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Differences in Spatial Patterns of Drought on Different Time Scales: An Analysis of the Iberian Peninsula

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Abstract. The differences in spatial patterns of drought over a range of time scales were analysed by the Standardized Precipitation Index (SPI). In a climatic area with a wide range of precipitation characteristics (the Iberian Peninsula), Pearson III distribution is flexible enough to calculate the drought index on different time scales. The Pearson III distribution was adapted to precipitation frequencies at time scales of 1, 3, 6, 12, 24 and 36 months. Spatial patterns of drought were analysed by Principal Component Analysis. The number of components found increased as the time scale did, which indicates great spatial complexity in drought analysis and uncertainty in drought classification, mainly at scales of 24 or 36 months, since the relationships between SPI series of observatories becomes more distant as the time scale increases. We concluded that there were no homogeneous regions with similar drought patterns that could be used for effective drought management or early warning.

Key words: drought, Iberian Peninsula, Pearson III distribution, principal component analysis, standardized precipitation index, time scales

1. Introduction

Drought causes huge losses in agriculture (Austin *et al.*, 1998; Quiring and Papakryiakou, 2003) and damages natural ecosystems (Kogan, 1995, 1997) and forestry (Orwing and Abrams, 1997; Abrams *et al.*, 1998). It leads to degradation of soils and desertification (Nicholson *et al.*, 1998; Pickup, 1998), social alarm (Morales *et al.*, 2000) and famine and impoverishment (García, 1984; Kanti, 1998).

Drought studies have received special attention in recent years because of climate change (Byun and Wilhite, 1999). The development of drought monitoring plans is a priority in many of these studies (Wilhite, 1997; Svoboda *et al.*, 2002). In addition, the atmospheric causes of droughts have also been analysed (Namias, 1983; Ropelewski and Halpert, 1987, 1989) in order to improve drought prediction (Cordery and McCall, 2000; Lloyd-Hughes and Saunders, 2002). Several studies analysed the spatial patterns of drought risk in order to assist agricultural or environmental management (Vicente-Serrano and Beguería, 2003; Dracup *et al.*, 1980; Lana and Burgueño, 1998).

However, these efforts have focused mainly on the development of drought indices, to identify and quantify drought's magnitude, duration, intensity and spatial extent, and to improve techniques for drought early warning and management (Wilhite and Svoboda, 2000). Numerous drought indices, using diverse variables for drought quantification, were developed during the 20th century (Heim, 2002; du Pissani *et al.*, 1998). Although temperatures or evapotranspiration are generally included in drought index calculation, precipitation is the most important parameter (Oladipo, 1985; Guttman, 1998; Keyantash and Dracup, 2002).

The most robust and effective drought index is the Standardized Precipitation Index (SPI), developed by McKee *et al.* (1993). This index enjoys several advantages over the others. Calculation of the SPI is easier than on more complex indices such as the Palmer Drought Severity Index (PDSI; Palmer, 1965), because the SPI requires only precipitation data, whereas the PDSI uses several parameters (Soulé, 1992). Moreover, the PDSI has some shortcomings in spatial and temporal comparability (Alley, 1984; Karl, 1987; Guttman, 1998). The SPI is comparable in both time and space, and is not affected by geographical or topographical differences (Lana *et al.*, 2001).

The SPI allows the determination of duration, magnitude and intensity of droughts (Hayes *et al.*, 1999). Its main advantage is that it can be calculated for several time scales (McKee *et al.*, 1995; Komuscu, 1999) and identifies various drought types: hydrological, agricultural or environmental.

The SPI has been extensively used for drought analysis in countries/continents such as the U.S.A. (Hayes *et al.*, 1999), Europe (Lloyd-Hughes and Saunders, 2002b), South Africa (Rouault and Richard, 2003), Hungary (Domonkos, 2003), Italy (Bonaccorso *et al.*, 2003), East Africa (Ntale and Gan, 2003), Greece (Tsakiris and Vangelis, 2004) and Korea (Min *et al.*, 2003).

Several studies focused on the SPI's calculation procedures, which identify the most appropriate frequency distributions (Guttman, 1999), the effect of time scales on the parameters (Ntale and Gan, 2003), and spatial and temporal comparability (Keyantash and Dracup, 2002). However, the SPI's spatial stability and coherence in relation to time scales have not been analysed.

In early drought warning and monitoring, accurate spatial classifications identify areas with homogeneous drought patterns in order to optimise resources and develop effective mitigation strategies. Although many studies have addressed the spatial classification of drought patterns (Karl and Koscielny, 1982; Eder *et al.*, 1987; Lana *et al.*, 2001), it is essential to check whether these classifications are stable over different time scales or not.

This article analyses with the SPI the stability of spatial patterns of drought as a function of time scales. The setting for the study was the Iberian Peninsula (Spain and Portugal), an area with complex precipitation patterns (Rodríguez-Puebla *et al.*, 1998; Serrano *et al.*, 1999; Rodó *et al.*, 1997) and frequent droughts (Olcina, 2001).

2. Methodology

2.1. CLIMATIC DATA

For drought analysis, 51 precipitation series with data between 1910 and 2000 were used. Nine of these series were obtained from the *Sistema Nacional de Informação de Recursos Hídricos* in Portugal (SNIRH, 2004) and the rest of them from the *Instituto Nacional de Meteorología* in Spain. Data were checked by means of a quality control process that identified anomalous records (ANCLIM program, Štìpánek, 2004). The homogeneity of each series was checked by means of the Standard Normal Homogeneity Test (Alexandersson, 1986; Alexandersson and Moberg, 1997), a technique widely applied in the homogenisation of climate records (Keiser and Griffiths, 1997; Moberg and Bergstrom, 1997). The few non-homogeneous series identified were corrected and temporal gaps were completed using linear regressions with respective reference series. Figure 1 shows the distribution of observatories in the Iberian Peninsula.

In the Iberian Peninsula, precipitation is highly variable in space and time (Rodríguez-Puebla *et al.*, 1998; Esteban-Parra *et al.*, 1998; Fernández-Mills, 1995). This is due to the peninsula's wide geographic diversity and its diverse atmospheric circulation patterns (Rodó *et al.*, 1997; Olcina, 2001). The precipitation decreases from North to South. In the North, annual mean precipitation is over 1,000 mm (the maximum recorded in Pontevedra: 1,641 mm); and in the centre and South, it is less than 400 mm (the minimum average of 210 mm was in Almería). Dry spells are long, mainly in the South, where periods of more than 120 days without precipitation

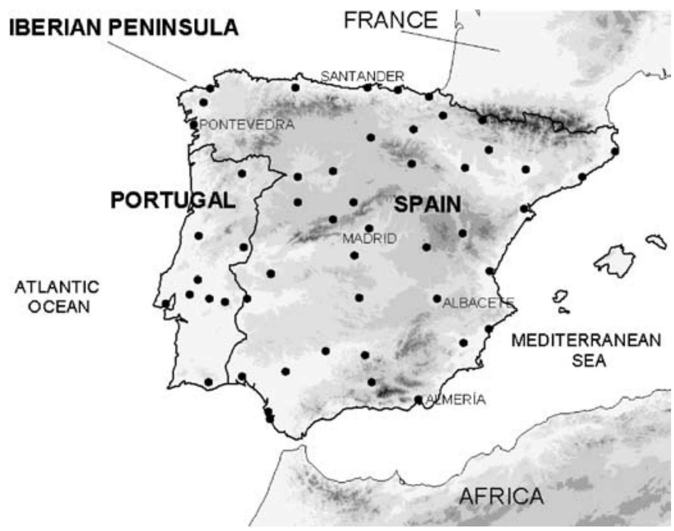

Figure 1. Spatial distribution of precipitation recording observatories used for drought analysis in the Iberian Peninsula.

have been recorded (Martín-Vide and Gómez, 1999). Moreover, annual precipitation is highly concentrated in a few days, mainly in the East (Martín-Vide, 2004).

2.2. CALCULATION OF THE DROUGHT INDEX

The SPI calculation starts with precipitation calculation over a range of time scales. The total precipitation $X_{i,j}^{k}$ in a given month j and year i depends on the time scale chosen, k. For example, the SPI for one month in a particular year i with a 12-month time scale is calculated by (Paulo *et al.*, 2003):

$$X_{i,j}^{k} = \sum_{l=13-k+j}^{12} w_{i-1,l} + \sum_{l=1}^{j} w_{i,l}, \quad \text{if } j < k, \quad \text{and}$$

$$X_{i,j}^{k} = \sum_{l=j-k+1}^{j} w_{i,l}, \quad \text{if } j \geq k$$

where $w_{i,l}$ is precipitation in the 1st month of year i [mm].

We calculated precipitation at time scales of 1, 3, 6, 12, 24 and 36 months, because these scales are useful for monitoring various drought types: agricultural or hydrological (Edwards and McKee, 1997; Komuscu, 1999). Sims *et al.* (2002) reported a strong relationship between SPI over short time scales and temporal variations of soil moisture, which determine water availability for vegetation and agriculture. Szalai *et al.* (2000) indicated that water resources in reservoirs are related to SPIs calculated over longer time scales, which allow hydrologic droughts to be identified. The longest time scales (24 or 36 months) monitor the impact of droughts on aquifers, which respond more slowly to drought (Changnon and Easterling, 1989).

The frequency distributions of precipitation series showed significant changes that depended on the time scale (Figure 2). At 1 month, distribution showed an inverse exponential shape, in which less precipitation is more frequent. An increase in time scale led to a gradual decrease in bias, but all the scales showed more frequent low than high precipitation. Therefore, to model the precipitation frequencies over a range of time scales, the most appropriate distribution of probability had to be determined.

To select the most suitable distribution of probability in SPI calculation, the L-coefficients of skewness and kurtosis were calculated in the 51 precipitation series at the time scales selected (Greenwood *et al.*, 1979; Sankarasubramanian and Srinivasan, 1999). With these statistics the empirical frequency distribution of precipitation series and a number of theoretical distributions can be compared (Hosking, 1990).

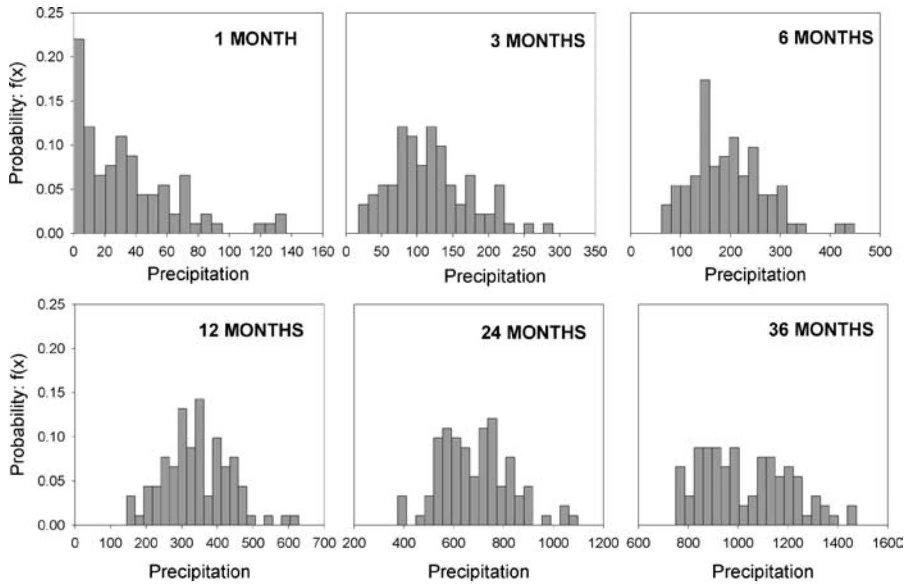

Figure 2. Frequency histograms of precipitation calculated at different time scales, observatory of Albacete.

τ_3 and τ_4 are the L-coefficients of skewness and kurtosis, respectively, and are calculated as follows:

$$\tau_3 = \frac{\lambda_3}{\lambda_2}$$

$$\tau_4 = \frac{\lambda_4}{\lambda_2}$$

λ_2, λ_3 and λ_4 are the L-moments of the precipitation series. These were obtained from probability-weighted moments (PWMs), using the formulae:

$$\lambda_1 = \alpha_0$$

$$\lambda_2 = \alpha_0 - 2\alpha_1$$

$$\lambda_3 = \alpha_0 - 6\alpha_1 + 6\alpha_2$$

$$\lambda_4 = \alpha_0 - 12\alpha_1 + 30\alpha_2 - 20\alpha_3$$

The PWMs of order s were calculated as under:

$$\alpha_s = \frac{1}{N}\sum_{i=1}^{N}(1 - F_i)^s x_i$$

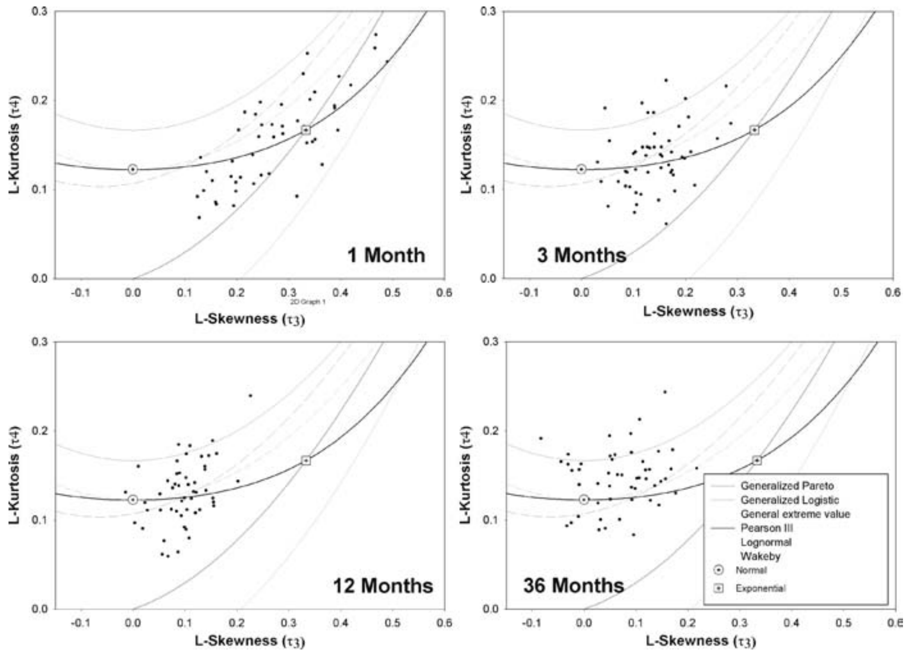

Figure 3. L-moment ratios diagrams for precipitation series at different time scales.

x_i is the data from a given precipitation series and F_i is the frequency estimator. F_i was calculated following the approach of Hosking (1990):

$$F_i = \frac{i - 0.35}{N}$$

where i is the range of observations arranged in rising order, and N is the number of data points. Figure 3 shows the L-moment diagrams for τ_3 and τ_4 at the time scales tested. In general, these statistical values of the precipitation series of the observatories oscillated around the theoretical curve of the Pearson III distribution. However, large differences were observed on different time scales. While for 1-month series the statistics from the observatories were near to exponential distribution, for the longer scales (i.e. 24 or 36 months) they were distributed in a cloud of points around normal distribution. This indicates the distinct characteristics of frequency distributions over different time scales. However, irrespective of the time scales, Pearson III distribution adapted well to the statistics from the observatories. In relation to time scale, the statistics oscillated along the theoretical L-curve of Pearson III distribution between the points that indicated the values of exponential and normal distributions.

In this paper Pearson III distribution was selected for SPI calculation at time scales of 1, 3, 6, 12, 24 and 36 months. The probability density function of a Pearson

III distributed variable is expressed as:

$$f(x) = \frac{1}{\alpha\Gamma(\beta)}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1} e^{-(\frac{x-\gamma}{\alpha})}$$

where α, β and γ are the shape, scale and origin parameters, respectively, for precipitation values $x > 0$; and $\Gamma(\beta)$ is the Gamma function of β. The parameters of the Pearson III distribution, when L-moment ratios have been calculated, can be obtained following Hosking (1990):

If $\tau_3 \geq 1/3$, then $\tau_m = 1 - \tau_3$ and β can be obtained using the formula:

$$\beta = \frac{\left(0.36067\tau_m - 0.5967\tau_m^2 + 0.25361\tau_m^3\right)}{\left(1 - 2.78861\tau_m + 2.56096\tau_m^2 - 0.77045\tau_m^3\right)}$$

If $\tau_3 < 1/3$, then $\tau_m = 3\pi\tau_3^2$ and β can be obtained using the following expression:

$$\beta = \frac{(1 + 0.2906\tau_m)}{\left(\tau_m + 0.1882\tau_m^2 + 0.0442\tau_m^3\right)}$$

$$\alpha = \sqrt{\pi}\lambda_2\frac{\Gamma(\beta)}{\Gamma(\beta + 1/2)}$$

$$\gamma = \lambda_1 - \alpha\beta$$

The probability distribution function of x is given by:

$$F(x) = \frac{1}{\alpha\Gamma(\beta)}\int_{\gamma}^{x}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1} e^{-(\frac{x-\gamma}{\alpha})}$$

and can be calculated analytically (Vicente-Serrano and Cuadrat, 2002).

Pearson III distribution is not defined for $x = 0$, which is a drawback as precipitation series may include months in which there is no precipitation. With this in mind, an adapted statistic $H(x)$ can be calculated using the following formula:

$$H(x) = q + (1 - q)F(x)$$

where q is the probability of zero precipitation. Edwards (2001) suggested that q can be calculated simply as m/n, where n is the total number of months and m is the number of months with no precipitation.

Pearson III distribution was well adapted to precipitation on all the time scales. The Pearson III models for precipitation series at different time scales in two observatories located in different climatic regions (North and Southeast) of the Iberian Peninsula are shown in Figure 4.

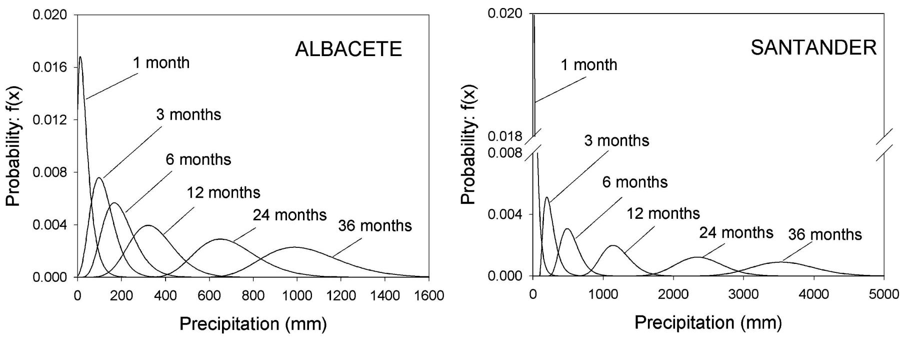

Figure 4. Pearson III models at different time scales in two observatories of the Iberian Peninsula.

After calculating $H(x)$, the mean is standardised as 0 and standard deviation as 1. This standardised variable is interchangeable with the SPI, and is commensurable with other SPI values over time and space. An SPI of 0 indicates precipitation corresponding to 50% of accumulated probability according to Pearson III distribution.

To transform $H(x)$ and obtain SPI, the approach formulated by Abramowitz and Stegun (1965) is used:

$$SPI = W - \frac{C_0 + C_1 W + C_2 W^2}{1 - d_1 W + d_2 W^2 + d_3 W^3}$$
$$W = \sqrt{-2\ln(P)} \quad \text{for } P \leq 0.5$$

P is the probability of exceeding a determined precipitation value, $P = 1 - H(u)$.

If $P > 0.5$, P is replaced by $1 - P$ and the sign of the resultant SPI is switched.

The constants are: $C_0 = 2.515517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, $d_3 = 0.001308$.

Figure 5 shows the SPI of precipitation series at the Madrid observatory from 1910 to 2000. On the shorter time scales (3 or 6 months), the dry and humid periods are short and high-frequency. The SPI for these time scales is considered an agricultural drought index (McKee *et al.*, 1993, 1995; Hayes *et al.*, 1999) because it indicates the water content of vegetation and the soil moisture conditions (Sims *et al.*, 2002; Ji and Peters, 2003).

At a time scale of 12 months, droughts were less frequent, but they lasted longer. The SPI at 12 months is considered a hydrological drought index, because it is used for monitoring surface water resources, e.g. river flows (Szalai *et al.*, 2000; Hayes *et al.*, 1999). At longer time scales (24 or 36 months), droughts lasted longer, but were less frequent, with few dry or humid periods recorded.

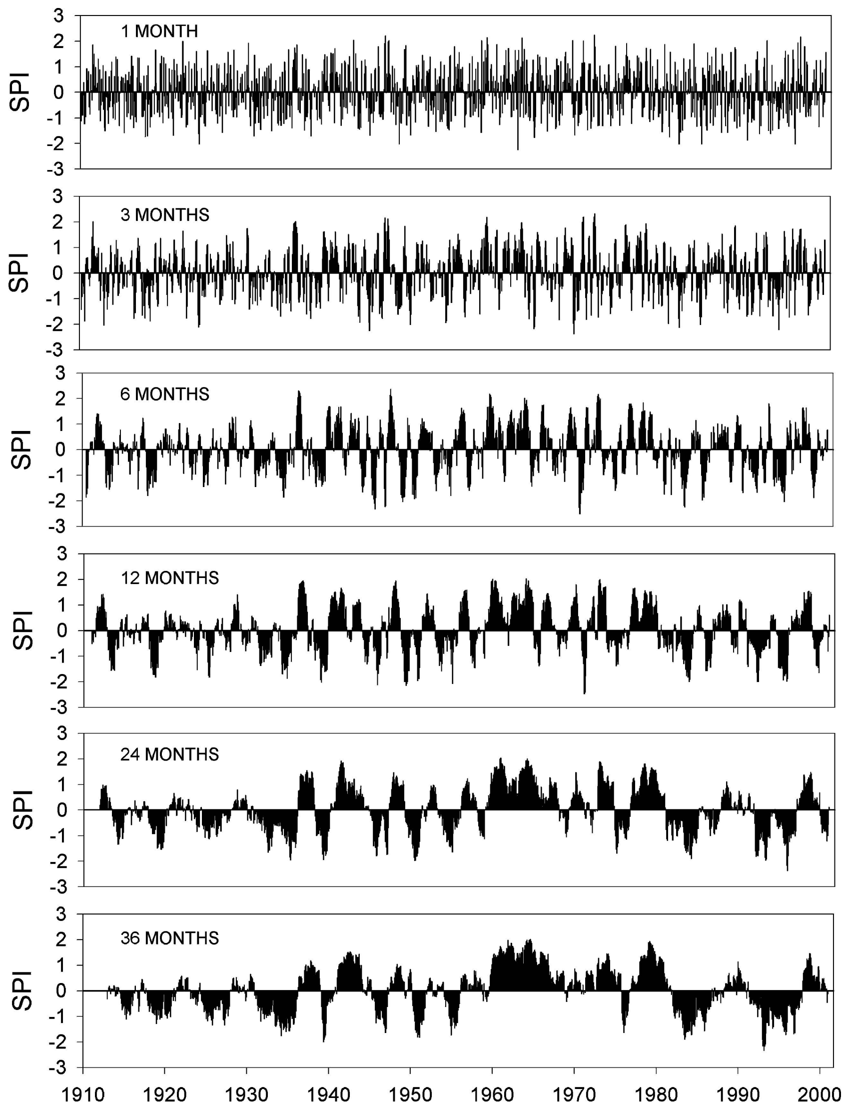

Figure 5. Evolution of SPI at different time scales. Observatory of Madrid.

2.3. ANALYSIS OF DROUGHT SPATIAL PATTERNS OVER A RANGE OF TIME SCALES USING PRINCIPAL COMPONENT ANALYSIS

Principal Component Analysis (PCA) was used to determine the spatial patterns of drought on different time scales (Karl and Koscielny, 1982; Bonaccorso *et al.*, 2003; Vicente-Serrano *et al.*, 2004). The application of PCA for climatic series can be performed in S or T modes (Serrano *et al.*, 1999). S-mode has been used to obtain general temporal patterns of climatic series: the observatories are the variables; and the time observations, the cases. The areas represented by each mode can also be identified by mapping the factorial loadings (correlation between each original variable and the principal components extracted). S-mode identifies regions in which the temporal variation of climatic variables has the same pattern.

From the SPI series of the Iberian Peninsula, we applied six PCAs, one for each time scale, to check whether the spatial patterns of drought changed in relation to time scales of drought, and whether the spatial patterns were stable. As the SPI is a standardised climatic variable, the final components obtained can be renamed as the common SPI of specific areas, identified by mapping the factorial loadings. This approach has also been used by Bonaccorso *et al*. (2003) in Sicily and by Lana *et al*. (2001) in the Northeast of the Iberian Peninsula.

The number of components was selected according to the criterion of eigenvalue >1, and the components were rotated to redistribute the final explained variance. The Varimax rotation was selected for this purpose (White *et al*., 1991; Serrano *et al*., 1999).

2.4. CLASSIFICATION OF THE IBERIAN PENINSULA ON THE BASIS OF DROUGHT PATTERNS

Different spatial classifications, based on the general drought patterns given by PCAs, were obtained by grouping the observatories through the maximum loading rule. Each observatory was assigned to the component with the highest loading value. This method has been used in climate classification by numerous authors, such as Karl and Koscielny (1982), Comrie and Glenn (1998), Bärring (1988) and Mallants and Feyen (1990) in the USA, Mexico, Kenya and Belgium, respectively. Six spatial classifications (one for each time scale) were constructed in this study.

2.5. EVALUATION OF SPATIAL UNCERTAINTY USING FRAGMENTATION AND DIVERSITY INDICES

The spatial stability of drought patterns for the distinct time scales was evaluated by means of fragmentation and diversity indices. For this purpose, category maps were created by means of the Thiessen polygons method (Vicente-Serrano *et al*., 2003). Several indices were obtained from these maps to test the coherence and spatial robustness of classifications. The indices selected have been extensively used in landscape ecology to analyse the spatial structure of category maps (i.e. Turner, 1990; Hargis *et al*., 1998). The indices were calculated with the Fragstat v. 3.3 software package (McGarigal and Markc, 1995). The following indices were selected:

- The Shannon Diversity Index (SHNI): this indicates the spatial concentration of classes. High values indicate more heterogeneity in drought classification.

$$\mathrm{SHDI} = -\sum_{i=1}^{m} (P_i \cdot \ln P_i)$$

  where P_i is the proportion of the surface occupied by class i.

- The mean area of each class (MA).
- The number of patches (N).
- The patch average:

  $$PA = N/C$$

  where C is the number of classes. The index indicates the degree of spatial fragmentation of final classes. High values indicate high spatial compartmentalisation in a large number of patches, which indicates more uncertainty in classification.
- Edge density (ED):

  $$ED = \frac{E}{A} \times 10000$$

  This index is based on contacts between distinct patches, where E is the total length (m) of edge on the map and A is the total area of the Iberian Peninsula. High values on this indicator also show large spatial compartmentalisation and, therefore, high heterogeneity and spatial uncertainty in classification.

3. Results

3.1. SPATIAL PATTERNS OF SPI FOR A RANGE OF TIME SCALES

The number of PCA components extracted using the SPI series increased as the time scale became longer (Table I).

At a 1-month time scale, 6 components were extracted, which explained 73% total variance of the SPI series. The same number of components and a similar percentage of variance were explained using series for a 3-month time scale. For 6 and 12 months, the number of components obtained increased to 7 and 9, respectively, although the percentage of total variance explained was similar to the variance explained at 1 and 3 months. This observation implies higher distribution of total variance among the components selected. At 24 and 36 months, the number of components was significantly greater than in the shortest scales, with an extraction of 10 and 11 components, respectively. For the longer time scales, the explained variance was more distributed than for the shorter ones and the total explained variance was also greater. The differences between total variance grouped by first component and the remaining ones decreased with increased time scale.

The spatial patterns of the factorial loadings obtained from PCAs using the SPI series for distinct time scales were similar at 1 and 3 months (Figures 6–11). The patterns were consistent and had a logical spatial structure that was consistent with climate influences in the Iberian Peninsula (Rodó *et al.*, 1997; Rodríguez-Puebla *et al.*, 1998; Serrano *et al.*, 1999; Olcina, 2001). In these classifications, the first component, which explained the highest percentage of variance, represented drought evolution for a large percentage of the surface area of the Iberian Peninsula. The other components represented smaller areas. These results indicate that the shortest time scales produce clear spatial patterns for drought evolution. The

Table I. Results of PCA analysis at different time scales

Total	% of variance	% accumulated	Total	% of variance	% accumulated
	1 month			24 months	
12.2	23.9	23.9	9.4	18.4	18.4
7.1	14	37.8	7.8	15.4	33.7
5.5	10.8	48.6	5.1	10.1	43.8
5	9.7	58.3	3.7	7.4	51.1
4	7.9	66.3	3	5.9	57.1
3.5	6.8	73	2.9	5.8	62.8
	3 months		2.7	5.3	68.1
12.7	24.9	24.9	2.3	4.4	72.6
5.9	11.7	36.6	2.2	4.4	76.9
5.2	10.2	46.8	1.5	3	79.9
4.8	9.5	56.2		36 months	
4.3	8.5	64.7	8.9	17.4	17.4
3.1	6.2	70.9	8.3	16.3	33.7
	6 months		5.5	10.8	44.5
13.3	26.2	26.2	3.6	7.1	51.6
5.8	11.4	37.6	3	5.8	57.4
4.7	9.3	46.9	2.9	5.6	63
4	7.9	54.8	2.7	5.3	68.3
3.7	7.2	62	2.6	5.1	73.4
3.2	6.2	68.3	2.2	4.3	77.7
1.9	3.7	72	2	3.8	81.5
	12 months		1.3	2.6	84.2
12.6	24.8	24.8			
4.6	8.9	33.7			
4.1	8.1	41.8			
3.8	7.5	49.2			
3.7	7.3	56.6			
3.4	6.7	63.2			
3.1	6.2	69.4			
1.9	3.8	73.2			
1.4	2.7	75.8			

spatial distribution showed great coherence because the distinct patterns represented homogeneous areas.

For a 6-months time scale, spatial drought patterns were similar to the shorter scales, although a new pattern was identified in the South of the Iberian Peninsula. Moreover, the spatial pattern of component 1 was displaced to the West. In spite of these small differences, the patterns were consistent with those obtained for shorter time scales, and their spatial organisation was also similar.

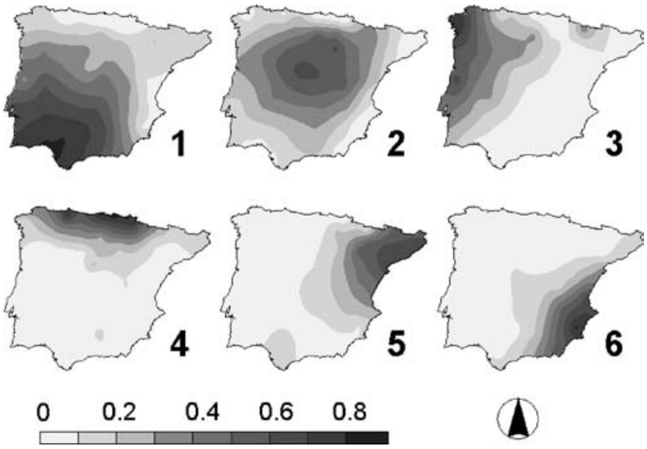

Figure 6. Loadings of PCA: SPI at time scale of 1 month.

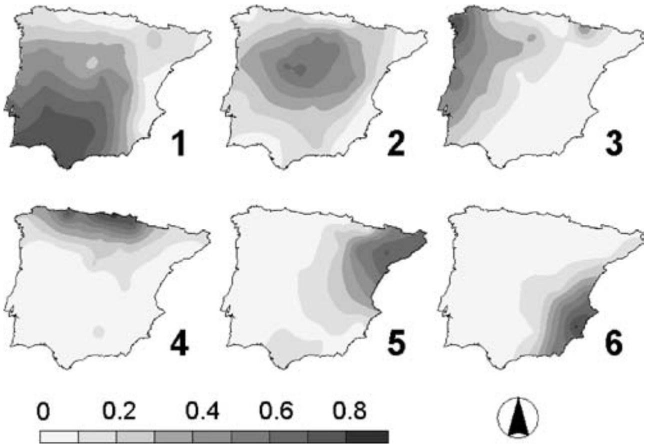

Figure 7. Loadings of PCA: SPI at time scale of 3 months.

However, at 12 months, the spatial fragmentation caused by the higher number of components extracted was greater. At this time scale, the area represented by each component was smaller and some spaces represented by a single component at time scales of 1, 3 or 6 months were divided. The drought evolution of these areas at 12 months was represented by several components. For example, at 1, 3 or 6 months, the Northeast of the Peninsula was defined as a homogeneous area in which drought evolution was represented by only one component, whereas at 12 months the area was represented by two components (7 and 8). This observation indicates more spatial variability in drought evolution at 12 months than for short time scales. In general, for a 12-month time scale the areas represented by each component had small surfaces, and new components for smaller areas were identified, which indicates more complex spatial patterns of drought evolution.

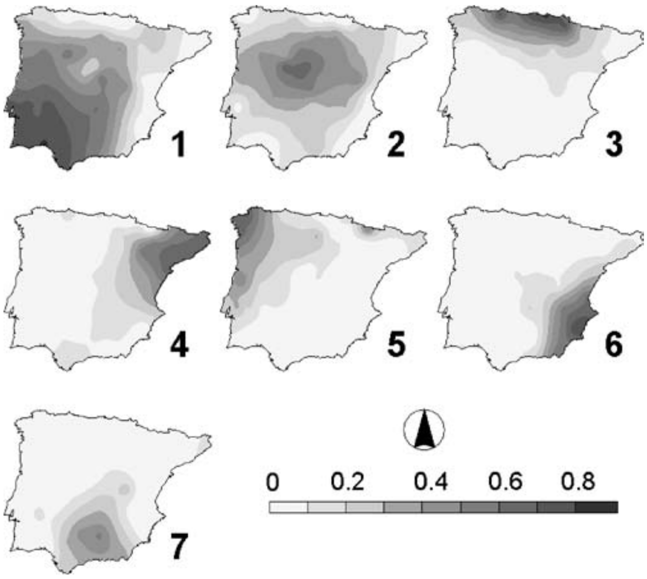

Figure 8. Loadings of PCA: SPI at time scale of 6 months.

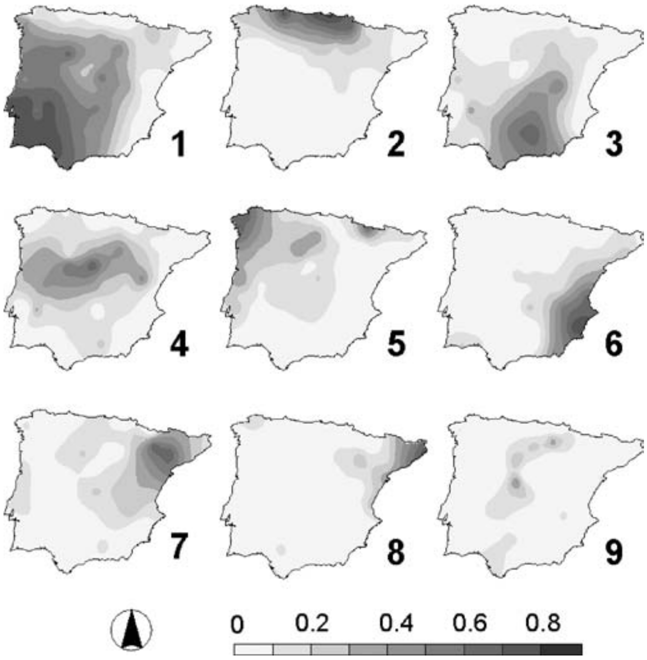

Figure 9. Loadings of PCA: SPI at time scale of 12 months.

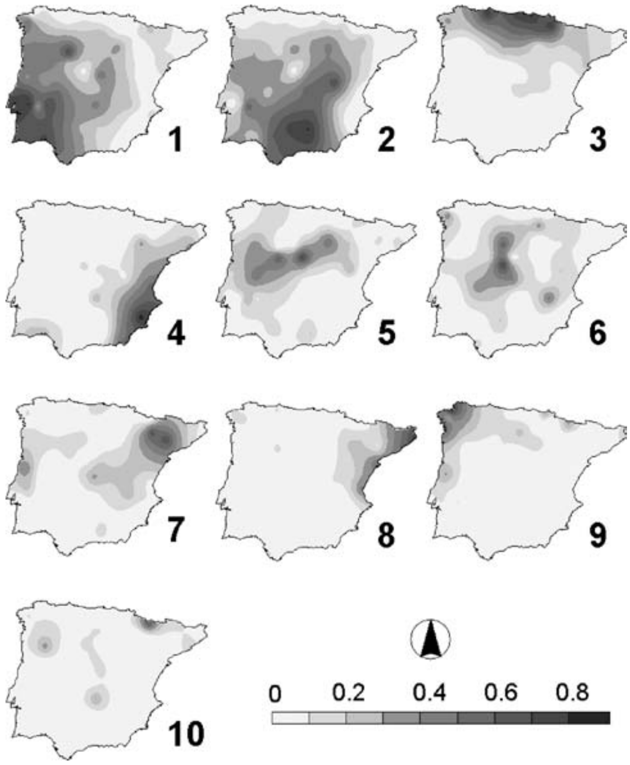

Figure 10. Loadings of PCA: SPI at time scale of 24 months.

For a 24-month time scale, spatial patterns were even more complex (Figure 10). The component representing inland areas of the Iberian Peninsula, which at 1, 3 or 6 months covered a large percentage of total SPI variance, disappeared at 24 months, and drought evolution in these areas was represented by distinct and more local components. The loading values decreased significantly and components obtained for this time scale were representative of more concrete areas. Similar spatial behaviour of droughts was also observed at 36 months, where drought patterns were very local (Figure 11).

The increase in spatial diversity was caused by the decrease in the correlation of SPI series between the observatories when time scale increased. Figure 12 shows the distribution of correlations between pairs of observatories (1275 pairs). The drought indices in different observatories were closer when the time scale was short, but for longer periods the drought conditions recorded at these observatories, in general, differed more.

3.2. IBERIAN PENINSULA CLASSIFICATION ON THE BASIS OF TIME SCALES

The spatial patterns of drought evolution in the Iberian Peninsula differed greatly in relation to the time scale (Figure 13). At 3 or 6 months, the classifications showed

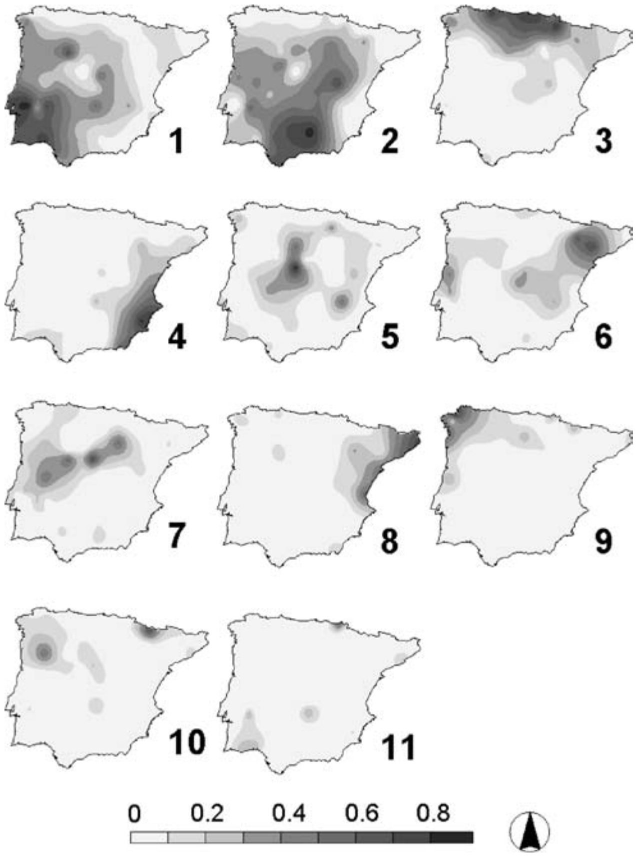

Figure 11. Loadings of PCA: SPI at time scale of 36 months.

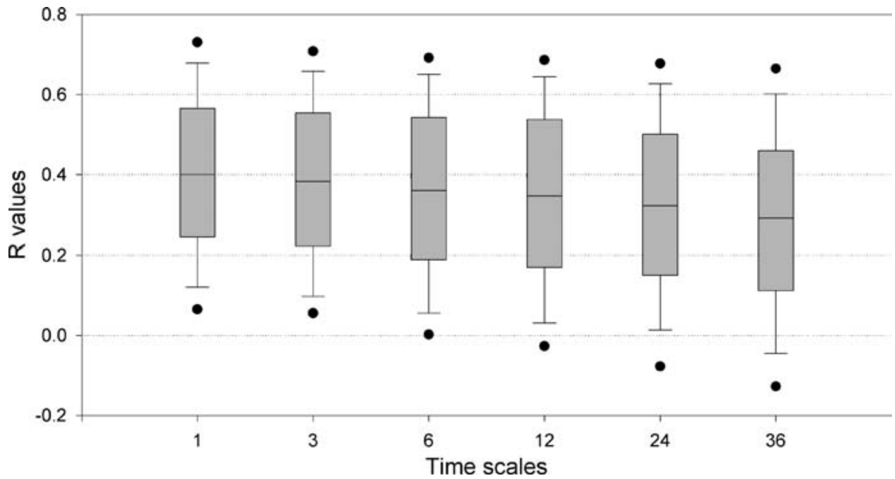

Figure 12. Differences in distribution of R-Pearson statistics between all pairs of observatories at different time scales.

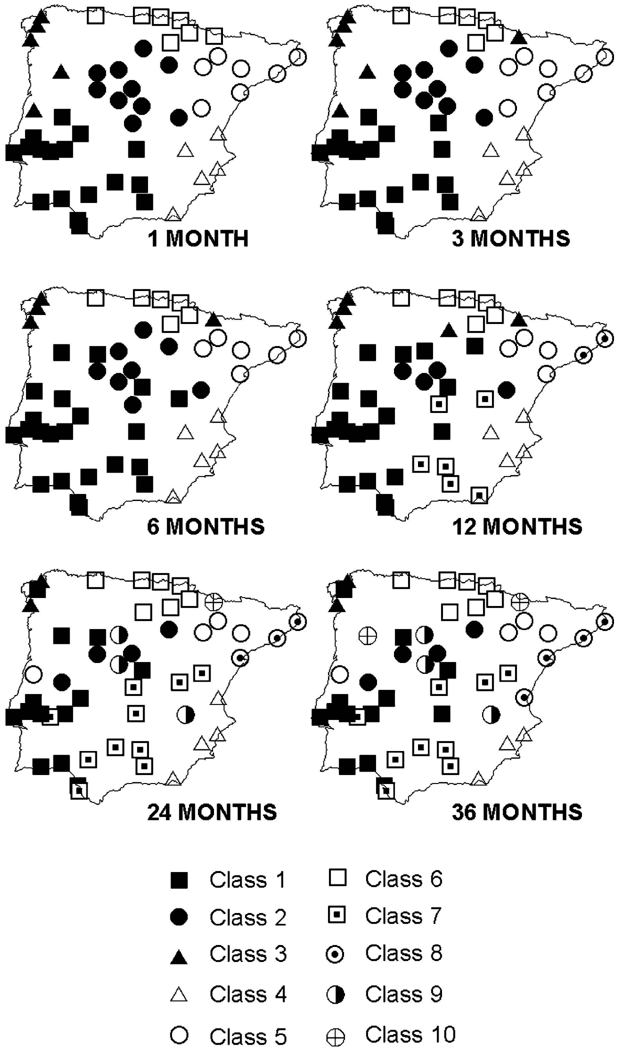

Figure 13. Classification of the Iberian Peninsula according to temporal evolution of SPI at different time scales.

few classes, which had a high spatial homogeneity. These classifications allowed drought monitoring and early warning of agricultural droughts by building regional precipitation series within these homogeneous areas.

The classifications for longer time scales showed higher complexity because the Iberian Peninsula was divided into more classes, and more spatial fragmentation was recorded. This introduces great complexity into the classifications, and indicates that the temporal behaviour of droughts is spatially more complex when time scale increases. The classifications for longer time scales are no use for obtaining

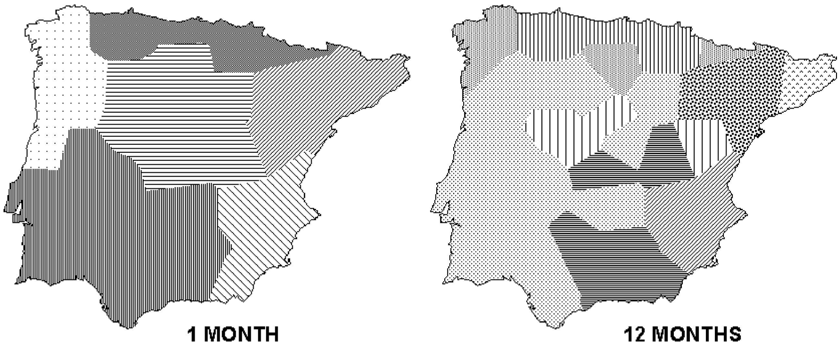

Figure 14. Example of continuos classifications according to temporal evolution of droughts at different time scales.

information on the regionalisation of drought behaviour in the Iberian Peninsula. For example, at 12 months, drought classes are very fragmented (Figure 14).

Table II shows the results of the application of diversity and fragmentation indices to continuous maps of SPI classifications over a range of time scales. The diversity index (SHDI) indicates an increment of spatial diversity when time scale increases. This increment indicates greater spatial heterogeneity in drought classification for longer time scales. This observation can also be deduced from the calculation of the mean class area (MA), which indicates a decrease in its values with increased time scale. Therefore, at time scales of 24 or 36 months, the distinct classes cover less surface.

However, the higher spatial heterogeneity observed in classifications for longer time scales was caused not only by the increment in the number of classes, but also by the spatial fragmentation of each drought class. The number of patches increased from 6 at a 1-month time scale (only one patch per class) to 20 patches at 36 months. Time scales higher than 1 month had more patches than classes, which indicates that classes represent areas that are separated from each other. This is very

Table II. Spatial heterogeneity statistics for SPI classifications at different time scales.

Time scale	SHDI	MA	*N*	PA	ED
1	1.68	969.8	6	1	0.123
3	1.67	969.8	7	1.16	0.126
6	1.51	969.8	7	1.16	0.133
12	1.78	727.4	13	1.62	0.163
24	2.03	581.9	17	1.7	0.200
36	2.12	581.9	20	2	0.211

SHDI: Shanon's Diversity Index, MA: mean area of each class ($\times 100\,\text{km}^2$), N: number of patches, PA: patch average, ED: edge density.

clear at time scales of 12, 24 or 36 months, at which the patch average increased significantly (1.62, 1.7 and 2, respectively). This finding introduces great spatial heterogeneity and uncertainty into classifications. The edge density (ED) confirms this behaviour, as it increased from the shortest time scales (0.12 at 1 and 3 months) to the longest (0.2 at 36 months). This increase is caused by the increased number of classes and patches and reaffirms the greater spatial uncertainty in the spatial classifications of drought behaviour over longer time scales.

4. Discussion and Conclusions

This study shows the spatial patterns of droughts as a function of time scale in the Iberian Peninsula. We used the SPI calculated over time scales of 1, 3, 6, 12, 24 and 36 months, because of its effectiveness in identifying hydrological and agricultural drought (Sims *et al*., 2002; Szalai *et al*., 2000; Yamoah *et al*., 2000).

The article shows that the spatial patterns and time scales of drought indices may differ greatly, and that the spatial behaviour of the index, when calculated for long time scales, is not coherent.

The spatial patterns obtained by means of PCA and the diversity and fragmentation indices used for testing the spatial coherence of drought classifications showed that the division of the Iberian Peninsula as a function of time scales is too complex to be applied in drought monitoring. Moreover, for the varied time scales, the classifications are not coherent climatically, because they give spatial patterns that are too complex.

The variability of spatial behaviour of drought in relation to time scales indicates the complexity of the drought phenomenon. However, interpretations of some indices as indicative of true drought conditions must be treated with caution.

Given the great spatial uncertainty of drought classifications on distinct SPI time scales, integrated monitoring systems that view the territory continuously over a range of time scales are the best tools for monitoring drought conditions (Tsakiris and Vangelis, 2004; Svoboda *et al*., 2002), or even several drought indicators used together (Steinnemann, 2003). Moreover, we must not discard the possibility of integrating other parameters into drought monitoring, such as soil moisture measurements, river flows, water levels in reservoirs, or even vegetation indices obtained from satellite data (Kogan, 1995, 1997).

In spite of the spatial uncertainty of drought indices calculated from climatic data, they are essential in accurate drought monitoring. Drought management plans that do not use real time information detect droughts when they reach critical proportions, but then it is too late to take mitigation measures (Wilhite *et al*., 1986).

Differences in drought conditions between neighbouring observatories, when time scales increase, can be determined by the weight that extreme precipitation events have on drought indices. In the Mediterranean area, extreme precipitation events have broad spatial variability (Martin-Vide and Llasat, 2000). On shorter time scales (i.e. 3 or 6 months), intense precipitation has a significant weight on drought indices only for a few months. However, the number of months in which these events have a significant influence on these indices increases in the longer time scales (24 or 36 months). The spatial location of extreme events causes significant differences between neighbouring areas in their drought index values over long periods, if long time scales are used. Therefore, the SPI computed at these time scales may not be an adequate indicator of true drought conditions.

In summary, the spatial behaviour of drought indices in the Iberian Peninsula should also be tested in other regions in which climatic or precipitation variability is not so high, to determine more accurately their usefulness. Moreover, although notable advances have been achieved in the development of drought indices, more effective tools and systems to control and mitigate the risk of drought need to be developed.

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