	14.1
Portugal	2258	63.6	11.8	8.4	9.3	6.9	24.6
Tagus	2018	68.2	10.8	7.7	7.4	5.6	21.0
Duero	2563	65.4	11.4	8.2	7.8	7.2	23.3
Minho	1664	50.4	15.6	11.2	11.5	11.1	33.8
Guadiana	1801	71.7	11.2	6.1	6.2	4.8	17.1
Guadalquivir	1777	73.8	10.2	5.5	5.7	4.7	16.0
Ebro	2651	73.7	10.4	5.3	6.0	4.5	15.9

of extreme precipitation days differs throughout the various domains analyzed (each ranking is computed over the domain area that is being analyzed). It should be noted that to be considered extreme, at least one pixel must have precipitation daily anomalies above two standard deviations [see section 2a and Ramos et al. (2014) for additional details]. The number of extreme precipitation days for the different domains are shown in Table 4.

To restrict the number of figures and tables, we show an example for the top 20 extreme precipitation days in the IP (Table 3), while the top 20 days for the other domains are shown in Table S1 in the supplemental material. Since the accumulated precipitation is recorded every 24 h, at 0700 UTC (0900 UTC) in Spain (Portugal), the time steps for a particular day range from 0600 to 0000 UTC, that is, the four time steps that better adjust to the accumulated precipitation.

As an example, we consider the intense precipitation observed in Iberia on 6 February 2001 (Table 3). This day corresponds to 24-h accumulated precipitation between 0700 UTC (0900 UTC) 6 February and 0700 UTC (0900 UTC) 7 February 2001 in Spain (Portugal). The four corresponding reanalysis time steps start at 0600 UTC 6 February and end at 0000 UTC 7 February 2001. For this particular day (6 February 2001), only one AR time step out of four possible AR time steps was found. In addition, this AR time step is associated with a persistent AR that was first recorded at 0000 UTC 5 February and last recorded at 0000 UTC 6 February 2001. That explains why the last column is marked with a “yes,” despite only one AR time step being recorded on this particular day. On the contrary, the first day of the ranking (6 November 1982) is characterized by the presence of an AR in all four of the time steps associated with this particular day. For the IP ranking, the first day of the top 20 without the presence of an AR in the vicinity corresponds to 12 December 1996, ranked nineteenth.

To summarize the results for the different domains, we have computed the number of days (in percent) according to the number of time steps of ARs (Table 4). The number of days without any AR time steps varies from 50.4% for the extreme precipitation days for the Minho basin to 78.5% for the days for the IP. Additionally, we have also included a column in the table that represents the sum of days (in percent) with the number of AR time steps higher or equal than two per day. According to Table 4, one can see that for the Minho basin, about one-third of the extreme precipitation days are characterized by least two AR time steps. For the western domains (Portugal, Tagus, and Duero), this value ranges between near 25% of the extreme days in Portugal and near 21% of the extreme days in Tagus. On the other hand, for the eastern and southern basins (Ebro, Guadiana, and Guadalquivir), the importance of the extreme precipitation days with at least two AR time steps is reduced to about one-sixth of the days.

To analyze if the contribution from ARs toward extreme precipitation events changes as we go from the highest extreme day (first day in the ranking) to the lowest extreme (last day of the ranking), we have evaluated, for the different eight domains, the number of AR time steps for each day of the ranking by dividing into 40 equally spaced bins (each bin represents 2.5% intervals). The first bin corresponds to the 2.5% most extreme precipitation days in the ranking, the following bin corresponds to the 2.5%–5% most extreme precipitation days of the ranking, and so on. The number of extreme precipitation days in each bin for the different domains is proportional to the total number of extreme precipitation days (Table 4). Therefore, the corresponding 2.5% bins in days for each domain are IP (152), Portugal (56), Tagus (50), Duero (64), Minho (41), Guadiana (45), Guadalquivir (44), and Ebro (66). For the sake of simplicity, only results for the IP and for selected river basins (Minho, Tagus, and Ebro) are shown (Fig. 8). For each domain, we show the percentage of days with zero AR time steps (red line) and with

FIG. 8. The number of AR time steps for each day of the ranking into 2.5% bin intervals [zero (red) and at least two (blue)] for the (a) IP, (b) Minho, (c) Tagus, and (d) Ebro basins. The first bin corresponds to the 2.5% most extreme precipitation days for the different domains while the last bin shown (50%) corresponds to the median ranking day.

at least two AR time steps (blue line). In addition, the results were smoothed using a running average of two bins. The other domains are shown in Fig. S1 in the supplemental material.

The behavior of the IP, Minho, and Tagus basins are very similar for the first 2.5% most extreme precipitation days of the ranking, where the percentage of these days with at least two AR time steps is always higher than 50%, varying from 70% for the Minho rank to 50% in the IP rank. As we move toward less extreme precipitation days (ranking extreme days between 5% and 15%), all ranks reveal a decrease in the percentage of days with at least two AR time steps, along with an increase of days with no AR time steps, which sooner (e.g., Tagus) or later (e.g., Minho) represent the majority of days. From the position of the ranking ranging from 20% onward, there is a stabilization in the number of days with zero AR time steps, around 75% in the IP

and Tagus basin and 60% in the Minho basin. For the Duero basin and for the Portuguese domain, a similar behavior was found (Fig. S1 in the supplemental material).

Taking a closer look at the Ebro basin (Fig. 8d), there is a clear dominance of extreme precipitation days without any AR time steps associated (around 75% of the days), without significant change throughout the days of the ranking (regardless of being more or less extreme). Likewise, the percentage of days with at least two AR time steps is virtually constant throughout the ranking. Therefore, the impact of ARs for the Ebro's extreme precipitation is rather limited. This insensitivity can be partially due to the shadow lee effect of the several high mountains located in northern Iberia between the Atlantic and the Ebro basin. It must be also mentioned that extreme precipitation events in sectors of Iberia located closer to the Mediterranean correspond quite often to deep mesoscale systems that occur

FIG. 9. Mean location [$\% (1^\circ \text{ lat})^{-1}$] of the ARs during anomalous precipitation days (blue) and nonanomalous precipitation days (light purple) for the (a) IP, (b) Minho, (c) Tagus, and (d) Ebro basins.

as a consequence of the intense evaporation provided by the warm waters of the western Mediterranean basin, that is, are often not related to moisture prevention from the Atlantic (Cortesi et al. 2013).

In the case of the IP, the orographic influence on precipitation intensity during ARs is rather limited to the northwestern sector, where the mountain ranges are particularly high (many peaks are higher than 1200 m). This fact differentiates, to a certain extent, the impact of ARs in IP from what happens in Northern California, where the orographic influence on precipitation distributions and intensities is more important (Neiman et al. 2014).

To evaluate the sensitivity of these results to the NCEP–NCAR reanalysis dataset since 1948, we have also computed the relationship between ARs and extreme precipitation days using ERA-Interim or the shorter NCEP–NCAR reanalysis (both since 1979). Obtained results are very similar for all eight domains considered (not shown), with the main conclusions remaining the same whatever dataset we used.

As shown above, the highest positions in the various precipitation ranks (except for the Ebro basin) are very often associated with the occurrence of ARs. But there

are also nonextreme days [days characterized by precipitation anomalies below two standard deviations, see section 2a or Ramos et al. (2014)] that are associated with the presence of a persistent AR (at least two AR time steps). To analyze this, for each day with the presence of an AR we have computed the mean initial maximum IVT location over the 10°W longitude, taking into account the AR time steps of that particular day. Therefore, we are comparing the latitudinal sensitivity of ARs within two different paradigms: 1) the days belonging to the extreme precipitation ranking associated with the presence of persistent ARs (Fig. 9; blue bars) versus 2) the nonranking precipitation days that are also associated with the presence of persistent ARs (Fig. 9; light purple). The results were divided into 1° bins between 35° and 45°N where the first bin 35°N corresponds to values between 35° and 36°N and the last bin 45°N corresponds to mean values equal to 45°N . Once again, for the sake of simplicity, results are only shown for selected river basins (Minho, Tagus, and Ebro) in Fig. 9 while the other subdomains are shown in Fig. S2 in the supplemental material. For the IP domain results vary significantly with latitude, with days that have the mean initial maximum IVT located above the 45°N bin, we

have near 40% of occurrence of extreme days (ranking days) and near 60% of occurrence of nonextreme days. However, this ratio changes if we move a few degrees to the south, as seen for the days that have the mean initial maximum IVT located between the 36° and 37°N bins, where all of these days correspond to extreme precipitation days.

Regarding the Minho basin, for the 39°N bin (between 39° and 40°N) 95% of the days correspond to extreme days. The contiguous bin also has high values (above 70%) corresponding to extreme days. As we analyze the bins farther north or south, the percentage of nonextreme days increases significantly. Concerning the Tagus and Guadalquivir basins, the bins with a higher number of extreme precipitation (higher than 50%) days correspond to those located below 41° (Tagus) and below 40°N (Guadalquivir), which is compatible with the location of both basins (Fig. 1). For these two river basins, as we move farther to the northern bins, the number of nonextreme days increases dramatically, reaching almost 100%. Results for the Ebro basin are similar to those found for the Guadalquivir basin.

It is important to mention the impossibility of matching the ranking days included in each subregion with the ranking days for the whole Iberia. The IP ranking includes all the grid points over the domain, which means that the anomalous precipitation can occur over any part of the domain; therefore, a direct comparison between the river basins (more localized over smaller subregions) and the entire IP cannot be done.

In this section, we have made a latitudinal sensitivity study on the occurrence (or not) of an extreme precipitation day given the prior knowledge that an AR took place. Considering the narrow nature of the ARs (Ralph et al. 2004; Ralph and Dettinger 2011), the occurrence (or not) of extreme precipitation days is highly sensitive to the latitudinal location of the ARs associated with the different subdomains.

7. Summary

Extreme precipitation events in the IP during the extended winter months have major socioeconomic impacts such as floods, landslides, extensive property damage, and losses of life, as shown in some long-term assessment studies (Liberato and Trigo 2014; Zêzere et al. 2014) and several studies that focused on extreme events (e.g., Fragoso et al. 2010; Liberato et al. 2011; Trigo et al. 2014; Liberato et al. 2012).

A comprehensive ranking of daily precipitation events relative to the entire IP, Portugal, and for the six major river basins (Minho, Duero, Tagus, Guadiana, Guadalquivir, and Ebro) was used (Ramos et al. 2014).

The main objective of this work is to provide a comprehensive analysis of these most extreme precipitation days and to evaluate to what extent these extremes are associated (or not) with the occurrence of ARs over the North Atlantic domain.

In this study, the identification of the ARs that affected the IP was performed by means of the IVT, following the methodology used by Lavers et al. (2012) and Lavers and Villarini (2013). For that we have used the NCEP–NCAR reanalysis from 1948 to 2012 and ERA-Interim from 1979 to 2012. A climatological assessment was performed restricted to persistent AR events that make landfall upon the IP (between 35° and 45°N, along 10°W) between 1948 and 2012 (for NCEP–NCAR reanalysis) and between 1979 and 2012 (ERA-Interim). The comparison between the number of persistent ARs computed with both datasets reveals that the number of ARs in ERA-Interim is about 30% lower than the one found for the NCEP–NCAR reanalysis. Nevertheless, the interannual variability of both series is very similar, with a correlation around 0.9. The use of a longer dataset to compute the ARs allowed for checking their potential role on the different precipitation extreme rankings previously obtained for eight regional sectors of Iberia.

The most important results obtained can be summarized as follows:

- 1) The composite for the persistent AR time steps shows negative SLP anomalies centered in Ireland with positive anomalies of SLP located over northern Africa. This strong SLP gradient configuration is required to allow for the fast advection of moisture toward the Iberian Peninsula associated with the AR. Overall, this configuration is in line with the results obtained by Lavers and Villarini (2013) for the United Kingdom. This configuration leads to the ARs hitting the IP being linked with the EA pattern, while the influence of other patterns such as the NAO or SCAND was found to be weak.
- 2) The association between the extreme precipitation days and the ARs was analyzed during the 1950–2008 period for the entire IP and, additionally, for seven smaller subdomains previously defined (Ramos et al. 2014). The highest positions in the various precipitation ranks are often associated with the occurrence of ARs, like structures being more important in the northern domains than in the southern domains.
- 3) The contribution from ARs toward extreme precipitation events varies significantly with the ranking positions and for most regions decreases significantly as we go from the highest extreme day to the lowest extreme day. For the Ebro basin, the impact of ARs for the Ebro's extreme precipitation is rather limited

and constant throughout the different days of the ranking.

- 4) It was shown that, given the narrow nature of the ARs, the occurrence (or not) of extreme precipitation days is highly sensitive to the latitudinal location of the ARs associated with the different subdomains.
- 5) A case study on one of the most extreme precipitation days in the IP that occurred on 4–5 November 1997 was analyzed. The large-scale atmospheric flow associated with these extreme rainfall and flash flood episodes on the IP resulted from the simultaneous occurrence of favorable thermodynamical conditions, including 1) the presence of an AR structure; 2) a lower-than-usual latitudinal location of the jet stream related to the presence of strong meridional temperature gradient; and 3) intense vertical instability in an area of upper-level divergence, in this case due to the presence of a cutoff low system. The same was found in previously studied extreme precipitation events in the IP (Liberato et al. 2012; Liberato and Trigo 2014).

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