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# Analysis of synoptic patterns in relationship with severe rainfall events in the Ebre Observatory (Catalonia)

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## Abstract

The study has obtained a classification of the synoptic patterns associated with a selection of extreme rain episodes registered in the Ebre Observatory between 1905 and 2003, showing a return period of not less than 10 years for any duration from 5 min to 24 h. These episodes had been previously classified in four rainfall intensity groups attending to their meteorological time scale. The synoptic patterns related to every group have been obtained applying a multivariable analysis to three atmospheric levels: sea-level pressure, temperature, and geopotential at 500 hPa. Usually, the synoptic patterns associated with intense rain in southern Catalonia are featured by low-pressure systems advecting warm and wet air from the Mediterranean Sea at the low levels of the troposphere. The configuration in the middle levels of the troposphere is dominated by negative anomalies of geopotential, indicating the presence of a low or a cold front, and temperature anomalies, promoting the destabilization of the atmosphere. These configurations promote the occurrence of severe convective events due to the difference of temperature between the low and medium levels of troposphere and the contribution of humidity in the lowest levels of the atmosphere.

**Keywords** Synoptic patterns · Severe rainfall · Southern Catalonia · Meteorological temporal scales · Intensity weighted index · Multivariate analysis

## Introduction

### Overview

In mid-latitude Mediterranean areas, intense rain is usually produced by intense convective systems, often embedded in larger low-pressure structures, with a particular organization highly affected by seasonal and local factors. In the specific case of Catalonia, located in the northeast of the Iberian Peninsula, with an intricate topography delimited in the north by the Pyrenees range and in the east by the Mediterranean Sea and the Prelitoral Range, the proximity of the sea is one of the most relevant factors (Fig. 1).

To investigate the trigger factors of a meteorological extreme rain situation, both the spatial and time rain organization must be analyzed by studying the association between the maximum amounts recorded in different temporal intervals for the same rain episode (Lorente and Redaño 1990; Casas et al. 2004). Thus, an objective classification of the intense rainfall episodes can be carried out

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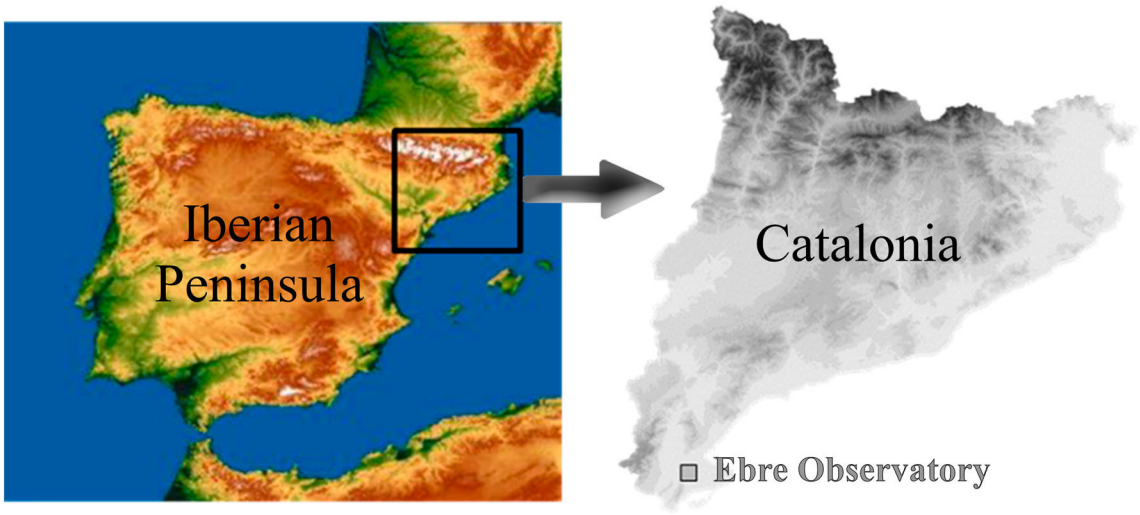


**Fig. 1** Geographical location of the Ebre Observatory

in base of their different temporal organizations. Some studies obtained classifications of extreme rain events registered at several locations of the Eastern seaside area of Catalonia, as Casas et al. (2004, 2010) who analyzed a selection of intense storms registered in the Fabra Observatory of Barcelona between 1927 and 1992 by a Jardí gauge, and by the urban rain gauge network of this city between 1994 and 2001, and Pérez-Zanón et al. (2015) who obtained the classification of severe storms from an almost centennial rainfall register (1905–2003) of the Ebre Observatory near Tortosa (Tarragona). In both cases, the selected storms resulted classified by cluster analysis in four groups, attending on their temporal characteristics: microscale, mesoscale, synoptic scale, and a fourth group of complex events. This last group showed high rainfall rates for a large temporal range associated with phenomena of different scales acting together, for instance, mesoscale organizations embedded into synoptic systems, situation that usually produce extremely intense rainfall and occasionally flooding.

The degree of severity or exceptionality of an extreme rainfall event is usually quantified in terms of the total amount of water collected in a given period of time. Thus, this period of time is commonly chosen depending on the geomorphological characteristics of the catchment area to determine, for instance, the time of concentration and response to exceptional rainfall in this particular area. Casas et al. (2004) suggested an intensity weighted index (IP) to establish an objective method of classification based on the rain amounts exceptionality for four representative durations of the characteristic scales of atmospheric motion: 5 min, 1, 2, and 24 h, representing microscale weather phenomena, meso-γ, meso-β, and synoptic scale, respectively (Thunis and Bornstein 1996). This index IP is useful to provide a single measure of the rainfall severity from a meteorological point of view, regardless of the consequences in a particular type of watershed. The index IP was applied by Pérez-Zanón et al. (2015) to quantify the degree of exceptionality of the high intense episodes recorded in the Ebre Observatory.

Multivariate analysis techniques are extensively used to find relationships between atmospheric circulation patterns and exceptional meteorological events, such as very intense AQ4 rain (Vicente-Serrano et al. 2009; Martínez et al. 2008; Martín-Vide et al. 2008; Houssos et al. 2008). A methodology based on cluster analysis (CA) and principal component analysis (PCA) was employed by Peña et al. (2011) to get a catalogue of synoptic patterns to explain the strong wind episodes in Catalonia, and by Aran et al. (2011) to characterize the typical meteorological conditions producing hailstorms on the inland Catalonian area of the Lleida plain. In the present work, this methodology has been applied to the selection of exceptional storms registered in the Ebre Observatory between 1905 and 2003, to identify the synoptic patterns contributing to the generation of such extreme rainfall events in this area.

## Previous work

Rainfall data used in this study were obtained from the digitalized records of two siphon gauges situated in the Ebre Observatory (Fig. 2) between 1905 and 2003, with an interruption from April 4, 1938, to May 1, 1939 due to the Spanish civil war.

After a frequency analysis performed on the maximum rain amounts for 16 different durations (5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, and 60 min, and 2, 6, 12, and 24 h), Pérez-Zanón et al. (2015) calculated the intensity–





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**Fig. 2** Location of recording rain gauges at the Ebre Observatory

duration–frequency (IDF) curves for the Ebre Observatory. According to those IDF curves, Pérez-Zanón et al. (2015) analyzed and classified a selection of 28 rainfall events with amounts exceeding the ID curve corresponding to 10 years of return period for any of the considered time intervals.

These 28 selected events were studied by Pérez-Zanón et al. (2015) to analyze the prevailing meteorological time scales involved and were classified using a cluster analysis in four Rainfall Intensity Groups (RIG): a first group (I) of microscale or highly local episodes, with a clear diurnal cycle and seasonal influence, a second group (II) of the events showing intense rainfall for mesoscale durations, a third group (III) of synoptic rainfall events, and a fourth group (IV) of complex episodes showing high intensities for a large time range, indicating that different scale meteorological processes have contributed together to produce precipitation. The values of the IP index measuring the degree of complexity of these events were also calculated.

## Objective of the present work

The aim of the present study is to obtain a classification of the synoptic patterns related to extreme rain events registered in the Ebre Observatory (1905–2003) taking their meteorological time scales into consideration to better understand high intense rainfall intensity events in the south of Catalonia and their possible forecasting in the future. By applying multivariate analysis, it is desired to obtain the synoptic patterns associated with these extreme events and study their link to the four RIG groups (I, II, III, and IV) to characterize the prevailing meteorological conditions favouring the different kind of heavy rainfall episodes in the area.

Compared to similar studies, the present work is providing two novelties: the first is related to the identification of the precipitation episode according to its meteorological time scale, while the second is the methodology followed to obtain the synoptic patterns; a multivariate analysis taking into account the main dynamic and thermodynamic atmospheric processes giving rise to rainfall.

## Data

For the 28 extreme episodes with a return period not less than 10 years for any duration from 5 min to 24 h registered in the Ebre Observatory between 1905 and 2003 (Pérez-Zanón et al. 2015), the synoptic patterns were determined from the daily grids of the mean sea-level pressure (SLP), temperature at 500 hPa ($T_{500}$) and geopotential at 500 hPa ($Z_{500}$), obtained from the twentieth century V2 Reanalysis Project (20CRP, Compo et al. 2011), extending the time coverage of the NCEP/NCAR Reanalysis Project (Kalnay et al. 1996). The 20CRP produces reanalyzes of weather maps with a horizontal spatial resolution of 2° from 1871 onwards.

## Methods

The synoptic patterns have been obtained by a multivariable analysis based on three steps: PCA, CA, and discriminant analysis (DA), applied to three atmospheric levels (SLP, $T_{500}$, and $Z_{500}$) to detect the principal dynamic and thermodynamic atmospheric processes (Fig. 3). The variables employed are the daily anomalies of SLP, $Z_{500}$, and $T_{500}$ (aSLP, a$Z_{500}$, and a$T_{500}$), corrected each grid point by the squared root of the latitude.

### Principal component analysis

The use of PCA for classifying synoptic patterns is twofold (Huth et al. 2008). In our analysis, PCA has been employed for the reduction of the variables dimension. This procedure has been performed on every third data set by the use

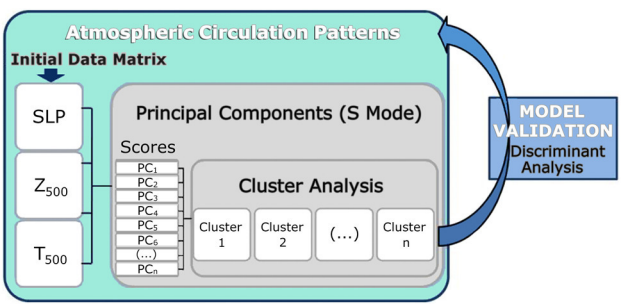


**Fig. 3** Scheme of the different multivariable analysis methodologies applied





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of an S-mode data matrix, with grid points as variables and observations as days. Both the correlation matrix and the Scree test have been employed to identify the principal components (Huth 1996; Cattell 1966). The Orthogonal Varimax procedure has been applied to rotate the components for minimizing the number of variables which have high factorial loadings (Richman 1986).

## Cluster analysis

The main synoptic patterns in relationship with heavy rainfall were detected using the non-hierarchical K-means technique performed on the matrix built by the individual factor scores matrix resulting from the PCA. For using this algorithm, the number of groups to obtain has to be defined beforehand. Despite different techniques were developed for other authors (Tibshirani et al. 2001; Ain 2010; Debatty et al. 2014), the election of the number clusters is still quite subjective. For this study, the "elbow method" was applied, which is based in choosing a number clusters, so that adding another cluster, the data would not be significantly better explained. Different parameters could be used to decide the number of initial clusters: the variance explained by clusters against the number of clusters (Thorndike 1953) or, the selected parameter for the present study, sum of squares (SSD) within clusters (Aran et al. 2011; Zhang 2016).

To determine the proper number of clusters to classify the extreme rain events spatial configuration, the next steps have been followed. First, the SSD for different number of clusters (from 1 to 28 in this case) considered are obtained by applying Ward method. The Ward method is similar to K-means (minimize SSD); however, it does not need a initial number of clusters. The graphical representation of SSD in front of the number of cluster considered allows to apply the elbow method to select the number of clusters: it corresponds to the position in which the highest change in the slope is found. This number of clusters will be initially used on the K-means to define the groups (Aran et al. 2011).

## Discriminant analysis

DA has been applied as a validation of the model and for re-classifying the bordering events (Michailidou et al. 2009). Since predefined classes are needed to perform a categorization by DA (Sioutas and Flocas 2003), the previous classification obtained from CA has been taken into account. Thus, the CA step has been used as a predictor for DA, that is, a CA specific group has been assigned to each day of the factor scores matrix of DA. Then, the discriminant functions, useful to re-classify new data, have been obtained by applying the Wilks' lambda criterion (Diab et al. 1991).

## Synoptic patterns related to RIG composites

To characterize the spatial configuration of the state of the atmosphere for each RIG, composites have been obtained. Thus, the mean value of each grid point has been computed for the days belonging to each RIG for SLP, $T_{500,}$ and $Z_{500}$. The spatial configuration of the synoptic patterns and the composites has been compared by the Pearson Product Moment correlation coefficient applied to SLP fields.

# Results

The synoptic patterns characterizing the atmosphere during the 28 extreme rainfall events have been obtained. The PCA applied to individual variables gives a reduction of seven components to explain SLP, nine in the case of $T_{500,}$ and six for $Z_{500}$. From the CA, seven clusters have been determined as the number of clusters necessaries to characterize the state of the atmosphere during these events. However, when applying DA, the number of clusters decreases to 5 due to the redistribution of the events in the group: at the beginning (after DA), the number of clusters were 6 (8) in the synoptic type 1, 1 (0) in the synoptic type 2, 2 (2) in type 3, 11 (12) in type 4, 5 (4) in type 5, 2 (2) in type 6, and 1 (0) in synoptic type 7. Thus, synoptic type 2 and 7, which originally had 1 event, disappeared.

After determining RIG composites, the correlation analysis was computed between them and the synoptic patterns (see Table 1 and Figs. 4, 5, 6, 7, 8). The highest correlation for RIG I is 0.89 with synoptic type 4. As it was described by Pérez-Zanón et al. (2015), this group is indicative of highly local or microscale rain episodes, characteristics of the late summer and fall with a clear diurnal surface heating effect involved in their convective development, since all them occurred after midday. The IP is low–medium index for this group, with values less than

**Table 1** Correlation coefficients of Pearson between the composites of the Rainfall Intensity Group (RIG) and the synoptic patterns computed from the multivariable analysis

| RIG | IP range | Synoptic pattern | Correlation |
|---|---|---|---|
| I | 0.55–0.80 | 4 | 0.89 |
| IIA | 0.64–0.86 | 5 | 0.91 |
| IIB | 0.74–1.02 | 6 | 0.77 |
| III | 0.48–0.75 | 3 | 0.33 |
| IV | 1.26–1.62 | 1 | 0.79 |





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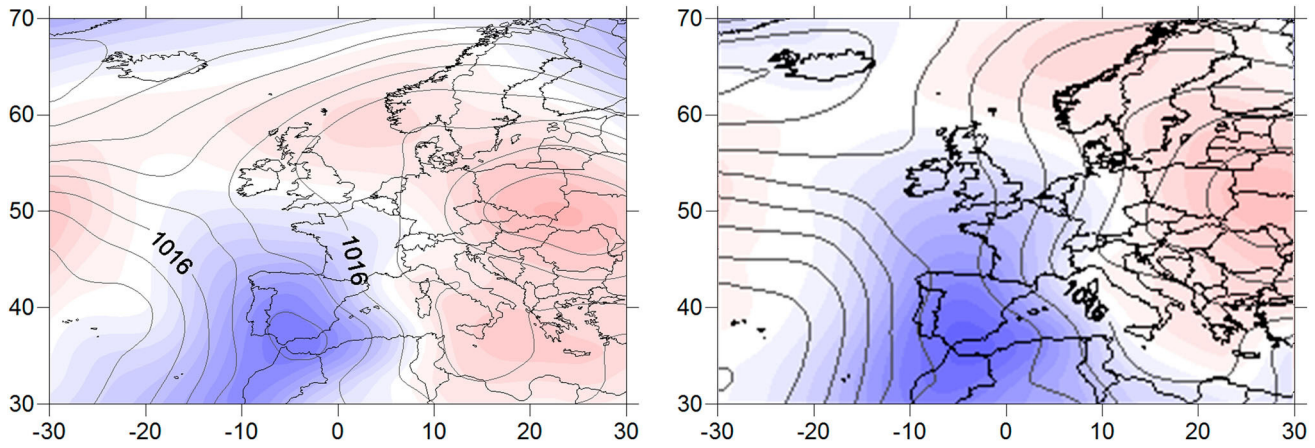


**Fig. 4** Composites of RIG I (left) and the maximum correlated synoptic type 4 (right). Lines represent SLP (hPa), while colored areas are aSLP with blue (red) colors represent negative (positive) anomalies. The synoptic configuration promotes precipitation in south Catalonia due to the SE flux linked to pressure and geopotential negative anomalies over the west of the Iberian Peninsula

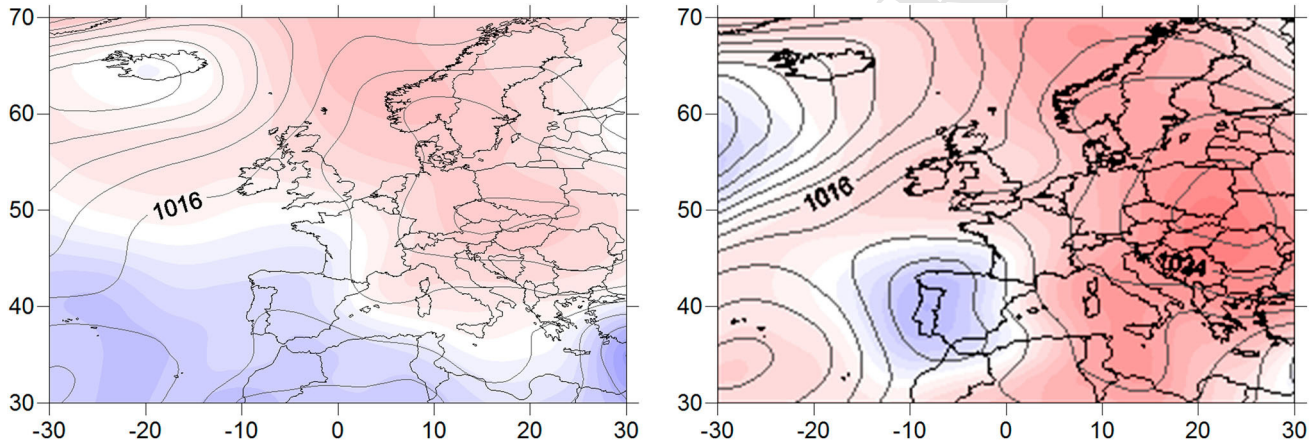


**Fig. 5** Composites of RIG IIA (left) and the maximum correlated synoptic type 5 (right). Lines represent SLP (hPa), while colored areas are aSLP with blue (red) colors represent negative (positive) anomalies. The synoptic configuration is related to the cut-off low-pressure system with cold air in the middle levels of the troposphere promoting instability and the occurrence of severe thunderstorms

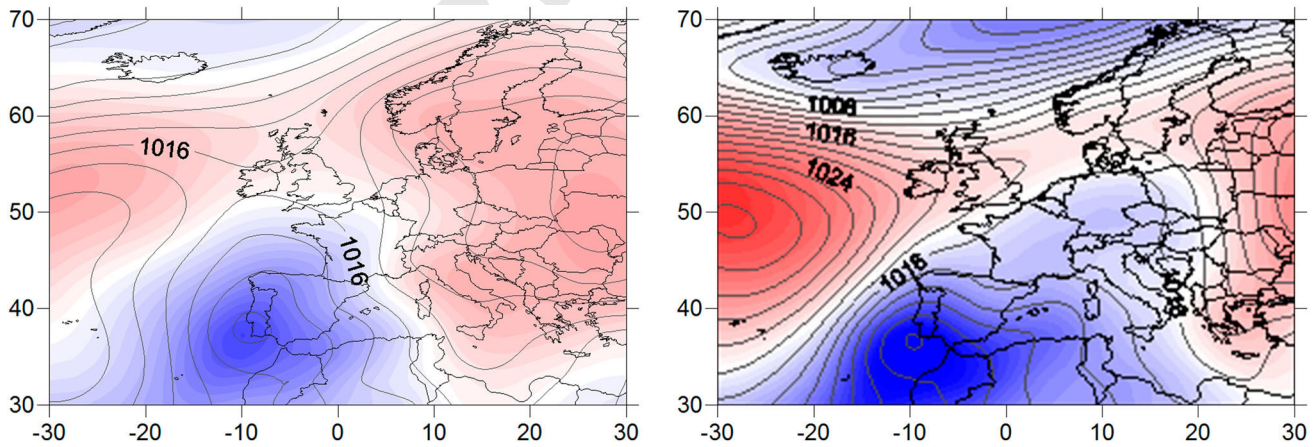


**Fig. 6** Composites of RIG IIB (left) and the maximum correlated synoptic type 6 (right). Lines represent SLP (hPa), while colored areas are aSLP with blue (red) colors represent negative (positive) anomalies. The synoptic configuration promotes precipitation in south Catalonia due to the east flux linked to pressure and geopotential negative anomalies over the Mediterranean area



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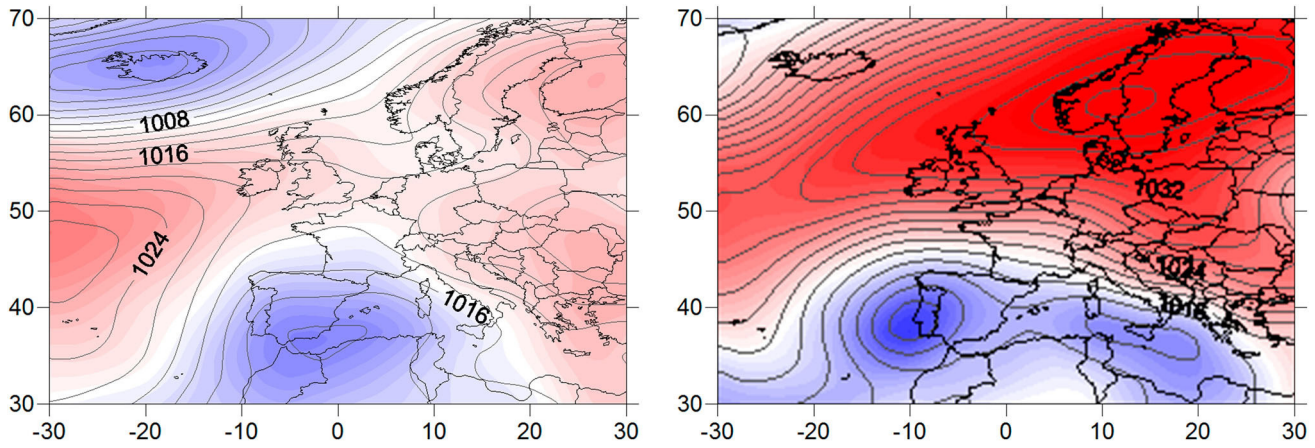


**Fig. 7** Composites of RIG III (left) and the maximum correlated synoptic type 3 (right). Lines represent SLP (hPa), while colored areas are aSLP with blue (red) colors represent negative (positive) anomalies. The synoptic configuration promotes precipitation in south Catalonia due to the east flux linked to pressure and geopotential negative anomalies over the Mediterranean area

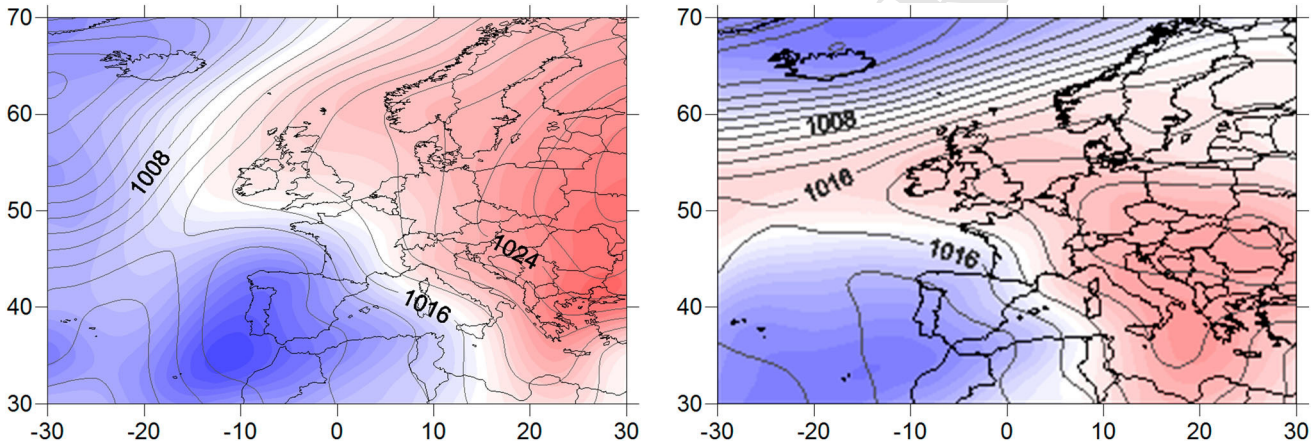


**Fig. 8** Composites of RIG IV (left) and the maximum correlated synoptic type 1 (right). Lines represent SLP (hPa), while colored areas are aSLP with blue (red) colors represent negative (positive) anomalies. The synoptic configuration promotes precipitation in south Catalonia due to the SE flux linked to pressure and geopotential negative anomalies over the Iberian Peninsula

1. The synoptic configuration promotes the precipitation in Catalonia due to the south-east flux linked with pressure and geopotential negative anomalies over the west of the Iberian Peninsula. The conjunction of wet and warm low flow from the Mediterranean Sea with cold air in the middle levels of the troposphere promotes atmospheric instability and the occurrence of thunderstorms.

The maximum correlation of RIG IIA has been 0.91 with synoptic type 5. The four events grouped as IIA showed high intensities until 35–60 min and were identified by Pérez-Zanón et al. (2015) as meso-γ-scale convective systems, at the edge of microscale. The IP is medium index, with values between 0.64 and 0.86. The synoptic configuration promotes the precipitation in Catalonia due to the south flow linked with pressure and geopotential negative anomalies over the Iberian Peninsula. The cut-off low-pressure system with cold air in middle levels promotes instability and the occurrence of severe thunderstorms.

The second division of group II, as it also characterizes mesoscale phenomena, RIG IIB has maximum correlation (0.77) with synoptic type 6. It presents high intensities for 12–24 h what is linked to meso-α and meso-β scales, typically in relationship with very dynamic Atlantic fronts moving slowly with strong mesoscale rain systems embedded (Pérez-Zanón et al. 2015). The IP shows a medium–high index, with values between 0.74 and 1.02. The synoptic configuration promotes the precipitation in Catalonia due to the east flow linked with pressure and geopotential negative anomalies over the Mediterranean area. The intense flow of east or south-eastern linked to this configuration with the anomalies of geopotential and temperature in middle levels stimulates intense thunderstorms,



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and a stagnation of this situation can cause long-lasting rainfall episodes.

RIG III, which shows a maximum correlation of 0.33 with synoptic type 3, corresponds to synoptic rain events, whose intensity is higher than the 10-year return period level for durations longer than 9 h. In this case, the IP is a low index, with values between 0.48 and 0.75. The synoptic configuration promotes the precipitation in Catalonia due to the east flow linked with pressure and geopotential negative anomalies over the Mediterranean area. The flow of east linked to this configuration with the anomalies of geopotential and temperature in the middle levels of the troposphere provoke rainfall in Catalonia: advective and long-largest rainfall with low intensities.

Finally, the RIG IV has a correlation of 0.79 with synoptic type 1. This RIG is associated with the most intricate storms, showing the combined action of processes corresponding to several meteorological scales. This kind of complex events is usually constituted by synoptic situations causing large-scale rain simultaneously to mesoscale convective systems producing extremely intense rainfall, with even embedded smaller convective cells. These episodes are the main cause of flooding in the area. The IP shows a high index, with values between 1.26 and 1.62. The synoptic configuration promotes the precipitation in Catalonia due to the south-east flow linked with pressure and geopotential negative anomalies over the Iberian Peninsula. The flow of south-east (warm and wet) provokes long-lasting rainfall in Catalonia. This rainfall may be both convective due to the high degree of the tropospheric instability and advective due to the anticyclonic blocking, which prevents the progress of the low-pressure center to the east.

## Discussion

Regarding similar studies, the analysis made provides two novelties: the first is related to the identification of the extreme precipitation episodes, while the second is the methodology to obtain the synoptic patterns associated with.

A precipitation event is usually defined as extreme when it exceeds a certain threshold of cumulative precipitation. However, different criteria are used to define this threshold (for more information, see Merino et al. 2017). In the present study, a return period of 10 years was used as threshold in the selection of the extreme rainfall episodes registered in the Ebre Observatory between 1905 and 2003 (Pérez-Zanón et al. 2015), classified in RIGs after taken into consideration their meteorological time scales. Then, the multivariate analysis in three steps (PCA, CA, and DA) has been carried out to obtain the specific synoptic patterns associated with the RIGs. This analysis has been performed on three atmospheric levels (SLP, $T_{500}$, and $Z_{500}$) to detect the principal dynamic and thermodynamic atmospheric processes related to intense rainfall generation. Furthermore, this technique can be used to re-classify new data (Aran et al. 2011; Peña et al. 2011).

The results show that the methodology used has been useful to obtain the synoptic patterns related to the four RIG groups (I, II, III, and IV), to better understand high intense rain intensity episodes in the south of Catalonia and their forecasting in the future. The prevailing synoptic conditions that favour heavy rainfall in this area have shown a good correspondence with the RIG classification.

The synoptic patterns are characterized by low-pressure systems that interact with the Mediterranean warm-air mass promoting the destabilization the atmosphere. The atmospheric configuration in $Z_{500}$ (Fig. 9) is dominated by negative anomalies of geopotential and temperature, showing the presence of a low-pressure center or an Atlantic cold front (Casas et al. 2004, 2010; Pérez-Zanón et al. 2015). These types of configurations enhance the occurrence of convective events due to the difference of temperature between $T_{500}$ and $T_{850}$ (warm air from the Mediterranean Sea and negative anomalies of temperature in middle levels) and the humidity input in the lowest levels of the atmosphere. Furthermore, the presence of a high-pressure system over Europe can provoke a stagnation of the synoptic situation causing long-lasting rain over the studied area.

Two different types of heavy rain can affect the lower part of the Ebre basin (Merino et al. 2017): (1) advective precipitations during winter and spring with low or medium convectivity linked to a zonal disposition of the synoptic configuration, producing heavy accumulated precipitation over several days and (2) the extremely convective summer and autumn storms are linked to the cyclones that become more intense over the Mediterranean Sea, producing long-lasting and intense rain due to the Mediterranean warm-air mass, the orographic uplift of the air mass, and the instability produced by negative anomalies of geopotential height at the middle levels of the troposphere (Peña et al. 2015).

Flood represents a high natural hazard for mid-latitude Mediterranean regions (Llasat et al. 2013); therefore, the precipitation rate behaviour must be contemplated for designing hydraulic works, and evaluate natural risk due to eventual extreme rain events (Casas et al. 2004, 2010; Beguería et al. 2011; Pérez-Zanón et al. 2015; Merino et al. 2017; Rodríguez-Solà et al. 2017). Particularly, in the south of Catalonia, heavy precipitation is normally connected with peak discharges measured in Tortosa (MAGRAMA 2015), located in the lower part of the Ebre basin, near of Ebre Observatory (Ruiz-Bellet et al. 2015). Two types of







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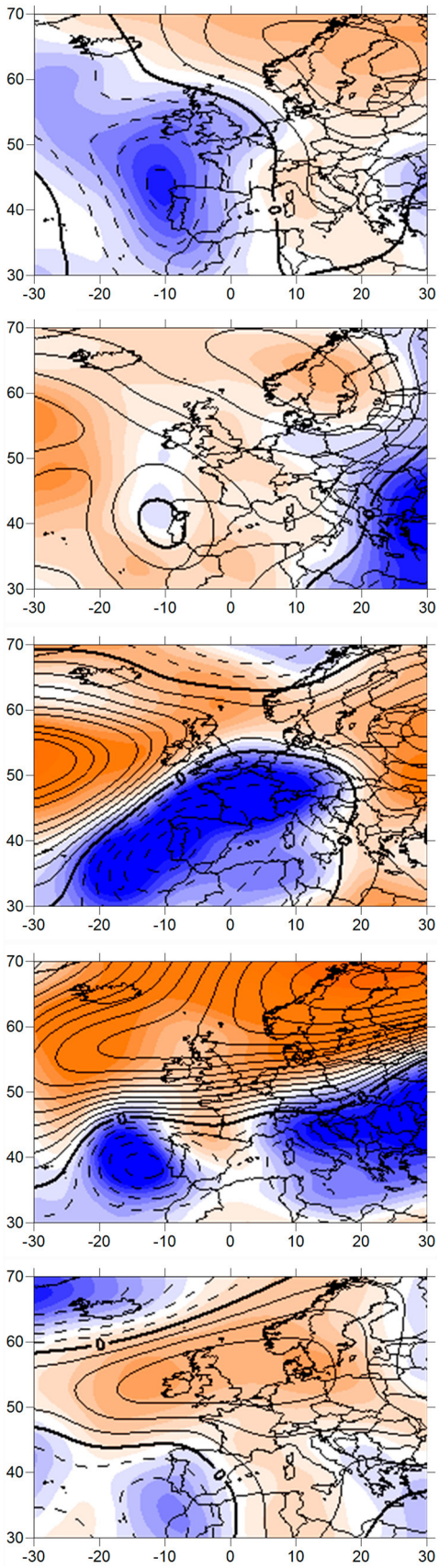

◀**Fig. 9** Composites of the synoptic patterns 4, 5, 6, 3, and 1 (up to down) for 500 hPa. Lines represents $aZ_{500}$ (m) and colored areas are $aT_{500}$ (0 °C) with blue (red) colors represent negative (positive) anomalies

behaviour within the flood series are detected in several analyses (Mazon et al. 2014; Ruiz-Bellet et al. 2015; Pino et al. 2016). The differences are linked to the two types of rainstorms. A more frequent behaviour related to flat-peak discharges might be caused by winter and spring advective rainfall of low or medium convectivity, while a less frequent one associated with high-peak discharges might be caused by highly convective summer and autumn storms. Therefore, extreme hydrological events in the Ebre basin seem to be controlled by the atmospheric dynamics acting both in the Mediterranean area (high-convectivity rainfall) and in the North Atlantic (long-lasting and advective rainfall). The most important flood events are a combination of the two atmospheric process and is related to the RIG group number IV (IP > 1.25). The main characteristics of the synoptic patterns corresponding to this complex rain episodes (14% of the investigated cases) are the existence of an Atlantic depression at the south-west of the Iberian Peninsula and a strong blocking anticyclone over Europe (Casas et al. 2004, 2010; Pérez-Zanón et al. 2015). In these situations, there is usually a moist and warm advective flow from the Mediterranean Sea, since the predominant wind over Catalonia is from the south-east both at 850 hPa and on the surface. These atmospheric configurations cause long-lasting advective rain while simultaneously convective phenomena associated with the south-east warm flow in low levels produce extremely intense precipitation (Peña et al. 2015; Pérez-Zanón et al. 2015).

It is important to remark that trends of extreme rainfall records over the twenty-first century are nowadays one of the most interesting topics in climate change studies (Beguería et al. 2011). The spatial and time analysis of precipitation data is a relevant research for a better understanding and prevention of the possible effects of climate change in rainfall extremes.

## Conclusions

The multivariate analyses have been a success to identify the main features to detect of the main dynamic and thermodynamic atmospheric processes. The synoptic patterns, which characterize the origin of the extreme rainfall in the Observatori de l'Ebre, have been found by a multivariate analysis applied independently to three atmospheric variables over the European sector. Therefore, the synoptic





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patterns, in addition to being able to characterize the spatial configuration of the atmosphere, capture differences in the intensity and temporal distribution at local scale of the rain.

The synoptic patterns associated with severe rain in southern Catalonia are featured by low-pressure systems advecting wet and warm air from the Mediterranean Sea in the low levels of the atmosphere. The most predominant flow is from south-east, followed by the east. The configuration in the middle levels of the troposphere is dominated by negative anomalies of geopotential, indicating the presence of a low or a cold front, and temperature anomalies, promoting the destabilization of the atmosphere. These types of configurations promote the occurrence of severe convective events due to the difference of temperature between the two levels analyzed (warm air from the Mediterranean Sea and negative anomalies of temperature at middle levels) and the humidity contribution in the lowest levels. Furthermore, the presence of a blocking high-pressure system over Europe can cause the stagnation of the synoptic configuration and produce long-lasting precipitation.

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## Compliance with ethical standards

**Conflict of interest** On behalf of all authors, the corresponding author states that there is no conflict of interest.

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