Temporal analysis (1940–2010) of rainfall aggressiveness in the Iberian Peninsula basins

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ABSTRACT

Rainfall aggressiveness causes environmental impacts and it is related to several natural hazards. Therefore, this parameter has been chosen as an environmental indicator. The present study is based on the monthly estimated rainfall using the Precipitation Runoff Integrated Model (SIMPA) for each Spanish hydrographic basin from 1940 to 2010. The main aim is to analyse temporal irregularity of rainfall aggressiveness in large geographic areas and to extract spatio-temporal patterns. For each year the rainfall aggressiveness was calculated using the Modified Fournier Index (I_{FM}) and Oliver´s Index of Precipitation Concentration (I_{PC}). The temporal variability of the annual series of these indices was analysed for each zone delimited. The results obtained made it possible to characterize the rainfall aggressiveness in the Iberian Peninsula and to determine its evolution over the past decades. They also reveal that the general pattern of the rainfall aggressiveness is determined by the dual effect of latitude (north–south) and longitude (east–west) as a result of the different maritime influences of the Atlantic and the Mediterranean watersheds.

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Finally a new variable is proposed, the Annual Aggressiveness Risk R_A, which summarizes the information provided by I_{FM} and I_{PC}.

Keywords: rainfall aggressiveness, concentration index, irregularity, basin, Spain

1. Introduction

Changes in rainfall intensity cause environmental impacts and are related to various natural hazards (Estrela et al, 2012;. Machado et al., 2001). Therefore, knowledge of the spatial and temporal variability of precipitation is relevant to characterize the regime of the hydrological basins, its exposure to risks and, if applicable, the adoption of prevention and mitigation measures (Krysanova et al., 2010; Middelkoop et al., 2001). In this paper we focus on estimating the aggressiveness of rainfall as an indicator of potential environmental impact. It is especially important to know the temporal evolution of the rainfall aggressiveness in areas like the Iberian Peninsula, which is characterized by irregular inter-annual and intra-annual precipitation (García-Barrón et al 2011, 2013).

The Iberian Peninsula is located in the climatic transition zone between the mid-latitudes and the subtropical climates, and it presents complex orographic features that influence the generation of precipitation. Furthermore, its peculiar geographical location between the Mediterranean Sea and the Atlantic Ocean determines a wide range of Mediterranean climates (De Castro et al., 2005) whose different rainfall characteristics reflect a wide range of landscape and environmental varieties. The peninsula's hydrological basins, except the Cantabrian one, show the characteristics associated with the Mediterranean climate: variability of rainfall, wet years mixed with recurrent droughts, high concentrations of rainfall over a few days and low rainfall during the summer (Lionello et al., 2006; Martín-Vide and Olcina, 2001).

We believe that the river basin is an appropriate spatial scale for assessing the natural hazards associated with rainfall, being the natural hydro-climatic area (González-Hidalgo et al., 2010). Several authors have also considered the river basin as the territorial unit for the analysis of precipitation and its impact (Angulo-Martínez et al., 2009; Barriendos and Rodrigo, 2006; Caramelo and Manso-Orgaz, 2007; González-Hidalgo et al., 2010; Kilsby et al., 2007; López-Moreno et al., 2013; Morán-Tejeda et al., 2012; Valencia et al., 2012). Therefore, understanding the evolution of aggressivity in each basin during the last decades, is crucial in order to undertaking water resource management and planning, including the water supply to populations, the organization of irrigation, the water infrastructure design, the flood and drought management, etc. To do this, it is necessary to develop new procedures that provide information about the behaviour of the hydrology of each studied zone over long periods.

Trends and the interannual and intra-annual variability at different time scales have been analysed with different approaches (Acero et al., 2011; Costa et al., 2012; De Luis et al., 2010a; Del Río et al., 2011; García et al., 2007; García-Barrón et al., 2011, 2013; Lorenzo-Lacruz et al., 2012; Martín-Vide, 2004; Sousa et al., 2010). The impact of rain on agriculture and forestry (Nippert et al., 2006; Pérez-Camacho et al., 2012; Sardans and Peñuelas, 2013), on erosion and desertification (Briggs et al., 1992; De Vente et al., 2008; Diodato et al., 2011; Vicente-Serrano, 2006) and on hydrology (Do Ó, 2010; Embid and Gurrea, 2004; Sousa et al., 2013) have also been widely studied from different perspectives.

From this point of view, it is important to analyse environmental indicators and to identify patterns that make it possible to infer consequences for large territorial areas. In this paper, the Spanish territory of the Iberian Peninsula has been divided into zones, largely coincident with the Spanish hydrographic basin; each one is represented by its total annual rainfall values and its intra-annual distribution. We selected rainfall aggressiveness as an environmental indicator parameter that will broaden the knowledge about the spatial variability of precipitation patterns in the zones.

Knowledge of rainfall aggressiveness is linked to several environmental study fields. Its effects are related to torrentiality, erosivity, landslides, floods, silting, etc. (Diodato et al., 2011; Gregori et al., 2006; Sousa et al., 2013). As an environmental indicator, it is based on the calculation of the Modified Fournier Index (I_{FM} from now on) (Arnoldus, 1980; Fournier, 1960), and it is complemented by the Precipitation Concentration Index (I_{PC} hereafter) (Oliver, 1980).

Both indices are based on monthly rainfall records. Some environmental impacts depend on the rainfall intensity of each event but, except for the modern automatic weather stations, traditional stations do not have high frequency rainfall records (in minutes). Moreover, torrential rain events in the Mediterranean area are often highly concentrated.

For example, for the direct calculation of rainfall erosivity at a regional scale (Angulo-Martínez et al., 2009) it is convenient to use a set of closely spaced (<15 km) weather stations, each of which holds high frequency records for at least twenty years. In Spain, the rain gauge network is recent, scarce and unevenly distributed; therefore, it is not possible to directly analyse the evolution of impacts using a network of high frequency local records across large regions over the course of a long period of time. Thus, to obtain information about the potential risks of rainfall in the area that have sufficient spatial and temporal validity, it is necessary to use alternative methods based on monthly data, as proposed in this work.

The usefulness and value of this new methodological approach, based on monthly rainfall data, is that it allows reconstructing the evolution of the rainfall aggressiveness in the large river basins of the Iberian Peninsula during the period 1940-2010. Subsequently, this approach can be used as a basis for linking the rainfall aggressiveness with hydrological processes that can have a great impact, such as the evolution of soil erosion, the silting of reservoirs, etc. The high rainfall variability entails a significant irregularity of the environmental effects associated with precipitation. Different studies of rainfall aggressiveness have been made from rainfall records. Gregori et al. (2006) highlighted the enormous versatility of the Modified Fournier Index (I_{FM}) to describe the characteristics of the rainfall regime and its relationship to some instability phenomena (quick flows, erosivity, shallow landslides etc.). Michiels et al. (1992) used the I_{PC} to describe the variability of rainfall in the Iberian Peninsula and considered that it was suitable to evaluate erosivity. De Luis et al. (2010b) executed both the I_{FM} and the I_{PC} to study the possible increase in erosivity in the Spanish Mediterranean area from a wide range of selected weather stations. I_{PC} has also been employed with monthly data from scattered weather stations across the Iberian Peninsula to analyse the temporal trend in rainfall and to describe spatial patterns (De Luis et al., 2011). In general, these papers focus on the analysis of annual or seasonal trends. In addition, there are many precedents for the use of these indices of aggressiveness (the I_{FM} and the I_{PC}) and the analysis of their relationship with other parameters in the Mediterranean area (Apaydin et al., 2006; Diodato and Belocchi, 2007) and in different climatic areas and different continents (Da Silva, 2004; Diodato et al., 2013; Elagib, 2011; Febles et al., 2009; Gabriels, 2006; Lee and Heo, 2011; Munka et al., 2007; Rey el al., 2012; Sauerborn et al., 1999 Vrieling et al., 2010). However, we believe that the analysis of the multi-annual irregularity of the indices proposed in this paper and applied to large basins provides an innovative approach that could broaden the study perspective.

For all these reasons, we intended to determine the specific temporal behaviour of rainfall aggressiveness in each zone and to establish the relationships between the different climatic areas in order to extract general patterns, if possible. Thereby, the overall objective of the study was to determine the evolution of rainfall aggressiveness during the period 1940–2010 in the defined Spanish zones. More specifically, by using the time series generated for both the I_{FM} and the I_{PC} the intentions were:

- To characterize the temporal irregularity of aggressiveness in each zone delimited by the comparative analysis of trends, interannual variability and disparity.

- To check whether the results reveal similarities and differences between the zones that allow for the establishment of a spatial pattern for each watershed (Mediterranean/Atlantic) or for the whole Iberian Peninsula.

The indicators of the rainfall intensity that we developed in this study allow a comparative analysis of the evolution of the rainfall aggressiveness in different basins for an extended period (1940-2010). As a result of this comparative analysis it is possible that a general pattern of evolution in the Iberian Peninsula, which may be supplemented by variations according to the geographic location, appears. The knowledge of these patterns of variation could have interesting implications for water planning (management of water resources, conservation of rivers, flow regulation, assessment of river ecosystems, ...) and, generally, for the development of environmental policies, besides serving as a basis for further studies of climate change scenarios.

2. Study area and data

The study area is the Spanish territory of the Iberian Peninsula, which is divided into large basins which are largely coincident with the boundaries of the Spanish hydrographic basins. We chose to aggregate small adjoining basins. The Water Information Service (Sistemas de Información del Agua, SIA in Spanish) of the Ministry of Agriculture, Food and Environment of Spain is responsible for the quality of water resources and environmental status management, and it is also in charge of the water risk prevention in the Spanish hydrographic basin.

In collaboration with some university departments, this service has developed the Sistema Integrado de Modelización Precipitación-Aportación (Precipitation Runoff Integrated Model) known as SIMPA (Estrela and Quintas, 1996). For climate information, SIMPA estimates the rainfall for each Spanish hydrographic basin, month by month throughout the simulation period, from data recorded by selected rain gauges of the official networks, which include the Spanish Meteorological Agency (Agencia Española de Meteorología, AEMET), the Spanish Hydrographic Service, etc. (Estrela et al., 1999; Ministerio de Agricultura, Alimentación y Medio Ambiente, 2013). SIMPA takes monthly precipitation from 1 km grid maps created by the Spanish Ministry of Environment by means of an interpolation procedure (the inverse to the square distance) with data from the more than 5000 weather stations of the Spanish network (Belmar et al., 2011). For this interpolation, double regression and ''white noise'' procedures were used to complete incomplete series without altering the natural variance of data, as well as specific procedures for the highest elevation areas (Estrela et al., 1999). The lack of rain gauges in the highest regions produces significant underestimations of the rainfall of many headwaters. To overcome this, SIMPA generated a rainfall time series based on specific regional algorithms analysing the factors that influence the process (precipitation, altitude, orientation, slope, etc.). The location of the stations used is available at Estrela et al. (1999) o MIMAM (2000). The SIMPA model has been frequently used to study hydrological processes in Spanish basins (Belmar et al., 2011; Bejarano et al., 2010; Chavez-Jiménez et al., 2013; Sánchez et al., 2011). The basic monthly datasets used in this study are the official SIA series, which are considered to be homogeneous and without gaps.

The capacity of synthesis of the SIMPA model, from the records of 5000 meteorological stations, has the advantage of being suitable for analysing reliably the development of estimated rainfall in large natural areas and over long periods. The development of a single dataset of rainfall representative of each case study area allows results to be obtained that enable direct comparisons to be made between all of the areas, including their evolution. This study covered the period from September 1940 to August 2010, and it considered the hydrological year. For this, ten zones were distinguished for the Spanish mainland (Fig. 1).

The zones are groups of basins, and the rainfall assigned to each zone was calculated from the monthly rainfall of each, weighted by their respective surfaces.

Fig.1 around here

With regard to the zones shown in Fig. 1, the Cantabrian zone (25,343 km^2) is formed by the basins of the northern slopes of the Cantabrian mountains that flow into the sea of the same name. The Atlantic watershed is composed of the Galicia zone, the Plateau [Meseta in Spanish] zones (the basins of the Douro [Duero in Spanish], Tagus [Tajo in Spanish], Guadiana) and the Guadalquivir zone. The Galicia zone (34,056 km^2) is formed by the grouping of the Miño-Sil river basin (52%) with other minor basins of this region. The Spanish basins of the rivers Douro (78,859 km^2), Tagus (55,764 km^2) and Guadiana (55,468 km^2) form their own zone. The Guadalquivir zone (57,700 km^2) groups the Guadalquivir river basin (87%) and that of other minor Andalusian rivers draining to the Atlantic.

The Mediterranean watershed is formed by the Jucar and Ebro Rivers, the Southeastern zone and the Catalonian zone. The Southeastern zone [Sureste in Spanish, SE] (40,128 km^2) is formed by the Andalusian Mediterranean (50%) and the Segura basins (50%). The Jucar (45,118 km^2) and Ebro (85,900 km^2) river zones are constituted solely by their respective basins. The Catalonian zone (18,047 km^2) is formed by the basins of small rivers within this region. The percentages in parentheses indicate the proportion of the area of the respective river basin district relative to the total area of the zone that it is included in.

3. Methodology

The present study is based on the analysis of the rainfall aggressiveness in the ten hydrological zones that appear in Fig.1. The annual precipitation series from 1940 to 2010 were prepared for these zones (Fig.1). Calculating the potential aggressiveness of the precipitation was carried out using the Modified Fournier Index (I_{FM}):

$$I_{FM} = (\Sigma p_m^2)/P \qquad (1)$$

where p_m is the monthly rainfall for each month (m = 1, 2, ... 12), and P is the corresponding total annual precipitation. However, it has been observed (García-Barrón et al., 2010) that high values of the I_{FM} index correspond to high total annual precipitation, so we believe that the intra-annual distribution is undervalued. Therefore, we also used jointly the Precipitation Concentration Index (I_{PC}).

$$I_{PC} = 100\ (\Sigma p_m^2)/P^2 \quad (2)$$

This index provides a dimensionless value for each year, which depends on the intra-annual distribution of rainfall, but it is independent of the size of the total value. If two different years Year A and Year A' have the same intra-annual distribution, namely the precipitation of the corresponding months are proportional $p_m = kp_m'$, where k is a constant, then the value of the $I_{PC} = I_{PC}'$ index is the same for both. The significance of the I_{PC} index is that it reveals that a high temporal concentration of rainfall can cause more severe impacts on the environment.

In our opinion, the combined interpretation of both indices provides more complete information on the rainfall aggressiveness since it allows the temporal irregularities of each zone to be characterized and analysed to identify the contrast in behaviour between them. Years that are considered to be at risk of aggressive rainfall are those where I_{FM} and I_{PC} are high. Conversely, simultaneously low I_{FM} and I_{PC} values indicate years of low and scattered annual rainfall, thereby reducing the potential aggressiveness of the rain.

The analysis of the annual series of potential aggressiveness I_{FM} and concentration I_{PC} aims to identify temporal irregularity. The following were used to highlight the temporal irregularity: the coefficient of variation for each complete series, the mobile variation coefficient using periods of eleven years, the indices of general and specific disparity, and the analysis of trend. These methods were applied successively to the two sets of indicators.

A similar methodology has been proposed by the authors in previous works (García-Barrón et al., 2011, 2013) for the study of direct datasets of rainfall, but the application of the analysis of the space-time irregularity of these indicators of aggressiveness is considered novel.

The mobile variation coefficient using periods of eleven years is defined as the ratio of the standard deviation of the partial subset formed by the reference year i and the previous ten to the corresponding mean

$$V_{i(11)} = \sigma_{(i\,,\,i-10)} \,/\mu_{(i\,,\,i-10)} \qquad (3)$$

Choosing an eleven year period, coinciding with the solar cycle, allows the smoothing of extreme annual values and highlights the sequence variability in the long-term time series (García-Barrón et al., 2011; Rodrigo and Trigo, 2007). Because of the complexity of the climate system, meteorological variables do not always show clear, unambiguous periodicities. Our choice of an eleven year period, corresponding to the solar cycle, is based on an objective criterion of energy-climate regulation (Dima et al., 2005).

The coefficient of variation of the entire series is referred to as V_N.

The general disparity index I_D is calculated as the square root of the sum of squares of consecutive deviations extended to all the calculated series, divided by the number of summands, and in turn divided by the mean value μ_R of the complete series. Thus, if r_i is a value calculated for the year i and r_{i+1} for the following year, then

$$I_D = (\{\, \Sigma[(r_{i+1} - r_i)^2] \,/\, N-1\}^{1/2}\,) \,/\mu_R \qquad (4)$$

The specific disparity index for the year i, I_{di}, considers only the elements $\{r_{i-1}, r_i, r_{i+1}\}$ of the time series, μ_i being the average of the three consecutive elements centered on i.

$$I_{di} = (\{[(r_i - r_{i-1})^2 + (r_{i+1} - r_i)^2] \;/2\}^{1/2}\,) \,/\mu_i \qquad (5)$$

In addition, to classify the risk of aggressiveness of rainfall we propose a synthetic parameter called *Annual Aggressiveness Risk* (R_A), derived from the indicators explained above

$$R_A = f\ (I_{FM}, I_{PC}) \qquad (6)$$

The R_A parameter has the advantage of unifying all the information, so as to allow a more concise interpretation of the rainfall impacts. The function f may be determined locally based on erosivity data measured during the simultaneous period with high frequency registers. For this, the R factor rainfall erosivity of the Universal Soil Loss Equation (USLE) is used. Thus, this procedure connects methods based on monthly data with intra-hour data analysis methods. In each case, the function f allows both the extrapolation into the past and the analysis of the evolution of aggressiveness in historical periods. We have used this methodology to analyze the aggressivity for each basin and to compare their behaviour on an interregional scale. However, because this methodological approach involves the regional aggregation of the precipitation data, the variations on shorter distances (intra-basins) have not been analyzed in this study. Additionally this methodology can also be applied to selected meteorological stations in every basin and then to establish spatial patterns within them.

4. Results and assessment

The annual series of the Modified Fournier Index and the Precipitation Concentration Index were calculated for each zone from precipitation datasets. In section 4.1 we present a general characterization of the I_{FM} series. In section 4.2 the temporal evolution is analysed in detail. Subsequently, a similar procedure was carried out for the I_{PC} series (described in sections 4.3 and 4.4). Finally, the joint interpretation of both indicators (4.5) and the analysis of the risk of aggressiveness (4.6) were implemented.

4.1. Characterization of the Modified Fournier Index (I_{FM})

The results of the temporal analysis of the complete series of the variable I_{FM} in each zone are displayed in Table 1. The order of the zones corresponds to the organization of watersheds explained in section 2. For the analyzed period (1941 to 2010) the mean value, the coefficient of linear trend, the coefficient of variation (V_N) and the general disparity index (I_D) are shown.

Table 1 around here

It is important to highlight that the Modified Fournier Index result is high ($I_{FM} > 120$ l/m^2) in the Cantabrian, Galicia and Guadalquivir zones, coinciding with the highest annual rainfall. It is moderate (I_{FM} <90 l/m^2) in other zones. These results confirm that I_{FM} is highly influenced by total annual rainfall, masking intense rain events of shorter duration.

The trend lines of the annual series show a slight up- or down-slope, but they are not statistically significant since the variance explained by the trend line is in all cases less than one percent ($R^2 < 0.1$). Therefore, the central value is not a good predictor of the temporal behaviour of rainfall aggressiveness. However, the cumulative relative deviations A_k, permit the distinction of multiannual sequences of different climatic behaviours. The cumulative value until the year k is obtained as the sum, extended to all preceding years, of the deviations δ_i of each annual index I_{FMi} from the mean μ_N of the entire series.

$$A_k = (\sum \delta_i) / \mu_N \quad (7)$$

where $\delta_i = (I_{FMi} - \mu_N)$, for $i = 1, 2, \ldots k;\ k \leq N$.

Fig. 2 shows the annual accumulation of the relative deviations from the mean of the I_{FM} in each zone during the period 1941–2010. The sawtooth of the horizontal sections of the graph (Fig. 2) indicate multiannual sequences of the values of the I_{FM} where deviations by excess and by deficit from the mean compensate. The descending [ascending] section is due to multi-year sequences with higher frequency of values of lower [higher] I_{FM} than the mean of the entire series.

Fig. 2 around here

Interestingly, all the analysed areas show an initial downward segment – with the sawtooth – resulting from the increased frequency of I_{FMF} values below the average; in 1958 the trend changes with an upward section (high values of I_{FM}) of different duration for each zone. In particular, the Cantabrian zone (Fig. 2a) shows a long upward section after 1958 until 1984, when the direction changes again. The Atlantic watershed zones (Galicia, Douro, Tagus, Guadiana and Guadalquivir zones: Figs. 2a, 2b and 2c) show matching profile graphics with a concurrence in the sawteeth, including the secondary minimum in 1995. All this denotes a common temporal pattern. The profiles of the Southeastern and Jucar zones (Fig. 2d) and the Ebro and Catalonian zones (Fig. 2e) also match. In the last thirty years there have been some zones (Ebro, Guadalquivir, Guadiana, Douro) whose annual I_{FM} values have fluctuated around their averages values (horizontal section). However, the other zones show a final section, as a result of repeated sequential years with I_{FM} values lower than the mean of the series in the last decades. We can say that initially all zones show a similar temporal behavior of their I_{FM}, with V-shaped graphs from 1941 to 1971 with their vertices in 1958, but in recent decades that analogy does not hold. Anyhow, it is noteworthy that 1958 is singular in the whole Peninsula, when a sequence break occurs.

Table 1 also shows the general irregularity of I_{FM} in each zone during the entire period from 1940 to 2010. Both the measure of variability V_N and disparity I_D reveal similarities between both statistics in their geographical distribution. The irregularity is low in the Cantabrian zone, indicating slight fluctuations of the annual I_{FM} value over time. In the Atlantic zones there is a south–north gradient and the Guadalquivir zone shows the largest amplitude in annual deviations of I_{FM} to the mean value (V_N) and to the successive values (I_D). From the interpretation of the characteristic I_{FM} value (first column of Table 1) and its irregularity (third and fourth columns of Table 1) we can deduce that the Cantabrian zone maintains stability in its high potential rainfall aggressiveness; in the Guadalquivir zone, the potential aggressiveness is high although the annual values are unstable, and in the Ebro the potential rainfall aggressiveness is low and the annual values are steady.

It is important to note that in the context of the whole Iberian Peninsula, the Mediterranean zones do not show the largest interannual irregularities in their I_{FM} indices. This is because, although locally intense rainfall events occur occasionally (Martin-Vide, 2004; Rodrigo 2010), they do not alter the permanent shortage of total annual rainfall on a basin scale. Consequently, except in the mountains or in the irrigated meadows, the main environmental feature of large areas of the Mediterranean basin is aridity.

For further comparison of the temporal behaviour during the study period, we used the Pearson Correlation Coefficient R between the annual series of I_{FM} of the delimited zones (Table 2). This allowed us to quantify the extent to which the zones have followed a similar development.

Table 2 around here

We can deduce (Table 2) that the interannual correspondence of the I_{FM} between the Plateau zones (Douro, Tagus, Guadiana) is very high ($\geq$ 0.80) and it is slightly lower than that of the rest of the Atlantic zones (Guadalquivir and Galicia). In the Atlantic watershed the temporal variations of the Modified Fournier Index maintained relative simultaneity. In the Mediterranean zones a northeast gradient is observed. Except for the neighboring Ebro and Galicia zones, the correlation between the Cantabrian and the other case study areas is very low ($\leq$0.20), indicating the different synoptic conditions that lead to precipitation in their respective watersheds.

4.2. Specific irregularity of the Modified Fournier Index

In each zone the foregoing characterization of the annual series of the I_{FM} during the entire period is complemented with the analysis of the specific interannual irregularity. For this, the mobile variation coefficient using periods of eleven years V_{11} was calculated as a first step (Fig. 3).

Fig. 3 around here

In the Cantabrian area the coefficient of variation V_{11} shows a decreasing profile from 0.20 to 0.10 during the observation period, indicating a progressive interannual stabilization of the I_{FM} index in recent decades. The graph for Galicia shows a succession of multiannual horizontal sections at different levels, framed between 0.25 and 0.35. A marked increase in the variability of the I_{FM} in the Guadalquivir zone is detected from 1980, when V_{11} goes from 0.30 to values above 0.50, and then finally a decline in the last decade; with less intensity, mostly from 0.20 to 0.30, the Plateau zones (Guadiana and Tagus) also exhibit similar behaviour. In Jucar and in the Southeastern zones during 1960–1980 and in the Ebro during the whole period analysed, the coefficient of variation V_{11} is limited between 0.10 and 0.25, suggesting slight interannual oscillations of the I_{FM} around its central value.

The irregularity of the time series of the I_{FM} index analysed using their variability is also reflected when using specific disparity as a criterion for study. This parameter indicates the amplitude of the difference between consecutive years (Fig 4). The annual index of disparity I_{di} shows a great simultaneity in behaviour between the Guadalquivir zone and the Plateau zones (Fig. 4a; to provide a better visualization, the Plateau zones have been grouped by their similar behaviour). These hydrological zones show their highest frequencies in the range from 0.30 to 0.40 and it shows that their relative maxima show a strong positive trend from 1971 to 1995. In the Ebro zone the I_{di} index, with marked fluctuations, maintains frequent values near to 0.15, whilst other Mediterranean basins oscillate more slightly around 0.3 (Fig. 4b). Due to their geographical proximity, the profile of the disparity in the Cantabrian zone (descending and with smooth fluctuations) contrasts with the one for Galicia (ascending and with wide fluctuations) (Fig. 4c).

Fig. 4 around here

4.3. Characterization of the Precipitation Concentration Index I_{PC}

As we have pointed out, in some situations the Modified Fournier Index I_{FM} does not evince the effect of the intra-annual distribution. Therefore, estimating aggressiveness is complemented by the calculation of the Precipitation Concentration Index I_{PC} based on the same data. Oliver (1980) established the classification under which I_{PC} values below 10 represent sparse rainfall throughout the year (uniform equipartition of rainfall throughout every month of the year is the minimum value 8.3); I_{PC} values over 15 indicate concentrated rainfall (more than 60% of the total annual rainfall occurs in only four months).

Table 3 around here

The averages of the concentration index in the zones of the southern half of the Peninsula are higher than in the northern half (Table 3). The south–north gradient of I_{PC} is observed in both the Atlantic and the Mediterranean watersheds. The highest frequencies of years with high intra-annual concentration values, $I_{PC} \geq 15$ and with marked seasonality are found in the southern areas: the Guadalquivir zone (55%) and the Southeastern zone (34%). However, the northern zones show the highest frequency of years with high dispersion throughout the year ($I_{PC} \leq 10$), specifically the Ebro zone (40%) followed by the Cantabrian zone (14%).

Table 3 also shows that the slope of the trend line of the annual series for the entire period of analysis is very low and not statistically significant in any of the zones. It also states that the general irregularity of the I_{PC} in the comparison between zones shows similar features for the entire period 1940–2010 in terms of variability V_N and disparity I_D. The I_{PC} concentration index shows low variability in the northern peninsula, in the Cantabrian (V_N = 0.09) and the Ebro zones (V_N = 0.10), compared to the Southeastern (V_N = 0.14), the Tagus (V_N = 0.17), the Guadiana (V_N = 0.17) and, especially, the Guadalquivir zones (V_N = 0.19). A similar spatial relationship is observed in the values of the general disparity I_D during the period 1941–2010.

The analysis of cumulative deviations of the I_{PC} during this period allows temporal sequences to be detected. Fig. 5 shows that the years 1958 and 1978 have a singular behaviour because they represent breaks in time sequences. In the graph for the Jucar zone and the Southeastern zone (Fig. 5d) this is clearly visible, but it can be extended to the other cases studied. A section where there is a downward trend with frequencies of years in which the I_{PC} value is lower than the average, and therefore where there is more concentratation around the winter months, ends in 1958. Except in the Catalonian zone, a new upward section starts in 1978 (Fig. 5e), suggesting greater intra–annual dispersion with shifts of the periods of rainfall to autumn and/or spring.

Fig. 5 around here

We have indicated that the Pearson Correlation Coefficient *R* between the annual series permits comparisons of the extent to which they have followed similar trends over the entire period from 1941 to 2010. The results in Table 4 reveal that the interannual I_{PC} correspondence is negligible between the Catalonian zone and the remainder ($R < |0.2|$), except for Jucar and Ebro. However, it is high among the zones of the Plateau with each other and with the Guadalquivir zone ($R > 0.6$), indicating simultaneity between the zones of the Atlantic watershed during the years of greatest concentration and also during the years of highest intra-annual dispersion.

Table 4 around here

4.4. Specific irregularity of the Precipitation Concentration Index I_{PC}

A space-time analysis of the specific interannual irregularity of the Concentration Index I_{PC} was performed using a similar approach to that used in Section 4.2. With this aim, we calculated the mobile coefficient of variation using periods of eleven years V_{11} whose partial results are shown in the Supplementary Electronic Material (from now ESM) Figure ESM-1. The area of Cantabria and the Ebro river show, in general, the least variability of I_{PC}, with the particularity of presenting an opposite behavior since 1964. The area of the Guadalquivir river presents the greatest variability of I_{PC}. The graphs of the southeast and the Júcar river areas show very similar profiles. Therefore, there is an uniform spatial pattern that can describe the specific interannual variability of I_{PC} in the Iberian Peninsula, except between the neighboring areas of the same basin.

Among the results of the specific disparity I_d of the I_{PC} index we have selected the most significant ones, which are those for Tagus/Guadiana and Galicia/Ebro basins (Fig. 6). It is important to note the temporal simultaneity reflected in the overlay profiles of the chosen zones, Tagus and Guadiana (Fig. 6a), are to a large degree coincident with the temporal evolution of Guadalquivir (not shown). In them, the relative maxima show an upward alignment in recent decades. This implies an increase in the range of intra-annual dispersion of rainfall in consecutive years. In the Galicia and the Ebro zones the time series reflects a decline in relative maxima, without concurrency, until 1970 (Fig. 6b). From that year, in the Ebro zone the maxima increase progressively, while in Galicia, after a sharp rise, the values tend to decrease again.

Fig. 6 around here

4.5. Comparison between the temporal evolution of the indices I_{FM} and I_{PC}

The joint interpretation of the temporal behaviour of the Modified Fournier Index (I_{FM}) and the Precipitation Concentration Index (I_{PC}) can be used to estimate the rainfall aggressiveness more accurately. Thereby, simultaneous high values of both annual indices correspond to high risk: high annual rainfall and very seasonally concentrated. In contrast, the simultaneous low values of both indices indicate relatively dry years but well-distributed rainfall throughout the year. Therefore, for the whole period of analysis, the association of pairs of values have been established for each year and zone. Fig. 7 shows the range width for both indices, the equation of the trend line and the Pearson coefficient of determination (R^2) calculated for the period from 1941 to 2010. For graphical representation we have chosen the following zones: Cantabrian (north)/Guadalquivir (southwest), Galicia (northwest)/Jucar (east), Ebro (northeast)/Guadiana (west), facilitating the visualization of the different rainfall patterns in the Iberian Peninsula.

Fig. 7 reveals that the range of values of both indices provides an identification of the zones. In all the zones the coefficient of the line is positive, suggesting that high/low annual values are associated with high values of I_{PC}, although with different statistical significance. However, the observed values of the determination coefficient R^2 below 0.5 are not enough to deduce that generally the wettest years (high I_{FM}) are due to excess rainfall concentrated in certain months (high I_{PC}). Although the trend lines are parallel (linear coefficient of 9.76 and 9.08, respectively) the range of the I_{PC} marks a difference between the Cantabrian zone and the Guadalquivir zone (Fig. 7a). In the Cantabrian zone, without large interannual fluctuations, there are frequently years when the intra-annual distribution of rainfall is very distributed throughout the months ($I_{PC} < 12$). In Andalusia (Guadalquivir), there is a great temporal diversity of both I_{FM} and I_{PC} indices, but years of intense seasonality ($I_{PC} < 15$) are frequent, which is associated with intra-annual unimodal distribution with a maximum in winter (García-Barrón et al., 2010).

In Galicia and Jucar the intra-annual distribution is similar between the two zones ($10 < I_{PC} < 15$) for all the years studied (Fig. 7b). However, the I_{FM} is higher in Galicia, which may be due to its greater total annual rainfall compared to the Jucar zone, with less annual precipitation and less interannual variability ($I_{FM} < 100$ l/m^2).

Ebro shows $I_{PC} < 12$ values, associated with a bimodal intra-annual distribution profile with maxima of rainfall in spring and autumn and a relative minimum in winter (Garcia-Barrón et al., 2010). In Guadiana the I_{FM} shows a wide range of values associated with the irregularity of the interannual precipitation resulting in dry years and wet years (similar to Guadalquivir but less intense) and also a wide range of I_{PC} ($10 < I_{PC} < 20$) corresponding to a large intra-annual variability (Fig. 7c).

Fig. 7 around here

The above results are justified by the precipitation regime in each zone. The storms of the SW and those of the NW, which are less intense, determine the rainfall of the Spanish Atlantic watershed, mainly in the zones of Guadalquivir and Galicia, although they slightly diminish in the Plateau zones (Douro, Tagus, Guadiana) because of the effect of continentality due to the greater distance from the sea. The influence of the Azores High, located southwest of Portugal for much of the year, limits the approach of SW storms which are deflected to northern regions. This also explains the gradient between the southwest and northwest in the Peninsula: the highest rainfall is more evenly distributed in Galicia, the same north–south effect, but more attenuated, occurs between the zones of the Plateau as well.

In the Mediterranean watershed, the difficulty the Atlantic winds have in reaching the headwaters and the proximity to the Mediterranean Sea (with factors related to seasonal atmospheric circulation in autumn and the wet influences from the northeast) make a difference to the rainfall regime compared to the Plateau. In the Cantabrian watershed, the narrow coastal strip (defined by the altitude of the next ridge that holds the flow of moisture and prevents its transition to the Plateau) receives heavy rainfall, with weak seasonality, due to the presence of the NW Atlantic fronts for much of the year. The Ebro zone also presents weather oddities in comparison to the Iberian Peninsula, mainly due to the water coming from the southern slopes of the Pyrenees, the isolation of the Plateau by the Iberian System mountain range and the connection between the influences of the Cantabrian and the Mediterranean Seas along the axis of the Ebro river basin.

4.6 Risk of aggressiveness of rainfall in the Guadalquivir zone

To classify the risk of rainfall aggressiveness, the R_A parameter, which summarizes the information provided by I_{FM} and I_{PC}, is proposed. A new series of annual risk of aggressiveness in the Guadalquivir zone was generated according to the procedure described in section 3.

In order to establish the weights of both the I_{FM} and I_{PC} components, two values have been chosen for the *R* erosivity factor calculated by the Andalusian Environment Information Network for the Guadalquivir river basin. This network provides monthly values of rainfall erosivity between 1991 and 2010 for the area, taking in account the rainfall data collected by the automatic weather stations. These values are determined by the regionalization of Andalusia based on the delimitation of homogeneous rainfall zones according to the rainfall intensity parameter. After that, for each of these regions one or more weather stations with high frequency records were selected and the regression equation between their R factor values and their total annual rainfall was calculated (Rodríguez Surián and Sánchez Pérez, 1995). The best-fit model has the form $y = a\,\chi^b$ (where a and b are local parameters) implemented on decadal total rainfall and giving coefficients of determination R^2 above 0.90.

Throughout the simultaneity period, the correlation coefficient between the erosivity *R* factor and the Modified Fournier Index (I_{FM}) is 0.9, and between *R* factor and the Precipitation Concentration Index (I_{PC}) is 0.55. Although it cannot be generalized to other geographic areas, it is important to highlight the high capacity of the I_{FM} Index to predict the aggressiveness impact. If we consider the two indices jointly, the fit equation estimated by multiple linear regression is

$$R = R_A + \xi\ ;\ \ R_A = 11.32\ I_{FM} - 61.6\ I_{PC} + 663.3 \qquad (8)$$

where ξ is a residual value of mean equal to zero.

Applying the equation to every year of the concurrency period we obtain the theoretical value of R_A as opposed to the reference value of R. Fig. 8 shows both series, whose high correspondence (correlation coefficient $R^2 > 0.88$) supports the validity of the procedure.

Fig. 8 around here

When extrapolating into the past, we have generated the series for the interannual aggressiveness risk in the Guadalquivir river basin during the period 1941–2010 from the values of I_{FM} and I_{PC}. The R_A series with an average value of 1909.3 (Megajoules · mm)/(hectare · year · hour) reveals no significant trend and is characterized by its high irregularity with a coefficient of variation (*CV*) of 0.41. Figure ESM-2 shows the time evolution of R_A. Years with values below the 25 percentile ($R_A < 696.8$) are considered years with low aggressiveness risk, while those over the 75 percentile (R_A values > 1273.4) are classified as high risk.

We consider the procedure for calculating the aggressiveness risk R_A in the long-term time series as a useful method for analysing the environmental impact. In future work the research team plans to apply the procedure to a set of automatic weather stations in Andalusia that maintain secular records of monthly precipitation.

5. Conclusions

The advantage of the methodology used, based on information provided by the SIMPA model, is that it provides series of environmental indicators for extended multi-year periods, representative of large areas, where extreme local values are damped. This allows the analysis, from a space-time approach, of the effects of rainfall over the entire Iberian Peninsula. The procedure for calculating the rainfall aggressiveness uses the Modified Fournier Index (I_{FM}) in conjunction with the Precipitation Concentration Index (I_{PC}), both based on monthly rainfall data. These indices – and their relationship to the spatial and temporal distribution of rainfall aggressiveness and its environmental effects – have enabled patterns to be studied associated with rainfall and its temporal variability (Apaydin et al., 2006). Therefore, the development and application of methodologies and analysis, such as those proposed for observing the patterns of interannual variability by these indices and their differential behaviour through case studies, are important in supporting the understanding the functioning of the socio-hydrological systems.

During the analysis period (1940–2010) the potential rainfall aggressiveness measured with I_{FM} is moderate in the Mediterranean Ebro and Plateau zones, and intense in the Guadalquivir, Galicia and Cantabrian zones. The I_{FM} and I_{PC} series do not show a significant linear trend over the entire period analysed, although several differentiated multiyear sequences can be identified. An interannual correspondence between the I_{FM} values of the Guadalquivir and the values of the Plateau zones and also between the Mediterranean zones together is detected, but it is very low between the Cantabrian and other zones, indicating differences in rainfall patterns. The largest interannual irregularity of aggressiveness, as measured by the variability and disparity of the I_{FM} series, occurs in the Guadalquivir zone; the basins of the Plateau show a simultaneous temporal development, although it is less intense. In addition, an increase in temporal variability in Guadalquivir can be detected over the last thirty years. By contrast, the Cantabrian zone presents the greatest stability in its time series with smooth fluctuations, although increasing over time.

The interpretation of the Concentration Index I_{PC} indicates that, although not uniformly, the rainfall in the Cantabrian and the Ebro zones is distributed throughout the year without excessive interannual oscillations. Therefore, in these zones the main feature is the interannual and intra-annual stability. However, both the Atlantic and the Mediterranean watersheds show a north–south gradient in their I_{PC}, so that in the Guadalquivir rainfall is highly seasonal and it is mainly concentrated in just a few months, with large interannual fluctuations. These large fluctuations are embodied in intra-annual rainfall concentration values that are changing over time, showing a north–south spatial pattern where interannual and intra-annual instability increases with decreasing latitude. In these areas this phenomenon can help to complement the study of the relationship between the processes of seasonality/concentration of rainfall and of factors controlling the seasonal dynamics of vegetation in the Mediterranean areas, where the intra-annual distribution of rainfall amounts and the response of vegetation cover involve differences in the processes of erosivity, soil instability and desertification on a larger scale.

Finally, a general pattern of rainfall aggressiveness in the Iberian Peninsula under a dual effect is shown: the effect of latitude, with a north–south increase in the irregularity of the indices studied; and the effect of longitude, marked by the different maritime influences on the Atlantic and Mediterranean watersheds. The space-time variability identified should be compared to other regional studies related to the assessment of the impact and vegetative response to seasonal rainfall in terms of vegetation cover in order to determine trends in the relationship of precipitation (vegetative response) and environmental risk in the context of climate change.

From the Modified Fournier index (I_{FM}) and the Concentration Index (I_{PC}), we calculated the risk of rainfall aggressiveness R_A. The first partial results obtained allow the risk of aggressiveness to be estimated, based on monthly rainfall records, which can connect with other indicators based on high-frequency records. This opens the possibility of its application in future research.

Preliminary results in the Guadalquivir river basin support the predictive ability of the aggressiveness risk R_A; future studies may reveal its utility to determine environmental impacts in other river basins.

Acknowledgements

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version.

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Table captions

Table 1

Characterization of the Modified Fournier Index (I_{FM}) in the Spanish zones defined from 1940 to 2010.

Table 2

Pearson correlation coefficient between the series of the Modified Fournier Index (I_{FM}) of the case studies during the period 1940–2010.

Table 3

Characterization of the Precipitation Concentration Index (I_{PC}) in the Spanish zones defined from 1940 to 2010.

Table 4

Pearson correlation coefficient between the series of the Precipitation Concentration Index (I_{PC}) of the case studies during the period 1940–2010.

Figure 1 (colour)

Figure
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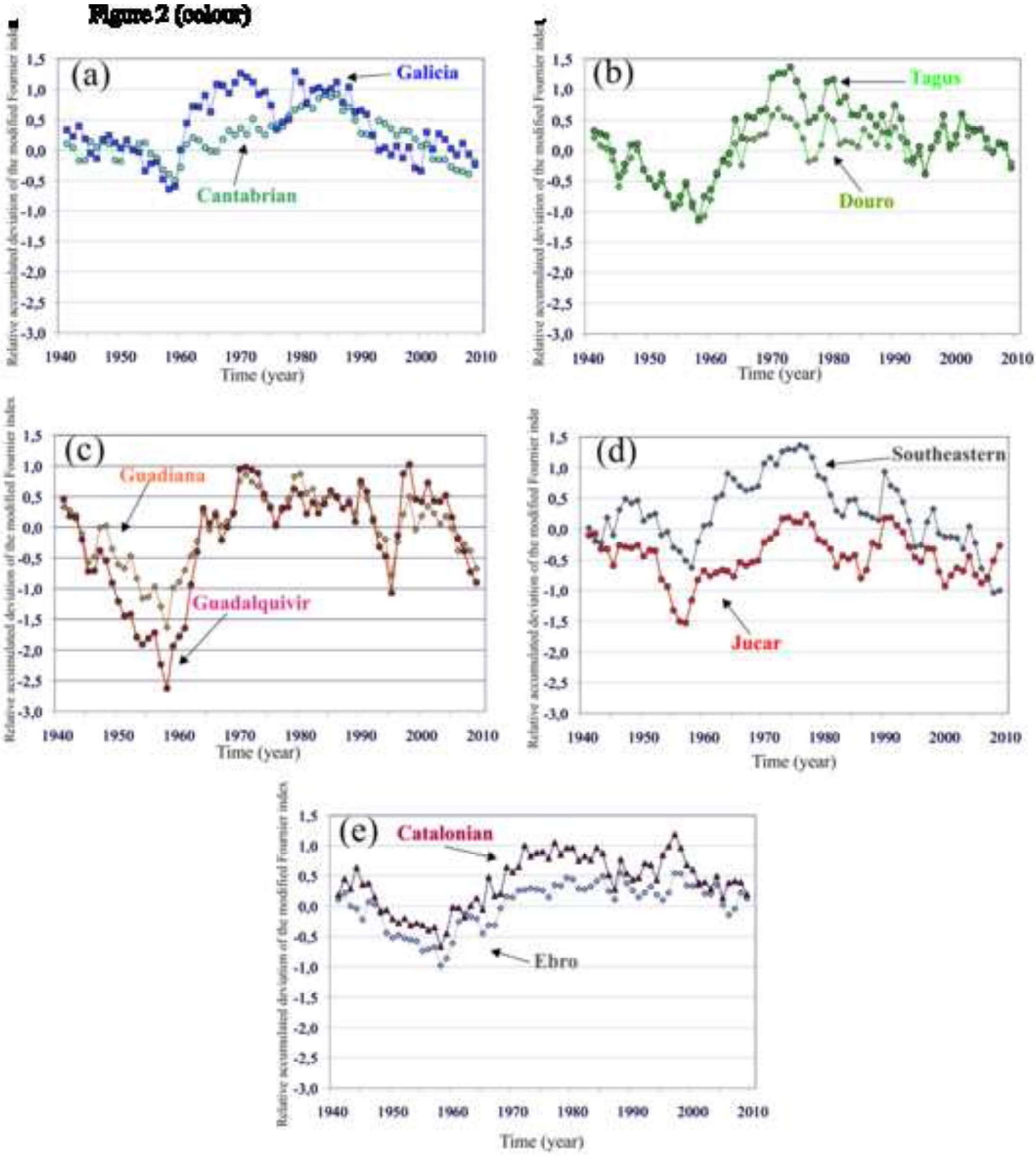

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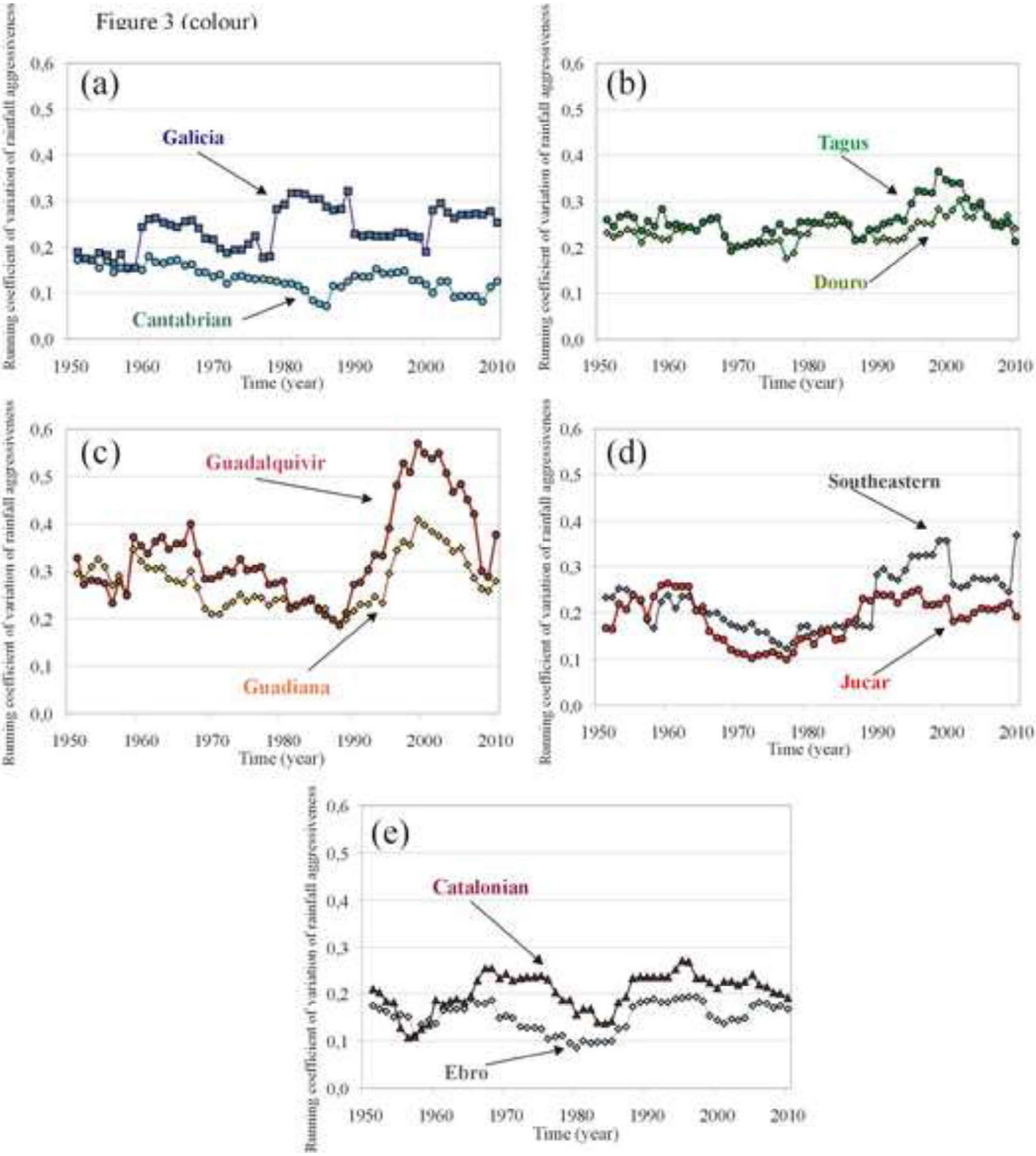

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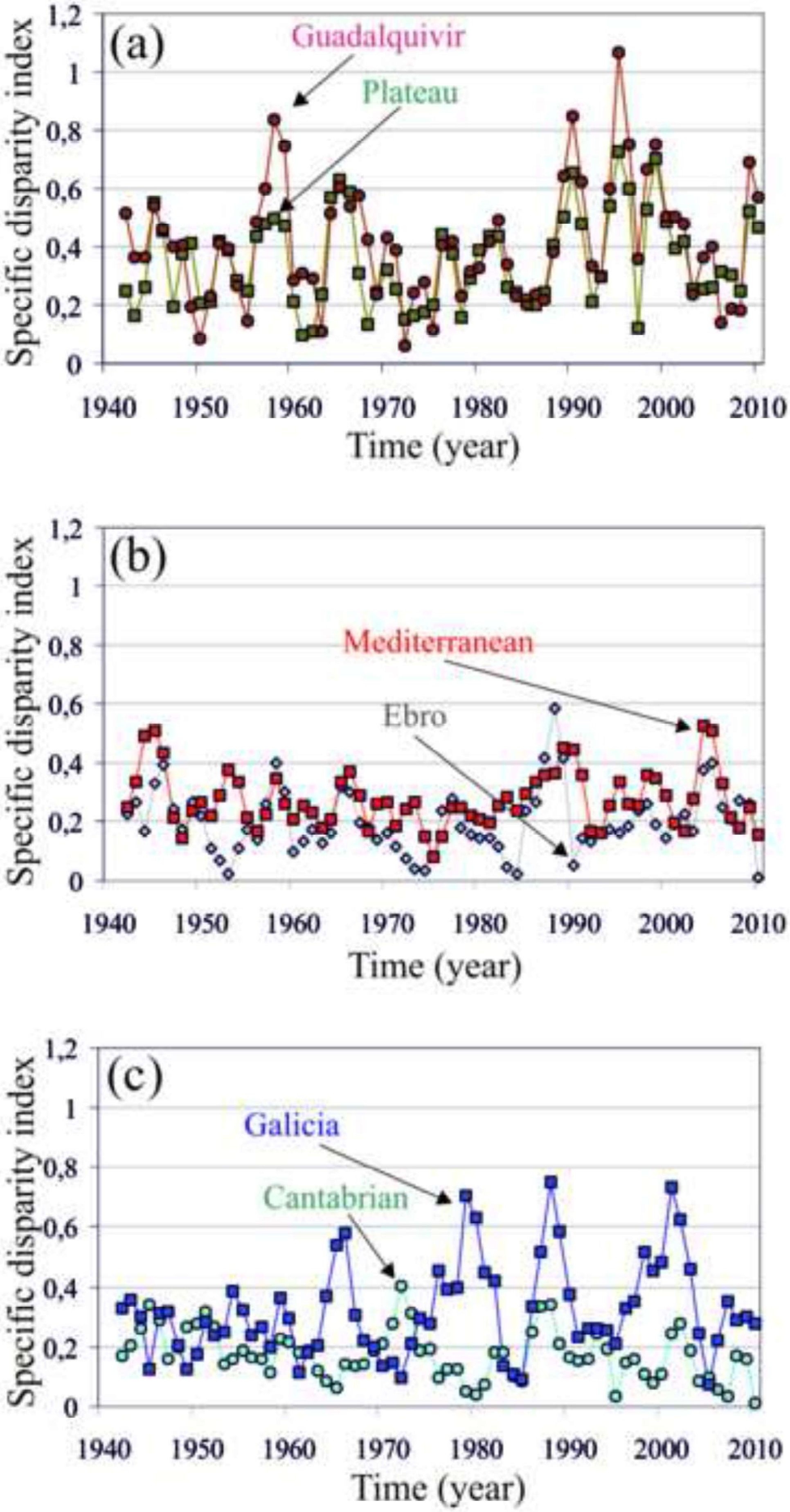

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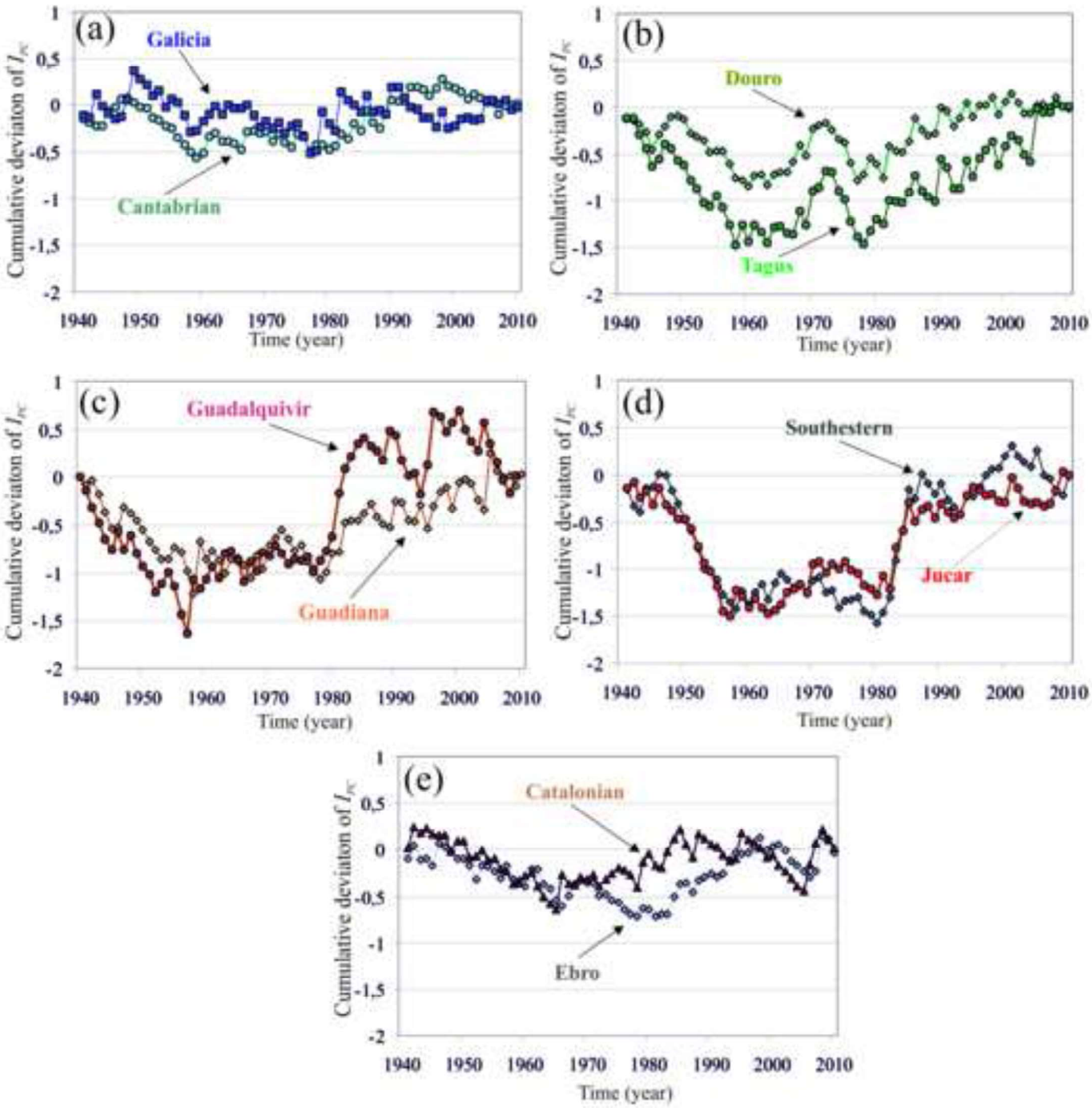

Table
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Table 1

I_{FM}	Average	Trend	V_N	I_D
Cantabrian	138.8	−0.06	0.14	0.19
Galicia	167.6	−0.15	0.24	0.36
Douro	72.8	+0.01	0.24	0.36
Tagus	83.7	−0.04	0.27	0.39
Guadiana	71.9	+001	0.29	0.41
Guadalquivir	120.7	−0.06	0.38	0.48
Southeastern	61.7	−0.04	0.26	0.35
Jucar	62.2	+0.07	0.20	0.26
Ebro	67.3	+0.01	0.16	0.23
Catalonian	82.2	+0.01	0.22	0.34

Table 3

I_{PC}	Average	% I_{PC} >15	% I_{PC} < 10	Trend	V_N	I_D
Cantabrian	10.82	0.0	14.3	0.00	0.09	0.13
Galicia	12.30	7.1	0.0	0.00	0.13	0.20
Douro	11.83	4.3	7.1	0.01	0.12	0.18
Tagus	13.16	20.0	1.4	0.03	0.17	0.25
Guadiana	13.68	22.9	0.0	0.02	0.17	0.26
Guadalquivir	16.57	55.7	0.0	0.02	0.19	0.26
Southeastern	14.14	34.3	0.0	0.02	0.15	0.18
Jucar	12.16	7.1	4.3	0.02	0.14	0.20
Ebro	10.44	0.0	40.0	0.01	0.10	0.14
Catalonian	11.61	1.4	8.6	0.00	0.12	0.17

Table 4

I_{PC}	Cantabrian	Galicia	Douro	Tagus	Guadiana	Guadalquivir	South-eastern	Jucar	Ebro	Catalonian
Cantabrian	1.00									
Galicia	0.36	1.00								
Douro	0.46	0.64	1.00							
Tagus	0.27	0.45	0.80	1.00						
Guadiana	0.16	0.39	0.63	0.90	1.00					
Guadalquivir	0.14	0.34	0.44	0.67	0.81	1.00				
Southeastern	0.09	–0.03	0.23	0.39	0.43	0.57	1.00			
Jucar	–0.03	–0.18	0.16	0.25	0.11	0.13	0.59	1.00		
Ebro	0.36	0.06	0.40	0.27	0.17	–0.01	0.16	0.31	1.00	
Catalonian	–0.16	0.06	0.00	0.00	–0.03	–0.05	–0.02	0.22	0.34	1.00

Table 2

I_{FM}	Cantabrian	Galicia	Douro	Tagus	Guadiana	Guadalquivir	Southeastern	Jucar	Ebro
Galicia	0.28								
Douro	015	0.79							
Tagus	0.05	0.69	0.91						
Guadiana	0.06	0.59	0.80	0.93					
Guadalquivir	0.08	0.53	0.71	0.83	0.91				
Southeastern	0.04	0.16	0.36	0.48	0.62	0.66			
Jucar	0.00	0.07	0.26	0.30	0.36	0.35	0.61		
Ebro	0.36	0.38	0.53	0.45	0.43	0.39	0.22	0.38	
Catalonian	0.01	0.19	0.15	0.16	0.19	0.19	0.09	0.26	0.56

Figure captions

Fig. 1. Map of the division of the Spanish zones studied.

Fig. 2. Cumulative deviations of the Modified Fournier Index (I_{FM}) in the Spanish zones defined.

Fig. 3. Mobile variation coefficient using periods of eleven years of the Modified Fournier Index (I_{FM}) in the Spanish zones defined.

Fig. 4. Specific disparity of the Modified Fournier Index (I_{FM}) of rainfall in the Spanish zones defined.

Fig. 5. Cumulative deviations of the intra-annual concentrarion of rainfall (I_{PC}) in the Spanish zones defined.

Fig. 6. Specific disparity of the Precipitation Concentration Index (I_{PC}) of rainfall in the Spanish zones defined.

Fig. 7. Pairwise comparison between synchronous values of the indices I_{FM} and I_{PC}.

Fig. 8. Comparison of the estimated values of R factor and those of the aggressiveness risk R_A calculated (1991–2010) for the Guadalquivir river basin.