Vol. 26: 5–15, 2004 | CLIMATE RESEARCH
Clim Res | Published April 19

Drought patterns in the Mediterranean area: the Valencia region (eastern Spain)

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ABSTRACT: We studied drought patterns in the Valencia region between 1951 and 2000 using 95 monthly precipitation series and the standardized precipitation index (SPI). The general evolution of drought was obtained by principal component analysis. The spatial patterns of the most significant components did not overlap. We also found differences in the frequency, duration and intensity of drought between areas. Drought increased significantly in the mid to northern area, whereas in the rest of the region the spatial patterns were more complex. Variability seems to be the main characteristic related to local factors. The results of these subregional analyses show that great caution should be exercised when applying global output results at the subregional level when such extreme events are managed.

KEY WORDS: Drought · Spatial patterns · Precipitation · Standardized precipitation index · Principal component analysis · Western Mediterranean · Valencia region

1. INTRODUCTION

Drought is considered to be an extreme climatic event and has received special attention from researchers examining the Global Change hypothesis (Changnon et al. 2000). It can be regarded as having been the most serious climatic risk in the 20th century (Obasi 1994) and has caused losses amounting to billions of US dollars (Bruce 1994). Therefore, drought research is needed so that counteractive measures can be taken (Wilhite 2000).

Climate models point to a future general increase in drought related to a decrease in precipitation. Using a high resolution model (2.5° × 3.75°) and a $2 \times CO_2$ scenario, Jones et al. (1996) predicted that by the end of the 21st century, Europe will face increases in the intensity, duration and spatial area of drought in the Mediterranean basin. As a consequence of atmospheric changes, Mediterranean landscapes located in transitional ecotone midland latitudes may be affected by the northern migration of the polar front due to increased evaporation and lower precipitation (Quereda et al. 2000). If precipitation decreases were confirmed in the Mediterranean basin (New et al. 2002), the regional consequences would be severe owing to the paucity of water resources in this area, the high demand for agricultural, industrial and tourist activities, and erosion and desertification processes (López Bermúdez & Sánchez 1997). However, global climatic models have limitations because of their scale resolution, and the model output patterns of drought are not consistent for areas with high precipitation variability, e.g. Mediterranean climate areas.

Spatial and temporal patterns of drought have been analyzed by several methods, ranging from satellite images (Kogan 1995) to historical records (Martín-Vide & Barriendos 1995), but drought is generally identified by climate elements (for review see WMO 1975 and Heim 2002), especially precipitation (McKee et al. 1993). Although the temperature and water status of soil have an effect, drought is always promoted by accumulated precipitation deficits. Thus, precipitation

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methods are useful tools for the identification of drought (Guttman et al. 1991, Redmond 2002).

The high dependence of drought on precipitation is the main reason for its varied spatial effects, as has been pointed out for England (Fowler & Kilsby 2002), Nigeria (Oladipo 1995), Turkey (Komuscu 1999) and the Iberian Peninsula (Pita 1987). For this reason, in environments with high spatial and temporal variability in precipitation, it is reasonable to expect the same variability in drought.

The eastern coast of the Iberian Peninsula is particularly suitable for drought analysis. It is a climate ecotone area located in the transitional subtropical zone under Mediterranean climate conditions, where the effects of climatic change are predicted to have particularly severe consequences (Lavorel et al. 1998). Precipitations are scarce and torrential, highly variable in time and space and with a contrasted seasonal regime (Romero et al. 1998). All the aforementioned characteristics lead to a dry season, variable in magnitude and duration, which imposes restrictions and adaptation to natural systems and human societies.

In the central sector of this coast (Valencia region), drought is recurrent, with high temporal and spatial variability because of topographic controls and weather types (Estrela et al. 2000). Furthermore, over the last 20 yr, the area has experienced an increasing demand for water resources (due to tourist activities, with more than 1 000 000 visitors yr^{-1}, and agricultural practices), and forest fires (Piñol et al. 1998), erosion and desertification processes have increased (Puigdefábregas & Mendizábal 1998).

Finally, information about precipitation, comprising annual (De Luis et al. 2000), seasonal (Sumner et al. 2000, González Hidalgo et al. 2001) and daily data (Egozcue & Ramis 2001, González Hidalgo et al. 2003, Peñarrocha et al. 2003), has been recorded in this area, which may allow us to provide a more accurate interpretation of the drought patterns analyzed.

We studied the spatial and temporal patterns of drought during the second half of the 20th century in the Valencia region using a high-density database. This paper is organized into 5 sections. In Section 2, we present the study area, the database, the method for drought identification and that for spatial and temporal analyses. In Section 3, the spatial and temporal drought patterns are shown. Finally, we discuss the possible consequences of drought patterns at subregional levels (ca. 20 000 km^2), and contrast the global results with model outputs at the regional level and the implications for a better management of water resources and the mitigation of drought events.

2. STUDY AREA AND METHODS

2.1. Study area

The Valencia region is located in the western Mediterranean basin (east coast of the Iberian Peninsula, Spain; Fig. 1) and comprises an area extending

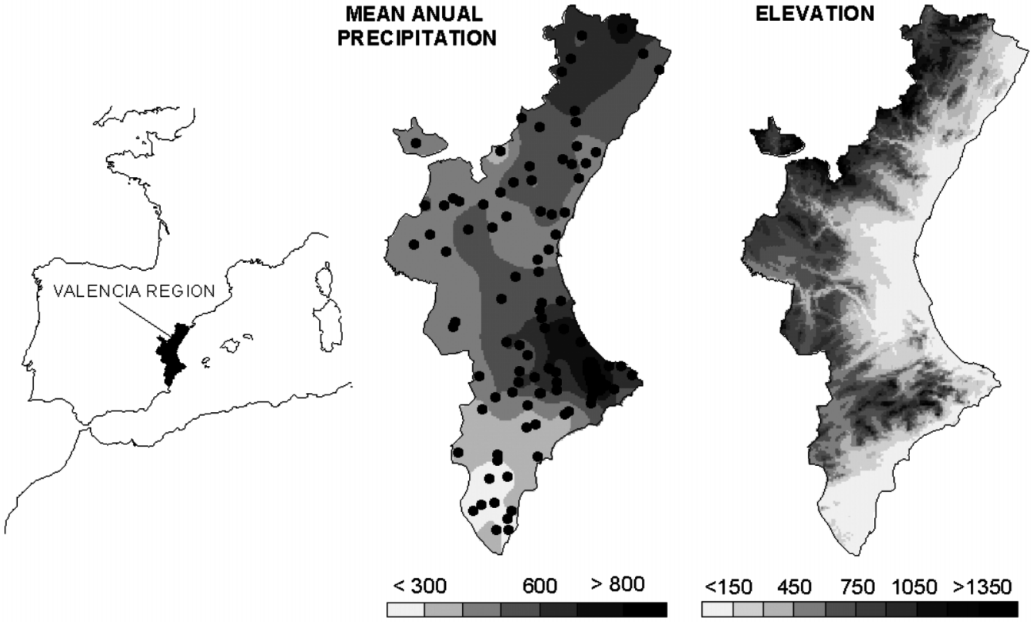

Fig. 1. Map of the Valencia region in eastern Spain. Annual mean precipitation and relief configuration. Dots represent location of rainfall weather stations (95)

between 38 and 40° N (24 000 km^2). Mean annual rainfall values are between 800 and <300 mm yr^{-1}, which follows a complex spatial pattern (N–S/E–W), and the relief is one of the most prominent factors in such spatial distribution.

Between 1961 and 1990, annual rainfall in the area generally decreased, while interannual variability (De Luis 2000, De Luis et al. 2000) and seasonal changes (De Luis et al. 2000, González Hidalgo et al. 2001) generally increased. However, the high spatial heterogeneity makes it difficult to establish an overall pattern.

Torrential precipitation is another characteristic of this area. Daily maximum rainfall varies on average between 120 and 50 mm d^{-1}, and represents a mean of 17 % (coastland) to 9 % (inland) of annual rainfall. The 10 days of heaviest rainfall in a year provide over 50 % of the annual rainfall. The percentage contribution of maximum daily rainfall to annual precipitation seems to be increasing (González Hidalgo et al. 2003). Such results indicate the extreme dependence of annual mean precipitation values on a few rainy days and suggest that drought has increased.

2.2. Data

Monthly data from 95 weather stations were used. The data cover the period January 1950 to December 1999, which is sufficient to calculate the drought index used in this paper (standardized precipitation index, SPI; Guttman 1999). The precipitation monthly series were obtained from a reconstruction process. Quality and homogeneity control were checked using the Alexandersson test (Alexandersson 1986, González-Hidalgo et al. 2002). The stations are irregularly distributed throughout the Valencia region and their records cover the longest period available for the highest quality data covering the area. The overall density of stations is 1 observatory per 200 km^2.

2.3. Drought evaluation using the SPI

Drought was analyzed using the SPI (McKee et al. 1993, 1995), which, although relatively recent, has been considered the most reliable index for measuring the intensity, duration and spatial extent of drought (Guttman 1998, Keyantash & Dracup 2002, Lloyd-Hughes & Saunders 2002). It is valid for all seasons and it is not affected by topographical factors. Thus, it is an excellent tool for research on spatial analysis, since it removes the temporal effects of various precipitation magnitudes (Lana et al. 2001). If the SPI is calculated using long records, the frequency of a given value is the same for all stations (Hayes et al. 1999) because the SPI is a normalization of precipitation. For this reason, it allows us to compare areas. The main shortcoming of the SPI is that it does not provide the real magnitude of drought (precipitation differences from mean values) or the absolute differences between sites. Another limitation is that it cannot be used for analyzing the spatial differences in drought risk because the same values of SPI are expected at all locations. SPI is calculated as follows:

$$\mathrm{SPI} = W - \frac{\mathrm{C}_0 + \mathrm{C}_1 W + \mathrm{C}_2 W^2}{1 - \mathrm{d}_1 W + \mathrm{d}_2 W^2 + \mathrm{d}_3 W^3} \tag{1}$$

where C_n and d_n are constants, W is calculated from $W = \sqrt{-2\ln(P)}$ for $p \leq 0.5$ and P is the exceedance probability of a given value of precipitation whose total series follows a Pearson III distribution. This distribution is the most suitable for computing the SPI (Guttman 1999, Vicente-Serrano & Cuadrat 2002). Fig. 2 summarizes the calculation procedure, where the cumulative distribution frequency of a precipitation series (biased because the events of high intensity show a low frequency) is transformed into a normal standard distribution where mean = 0 and standard deviation = 1.

The transformed distribution allows us to determine the intensity of precipitation deficit by reference to a

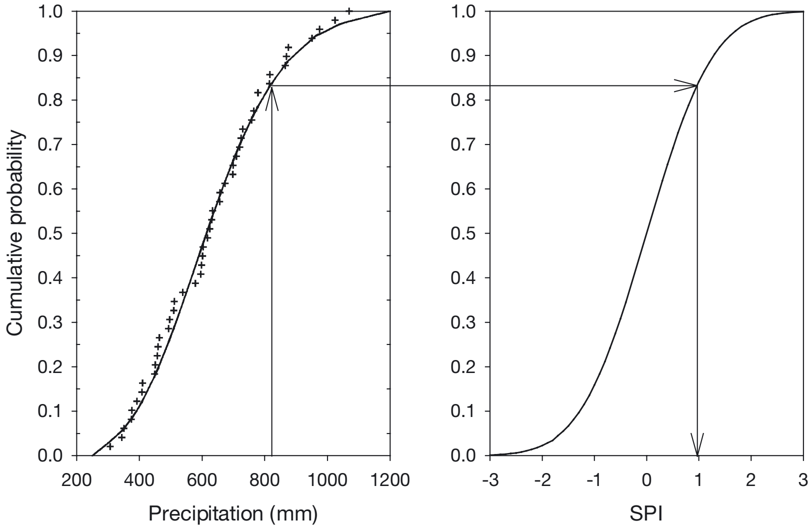

Fig. 2. Example of equiprobability transformation from a Pearson III fitted distribution to the standard normal distribution. Annual data from Valencia weather station. SPI: standardized precipitation index

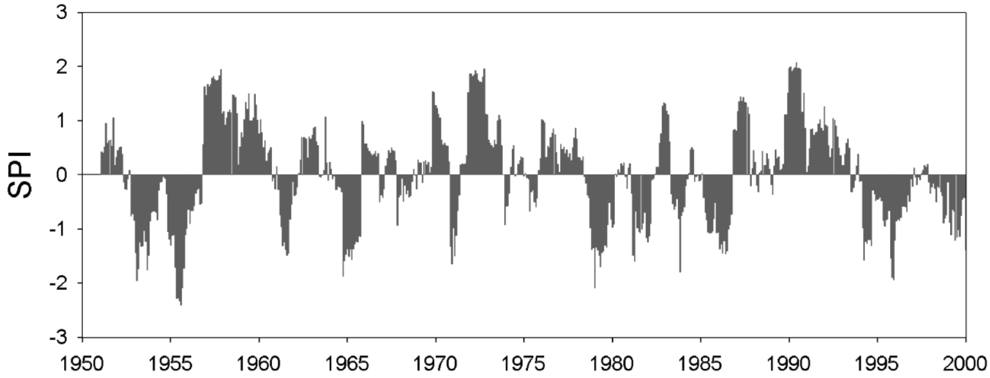

Fig. 3. Example of SPI evolution in the Valencia weather station

mean value. This facilitates the spatial comparison of drought conditions and is an excellent tool for monitoring drought at various temporal scales (McKee et al. 1995, Komuscu 1999).

In this article, the SPI series were computed from the 95 weather stations of the Valencia region from January 1951 to December 1999 at a temporal scale of 12 mo. This scale avoids intra-annual frequency variations and allows us to identify the hydrological drought and detect the main dry periods (see Vicente-Serrano & Cuadrat 2002 for a detailed discussion about the usefulness of SPI computation at several temporal scales). Fig. 3 shows an example of an SPI series (Valencia weather station) where negative values point to a pluviometric deficit.

The probabilistic characteristics of SPI allow us to classify several drought categories (McKee et al. 1993). Here, we used the classification suggested by Agnew (2000), based on the frequency distribution of SPI values (Table 1). This classification is more suitable for the study area than that proposed by McKee et al. (1993), because drought is a frequent phenomenon in the Mediterranean area. Following Agnew's classification, 20 % of records are indicative of water deficits of varied magnitude, in agreement with the criteria of the National Institute of Meteorology of Spain (Almarza 2000).

Table 1. Drought classification by standardized precipitation index (SPI) value and corresponding event probabilities according to Agnew (2000)

SPI value	Category	Probability of occurrence
<1.65	Extremely wet	5
1.28/1.64	Severely wet	10
0.84/1.27	Moderately wet	20
−0.84/0.84	Normal	50
−1.28/−0.83	Moderate drought	20
−1.65/−1.27	Severe drought	10
<−1.65	Extreme drought	5

2.4. Temporal analysis

Several researchers have shown that principal component analysis (PCA) is an efficient tool for analyzing temporal drought patterns (Klugman 1978, Karl & Koscielny 1982, Bonaccorso et al. 2003). In this paper, we used PCA in S-mode, i.e. each station is the variable to be summarized and the cases are the monthly precipitation values (Serrano et al. 1999). We had 95 variables (one for each SPI series of each weather station) and 588 cases (months from January 1951 to December 1999). The values of SPI were easily included in different months because they were normalized and thus comparable.

We obtained the most general patterns of drought evolution in the Valencia region and determined the spatial extent of each component series by mapping the factorial matrix values (correlation between each component and the original SPI series of 95 stations). Finally, as the 95 SPI series were normalized, each component value showed the SPI for a given area, and so the PCAs in S-mode determine areas where the evolution of drought shows the same temporal characteristics.

Components were selected following Briffa et al. (1994), although we were more restrictive with total variance explained by selected components (70 % of total). Finally, we used a rotation of components (Varimax), which provides more stable spatial patterns, since rotation produces a clearer division between components, preserves their orthogonality and provides more physically explainable patterns (Richman 1986).

The spatial distribution of components is shown by mapping the factorial matrix values by means of splines with tension (Vicente-Serrano et al. 2003) using ArcView 3.2 SIG. Finally, the local study of drought was carried out by trend analysis using the SPI series of each of the 95 weather stations and non-parametric Spearman rank-correlation ($p < 0.05$).

2.5. Spatial analysis

According to the SPI definition, the probability of occurrence of a determined SPI value is the same for the different areas represented by components, i.e. the index cannot be used for estimating the spatial differences in drought risk. Nevertheless, the temporal patterns of drought can differ due to the temporal succession of SPI values. This allowed us to analyze spatial differences in drought risk related to its magnitude and duration (Dracup et al. 1980). An SPI series characterized by frequent but short moist and drought periods has a different drought risk than other series of SPI with fewer but longer drought periods. The latter indicates a higher drought risk, because the magnitude of drought is proportional to duration (Tarhule & Wo 1997, López Bermúdez & Alonso 2001) and a higher magnitude involves a more severe water deficit.

The probability of occurrence of drought characterized by a given duration or magnitude can be estimated using non-parametric stochastic methods. These methods have been widely applied to hydrological series (Bobée & Rasmussen 1995), although they are less frequent in drought analysis (see Abaurrea & Cebrián 2002, ARIDE 2003[1], Vicente-Serrano & Beguería 2003).

The magnitude and duration of each drought event were analyzed from the series produced in the previous temporal analysis. We estimated drought magnitude as the cumulative sum of monthly SPI values considering drought under a certain threshold (Dracup et al. 1980); duration was classed as the number of months in which the SPI values remained under this threshold. In both cases, the threshold considered was SPI < −0.84, which represents the limit of moderate drought according to Agnew (2000).

The magnitude and duration series were adjusted to a probability distribution to test whether risks of drought occurrence differed between the areas represented by each temporal component. To select the most suitable probability distribution for adjusting magnitude and frequency drought series, we used a diagram of L-moment ratios, which is more robust than other methods (Sankarasubramanian & Srinivasan 1999). The final distribution was selected by comparing the parameters of each series (L-skewness and L-kurtosis) with the parameters of different theoretic distributions (Hosking 1990). This method determines the suitability of the proposed distribution.

Finally, we analyzed the evolution of surface affected by drought events of varying intensity by interpolation of SPI values at each station. We applied the Thiessen polygon method and the monthly value of SPI at the surface represented by each weather station, calculating the annual percentage of the study area under several drought intensities. The evolution of the percentage of study area affected by various drought intensities was analyzed using the non-parametric Spearman-rho coefficient to determine significant trends (e.g. Balling et al. 1992, De Luis et al. 2000).

3. RESULTS

3.1. Spatial patterns of drought

The 4 main components of PCA explained 71 % of total variance and we found a break point with the values of variance of the fourth and fifth components (Fig. 4). We selected these 4 components for subsequent discussion and analysis.

The first component explains 25.3 % of total temporal variance, and represents mainly the drought evolution of northern coastland areas (Fig. 5). The second component (23.9 % of total variance) mainly represents the central Valencia region. The central inland mountain area is attributed to the third component (12 % of variance), while drought patterns in the southern area of the region are represented by the fourth component (9.4 % of variance).

All the aforementioned patterns are clearly spatially distributed and do not overlap. As a consequence, the series of each component represents the temporal evolution of drought in a specific area.

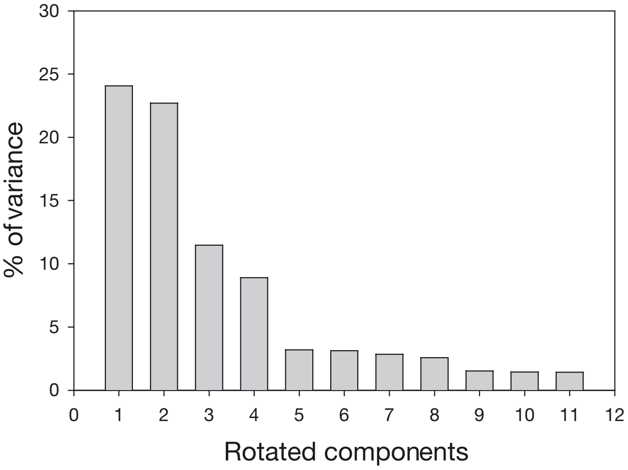

Fig. 4. Percentage of variance explained by components

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[1] ARIDE (2003) Assessment of the regional impact of droughts in Europe. European Community Framework Programme for Research and Technical Development Environment and Climate Work Programme. Final Report. www.hydrology.uni-freiburg.de/forsch/aride/

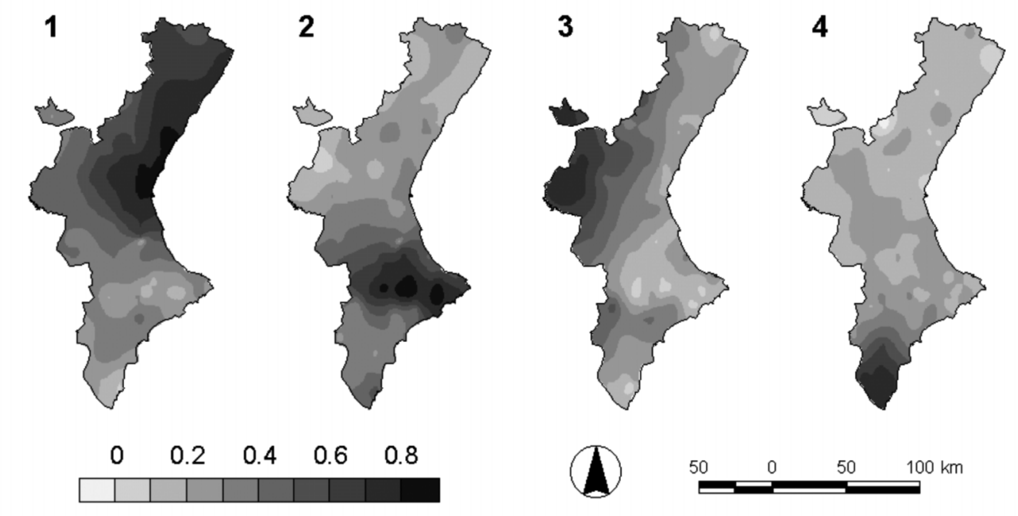

Fig. 5. Spatial distribution of matrix correlation values. Components 1 to 4

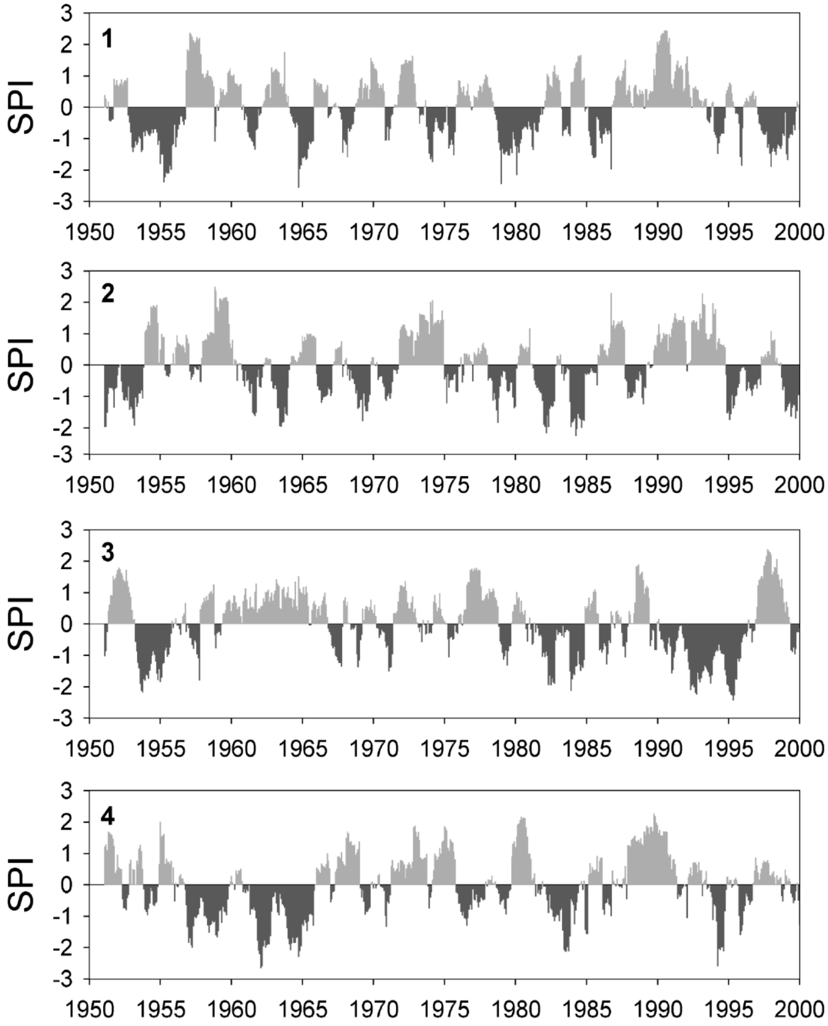

Fig. 6. Temporal evolution of Components 1 to 4

3.2. Temporal drought patterns

The temporal evolution patterns of Components 1 to 4 are shown in Fig. 6. In the northern coastal area of the Valencia region (Component 1), several drought episodes were detected: in the mid 1950s, the beginning of the 1980s and at the end of the 1990s. All these episodes were prolonged in time, with critical and extreme situations. Short events were found during the 1960s and in the mid-1980s.

The behavior of Component 2 is more complex than that of Component 1. Thus, in the central area of the Valencia region, drought events are more frequent but less important.

In inland areas (represented by Component 3), the frequency of drought is lower than that observed in Components 1 and 2, and the most severe drought episodes were recorded at the beginning and end of the period analyzed. The frequency of drought is lower than that observed in Components 1 and 2, the most severe episode being recorded in 1990. In this area, as in the abovementioned ones, the episode of the mid-1950s is also shown, and as a consequence practically ⅔ of the Valencia region suffered severe drought (see distribution of Components 1 and 3).

Successive severe episodes of drought, in both duration and intensity, were recorded in southern areas

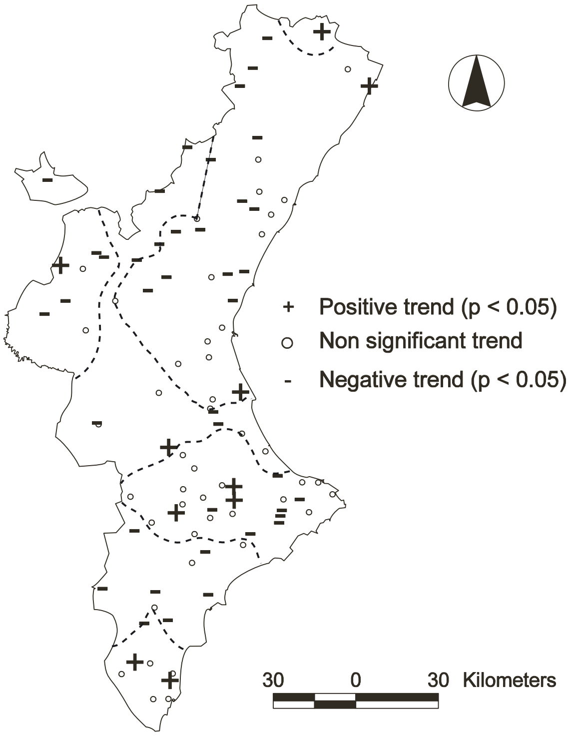

Fig. 7. Spatial distribution of SPI trends (1951–2000). **+**: significant increment of SPI values; **–**: significant decrease; ○: non-significant trends ($p < 0.05$). See text for details. - - -: inter polation boundaries of Components 1 to 4 ($r = 0.6$)

around 1955 and 1965 (see Component 4). Severe episodes were also recorded at the beginning of the 1980s (10 mo with $SPI < -0.84$), and a short but very severe episode was detected between 1993 and 1994. The temporal evolution of drought in this area is similar to that observed in the central area (Component 2), characterized by the low frequency but high intensity of drought events.

The trend of drought (expressed by SPI evolution) is shown in Fig. 7. Note that a negative mark indicates that drought increased over time (i.e. the negative value of SPI increased). The rise in droughts is mainly located on the coastland of central northern areas and in northern mountainous inland, although there is a large spatial variability, mainly in areas of central coastland regions with positive, negative and non-significant trends.

3.3. Spatial differences in drought risk

As pointed out above, spatial differences in risk of drought are attributable to differences in the probability of drought magnitude and duration. Such probability is determined by using a non-parametric distribution. Fig. 8 shows the distribution of L-coefficients of duration and magnitude series obtained from the previous analysis. Various theoretical distributions are also shown. We found that the most suit-

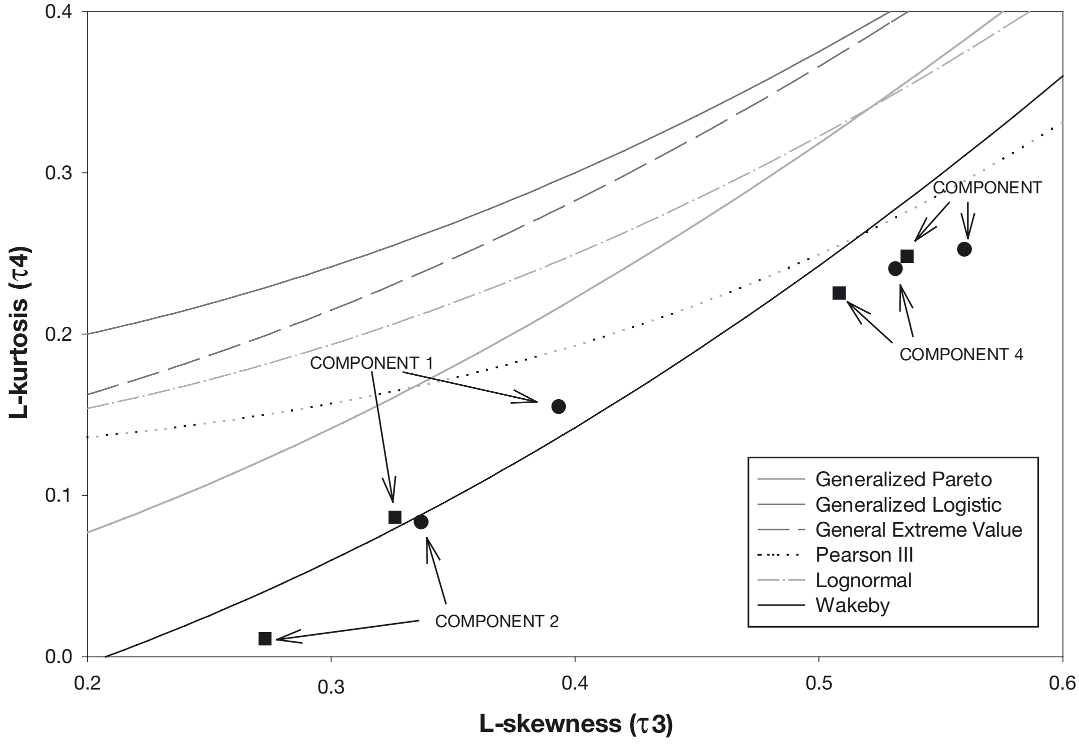

Fig. 8. L-moment ratios for drought magnitude and duration series. k: parameters of duration series; p: parameters of magnitude series

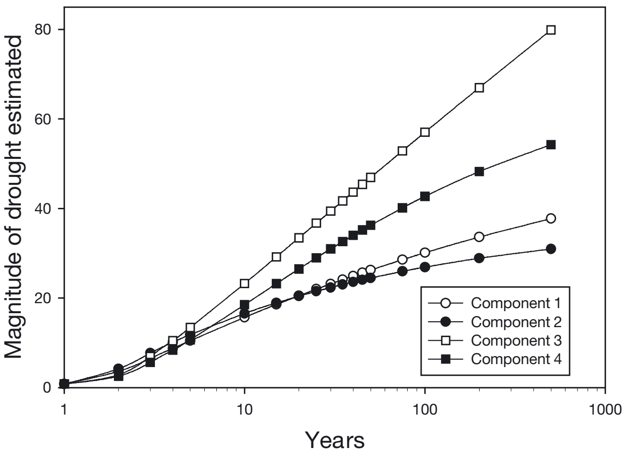

Fig. 9. Maximum drought magnitude (in accumulated SPI values) in a period of T yr for Components 1 to 4. x-axis is a log scale

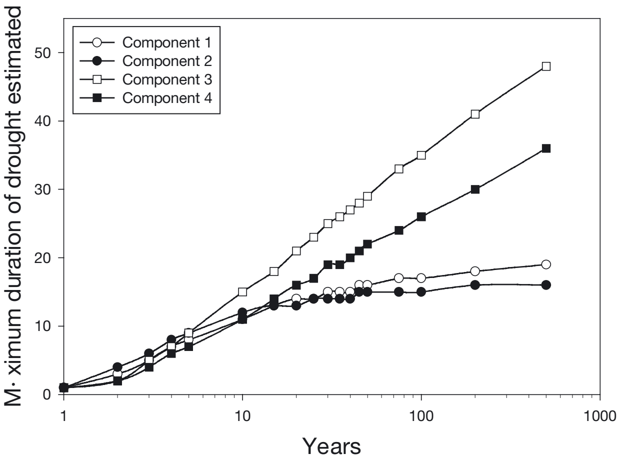

Fig. 10. Maximum drought duration (in months) in a period of T yr for Components 1 to 4. x-axis is a log scale

able distribution for the duration and magnitude drought series of the 4 components is the Wakeby distribution.

A random variable x is distributed as a Wakeby distribution if it is distributed as:

$$x = m + a\left[1-(1-F)^{b}\right] - c\left[1-(1-F)^{-d}\right] \qquad (2)$$

where $F = F(x) = P(X \leq x)$. m, a, b, c and d are the parameters of the distribution.

The large number of parameters in the Wakeby distribution (Eq. 2) improves the fitting of data compared with the distributions characterized by fewer parameters (Rao & Hamed 2000). The parameters can be obtained only by using Probability Weighted Moments (Greenwood et al. 1979). By replacing F by $1 - (1/T)$ in Eq. (2), where T is the return period, the T-year quantile is calculated as in Eq. (3). This measurement indicates the risk of occurrence of one drought of determined duration or magnitude in a period of T years. Higher magnitude or duration predicted by the probabilistic method indicates a higher risk of drought.

$$x_T = m + a[1-T^{-b}] - c[1-T^{d}] \qquad (3)$$

where x is the T-year quantile or return period of a drought of given duration or magnitude. The highest magnitude of drought expected is related to the inland northern mountain areas represented by Component 3 (Fig. 9), where rainfall decreased during the second half of the 20th century (De Luis et al. 2000). The southern area, as defined by Component 4, also shows high probability of high magnitude droughts. In areas represented by Components 1 and 2, the probability of high-magnitude drought is lower than previous periods. As a consequence, drought risk greatly varies within the Valencia region.

Similar results were obtained for the duration analysis. Fig. 10 shows the maximum duration of drought expected in several recurrence intervals. The highest probability of long-duration drought is related to areas under Components 3 and 4, while in the areas represented by Components 1 and 2, the expected maximum length is lower. For a 100 yr interval, the probability of maximum drought in inland areas is more than 2.3 times the maximum drought in the coastland area (35 and 15 mo, respectively).

Finally, the total area covered by drought intensities during the second half of the 20th century is shown in Fig. 11. From 1950 until 2000, 25% of the Valencia region was frequently affected by moderate drought, mainly from 1980 to 1985 and around 1995 and 2000, but during the episodes of the decades of 1950, 1980 and 1990, a large surface of the Valencia region was affected by episodes of high-magnitude drought.

The area affected by moderate drought shows a slow but significant trend (rho = 0.13, $p < 0.01$). The total area affected by different drought intensities (rho = 0.09, $p < 0.05$) also increased. These results should be viewed bearing in mind the high spatial diversity found at the study area.

5. DISCUSSION AND CONCLUSIONS

Mediterranean areas show a general decrease in precipitation (Briffa et al. 1994, Lana et al. 2001), and an increase in the number of extreme events such as drought and floods (Maheras et al. 1992, Gajic-Capta 1993, Ben-Gai et al. 1998, Szinell et al. 1998). Moreover, the future trends in drought conditions suggested by climatic models show a general increase in drought in the Mediterranean region in the 21st century; more

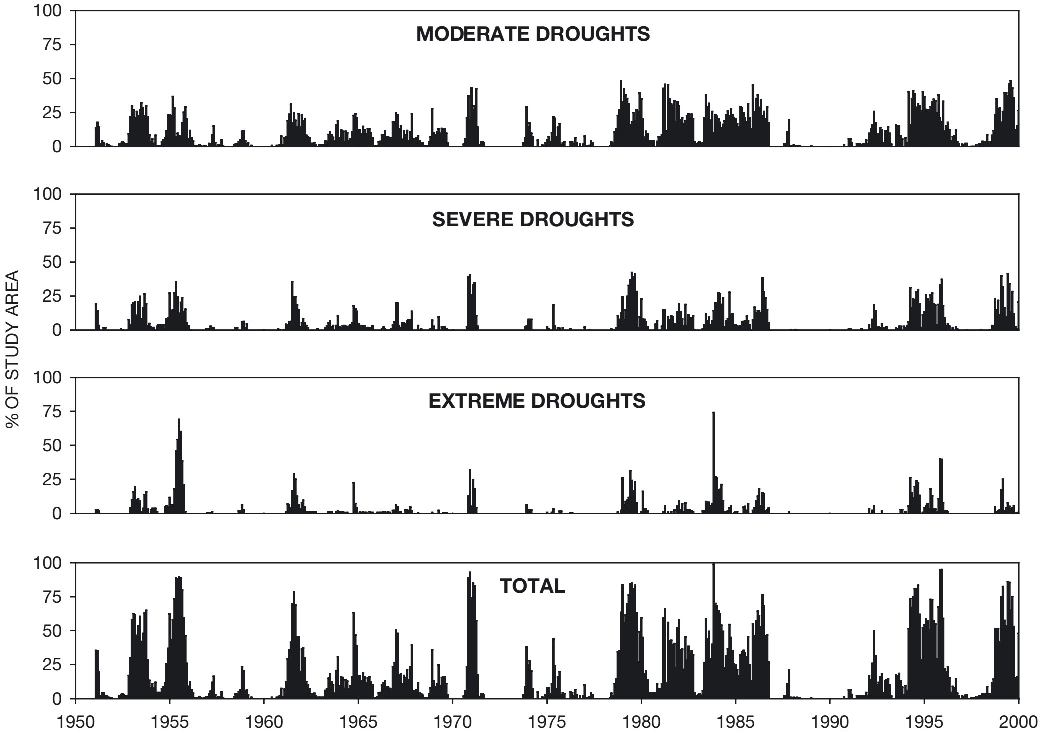

Fig. 11. Evolution of percentage of study area affected by different drought intensities

dry conditions are expected in this area if the increase in greenhouse gases continues, as suggested by Jones et al. (1996). The increment in precipitation variability (Houghton et al. 2001) and extreme rainfall events may also intensify the consequences of drought for agriculture and the environment, thus increasing the risk of erosion and desertification (López Bermúdez & Sánchez 1997, Pickup 1998).

Nevertheless, the results provided by the analysis of historical data show a great variability in drought trends in the Mediterranean region. Lloyd-Hughes & Saunders (2002) recently analyzed the drought trends over the whole of Europe between 1901 and 1999 using the SPI but failed to find significant trends in the long term.

In the Valencia region, we have shown the extreme spatial variability of drought patterns that increase overall. We have also observed an increase in areas affected by drought. Nevertheless, the global results show a very high degree of variability, and many weather stations do not show any trend in SPI. Several factors can account for this spatial variability, namely local relief, the synoptic weather types and the complexity of atmospheric patterns (Estrela et al. 2000, González-Hidalgo et al. 2003). In any case, the spatial diversity of drought was detected because we used a very dense database. Such results suggest that at the subregional level, drought patterns should be studied with a high amount of empirical data, since spatial variability can be relevant.

Drought variability in the Valencia region is expressed in 4 main patterns clearly disaggregated in 20 000 km^2 that do not overlap. Furthermore, the temporal evolution of each component differs between areas, as reported by Estrela et al. (2000), who found high temporal differences in drought evolution between individual weather stations. Trend analysis also revealed high spatial variability and pointed to the risk of inferring the drought trends in the Mediterranean region.

If we compare our results with those reported by studies at the continental scale (Briffa et al. 1994, Lloyd-Hughes & Saunders 2002), we can conclude that in areas under Mediterranean climate conditions, the model outputs are not the best approach for the subregional management of such phenomena, which are highly variable in space (Oladipo 1986, Martín-Vide 2001). In climatic transitional areas, drought can strongly depend on local factors and thus on the high spatial variability, which is accompanied by high temporal uncertainty in the future.

According to Wilhite & Svoboda (2000), the first step for managing drought risk is to establish drought management areas and divide the region into subregions following criteria such as drought risk. The subregional distribution of drought obtained in this study may be useful for the drought management of the study area, considering differences in the frequency, magnitude and duration of drought episodes. We believe that our results, at such a fine scale, come from the spatial density of precipitation data used, which is the key point of our analysis. Our data imply that the drought phenomenon should be further analyzed at local scales to obtain valid criteria for water resource management.

Acknowledgements. The authors wish to acknowledge financial support from the following projects: BSO2002-02743, REN2002-01023-CLI and REN2003-07453 (financed by Ministerio de Ciencia y Tecnología, Spain, and FEDER), and 'Programa de grupos de investigación consolidados' (grupo Clima, Cambio Global y Sistemas Naturales, BOA 147 of 18-12-2002), financed by the Aragón Government. We also thank Mr. R. Rycroft for the linguistic revision.

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Editorial responsibility: Allan Perry,
Swansea, UK

Submitted: October 25, 2003; Accepted: March 13, 2004
Proofs received from author(s): April 12, 2004