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SPATIAL ANALYSIS OF RAINFALL TRENDS IN THE REGION OF VALENCIA (EAST SPAIN)

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ABSTRACT

This paper examines the spatial and temporal rainfall characteristics of the region of Valencia, Western Mediterranean Basin (east Spain), during the World Meteorological Organization (WMO) normal period 1961–1990. The study used a dense and homogeneous daily precipitation database comprising 97 rain-gauge stations. Total and monthly rainfall concentrations have been studied in the context of their mean values, interannual variability and spatial diversification. Trends have been analysed using both parametric and non-parametric tests. In order to establish the spatial distribution of rainfall patterns and to detect homogeneous areas with similar rainfall evolution, a statistic based on the Cramér–von Mises test is proposed. The kriging interpolation methods for characterizing the magnitude of observed changes is used.

Areas with contrasting rainfall evolution are identified. In more humid areas, a significant decrease in annual rainfall associated with significant increases in interannual rainfall variability is observed. In inland zones, decreases in total annual rainfall and increases in interannual variability are less clear, but there are indications of an increase in monthly rainfall concentration. In these inland zones, where more forest and woodland areas are located and forest fires are frequent, the observed trends could greatly affect desertification through changes in the disturbance regime. In more arid areas, local variability in rainfall evolution is higher and no significant changes can be defined.

KEY WORDS: Mediterranean; Spearman test; Cramér–von Mises test; rainfall trends; rainfall variability; spatial analysis; desertification

1. INTRODUCTION

Rainfall variability in space and time is one of the most relevant characteristics of Western Mediterranean climates (Romero *et al*., 1998). This is especially relevant in areas that are mainly reliant on Mediterranean Sea dynamics (Sumner *et al*., 1993; Millán *et al*., 1995). The region of Valencia is a good example of this, as rainfall is extremely variable on all temporal scales (Pérez-Cueva, 1994; De Luís *et al*., 1996, 1997). Thus, owing to its manifestation as a deficient resource (Pérez-Cueva, 1983; Quereda, 1983) and as a catastrophic agent (Gil-Olcina, 1989), rainfall has always been the surface climatic variable of primary interest in this region.

The changing precipitation pattern, and its impact on surface water resources, is an important climatic problem facing society today. Associated with global warming, there are strong indications that rainfall changes are already taking place on both the global (Bradley *et al*., 1987; Diaz *et al*., 1989; Hulme *et al*., 1998) and regional scales (Maheras, 1988; Yu and Neil, 1993; Rodríguez-Puebla *et al*., 1998). Future climate changes may involve modifications in climatic variability as well as changes in averages (Rind *et al*., 1989; Mearns *et al*., 1996); indeed, variability changes may have the largest impact on some responses (Katz and Brown, 1992). Thus, rather than mean values, interannual variability is defined by many as one

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of the most important indicators of the reliability of the rainfall resource (Semenov and Porter, 1994; Corte-Real *et al.*, 1998).

The implications of these changes are particularly significant for areas already under stress, such as regions that suffer a water shortage through a combination of a dry climate (or a highly seasonal rainfall regime) and excessive demand. The Mediterranean Basin is such a region (Palutikof, 1996). Mediterranean regions are transitional climate zones where it has been hypothesized that climatic changes may have the greatest effects (Lavorel *et al.*, 1998).

Research into historical changes in the climatic system using instrumental records is recognized as one of the necessities of climate change research (Houghton *et al.*, 1990). Historical climate records provide the context of natural variation against which anthropogenically forced climate change will have to be detected. Model evaluation needs measurement data of the variables that are directly comparable with model outputs over, at least, a 30-year period (Hulme *et al.*, 1995; Moron *et al.*, 1995); thus, the World Meteorological Organization (WMO) normal period is recommended.

In this context, many studies on rainfall variations have been carried out in recent years. They have provided insight into the direction and the significance of rainfall trends. Since around 1970, there has been evidence of changes in rainfall patterns in the Mediterranean Basin (Maheras, 1988; Maheras and Kolyva-Machera, 1990; Wheeler and Martín-Vide, 1992). Romero *et al.* (1998) referred to a trend for decreasing precipitation and changes in seasonal distribution since the 1960s on the Mediterranean coast of Spain that are in agreement with general circulation model (GCM) predictions. However, intraregional variations are much larger, and different patterns are found between zones where the Atlantic influence is substantial (western and northern Andalucia and northern Catalonia) and others that mainly rely on Mediterranean dynamics (the region of Valencia). In this purely Mediterranean area, trends are less clear.

As has been noted, Valencia is exposed to purely Mediterranean flows and local factors (especially convection and topographic configuration) produce rainfall that is highly variable in space and time. Thus, in this region, a significant part of precipitation variability occurs at the micro-scale and spatial coherence is quite small (Camarasa, 1993; Millán *et al.*, 1995). Under these conditions, the significance and magnitude of changes at a regional scale are difficult to ascertain. Nevertheless, it is important to assess the changes that may be occurring on a spatial and a temporal basis. A complete description of intraregional rainfall variability and changes is of great interest, especially in areas with strongly contrasting rainfall regimes and with associated environmental problems (Bigg, 1991).

If we intend to draw meaningful conclusions on rainfall trends in space, a dense and homogeneous network is required (Groisman and Legates, 1995; Peterson *et al.*, 1998). Climate change studies (Groisman and Legates, 1994; Hulme, 1995) show that large-scale changes in annual precipitation over land areas can be documented when a dense network database is used, i.e. 5–10 times more stations than is required for documenting global changes in surface air temperature (Vinnikov *et al.*, 1990). This is especially relevant in areas with strongly contrasting rainfall regimes.

In rainfall change detection using empirical data, two complementary statistical techniques are commonly used: non-parametric and linear models. As noted by several authors (Yu and Neil, 1993; Suppiah and Hennessy, 1998), complementary information can be obtained from such techniques. Thus, a non-parametric model, such as the Spearman rank correlation test to detect statistical significance, can be complemented with a linear model, such as least square regression, to determine the magnitude of the trend.

In rainfall trend research, geostatistical methods of interpolation, such as kriging, have been applied to describe changes in magnitude (e.g. rate of change measured as the slope of linear models). These methods offer a good approach to the spatial distribution of magnitude of change, but provide no information on their significance. On the other hand, spatial analysis of signs of trends is rarely carried out (Loureiro and Coutinho, 1995; Suppiah and Hennessy, 1998). This may be partly because of the involved difficulties associated with the spatial analysis of categorical data obtained from non-parametric trend techniques such as Spearman's test.

We have applied a statistical analysis, based on the Cramér–von Mises non-parametric test, for a difference between two univariate probability distribution functions (Conover, 1980). The test is based on the three possible temporal evolutions of any rainfall variable: positive, negative and zero trends. The null hypothesis is that there are no differences in the spatial distribution of each pair of signs. When no significant differences are obtained, no intraregional pattern can be defined and it can be concluded that trends are randomly distributed along the study area. In other words, exclusively local factors are responsible for the spatial variability of trends. If significance is obtained, some intraregional areas with contrasting rainfall evolution can be defined.

The main objectives of this paper are: (i) to describe the spatial patterns of rainfall amount and concentration, and the interannual variability of annual and monthly rainfall concentration along the WMO normal period 1961–1990 in 97 locations in Valencia; and (ii) to test for changes in these variables. The results are discussed in the context of the main ecological and water resource problems affecting the study area.

2. METHODOLOGY

2.1. Rain-gauge database

The region of Valencia is located in the Western Mediterranean Basin, along the Mediterranean coast of Spain (Figure 1). It comprises an area extending between 38° and 40°N. It is characterized by important coastal relief units (Figure 2), which play a decisive role in the influence of Mediterranean and Atlantic fronts (Camarasa, 1993; Quereda, 1994).

In order to examine the spatial and temporal variability of precipitation in the region of Valencia, daily rain-gauge datasets for 97 locations are used. The original source (Pérez-Cueva, 1994), comprising 210 stations, was checked for inhomogeneities using metadata information and linear regression methods (Pérez-Cueva, 1994; Peterson and Easterling, 1994; Easterling and Peterson, 1995). From these, only complete and homogeneous series covering at least the WMO normal period 1961–1990 are used. The database length ranges from 30 to 41 years (1950–1990 period). These stations are distributed irregularly throughout the region of Valencia and represent the longest period available for the highest quality data covering the area (Pérez-Cueva, 1994). Figure 2 shows the spatial distribution of rainfall stations, the orography of the region and some geographical features mentioned in the text.

2.2. Rainfall mean characteristics

We calculate annual rainfall (R) for each station. In order to study monthly heterogeneity of rainfall amounts, a modified version of Oliver's (1980) Precipitation Concentration Index (PCI) (De Luís *et al.*, 1997) is used. This index, described as

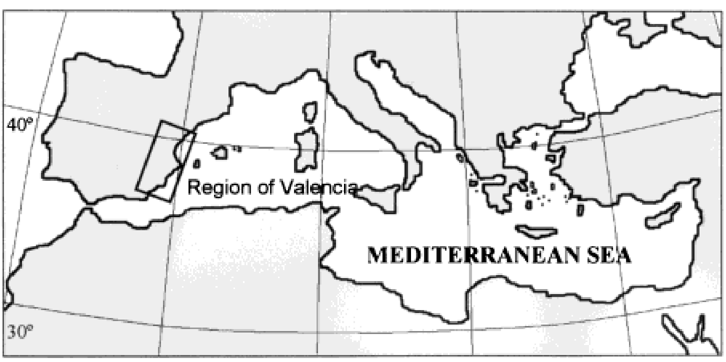

Figure 1. Location of the study area: region of Valencia (east Spain)

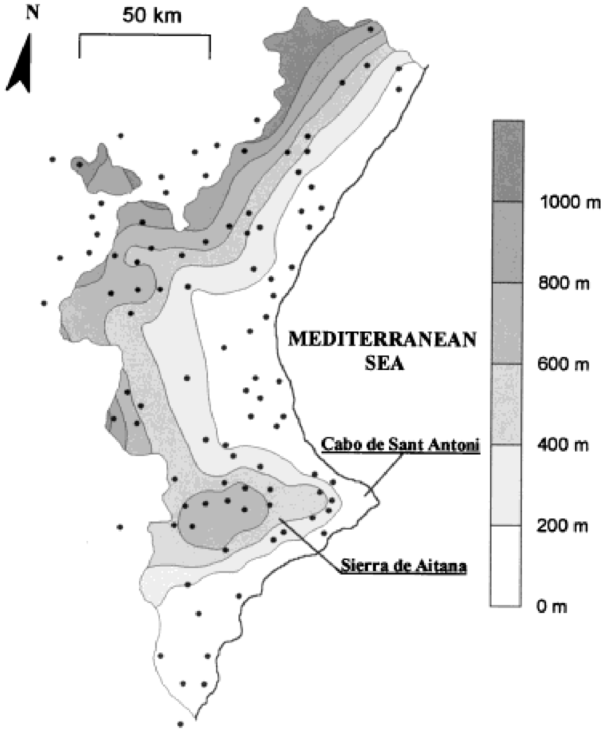

Figure 2. Smoothed version of the orography of the region of Valencia. Dots correspond to the location of the meteorological stations whose datasets were used for this study

$$\mathrm{PCI} = 100 * \frac{\sum_{i=1}^{12} p_i^2}{\left(\sum_{i=1}^{12} p_i\right)^2}$$

where p_i is the rainfall amount of the ith month, has been calculated for each of the 97 locations and for each of the 30 years being considered. As described by Oliver (1980), PCI values below 10 indicate a uniform monthly rainfall distribution in the year, whereas values from 11 to 20 denote seasonality in rainfall distribution. Values above 20 correspond to climates with substantial monthly variability in rainfall amounts.

For these two time series, mean values ($\bar{R}$ and $\overline{\mathrm{PCI}}$) and coefficients of variation (CVR, CVPCI) are computed. Kriging interpolation methods (Singh and Chowdhury, 1986; Lebel *et al.*, 1987) are used to describe the spatial patterns of these variables.

2.3. Trend analysis

2.3.1. Variables considered. To test for trends in mean values, time series of annual rainfall (R) and annual PCI values were used.

There are difficulties in testing for changes in interannual rainfall variability, owing to the problems involved in defining an adequate measure that reflects changes in variability rather than changes in mean values. For example, because the standard deviation (S.D.) closely co-varies with mean rainfall, the difference between, or the ratio of, 2 S.D.s is not necessarily the best measure to use when mean rainfall conditions are themselves changing. Instead, a measure of relative variability is recommended to represent changes in reliability (Hulme, 1992; Türkes, 1996).

Thus, to test for changes in interannual rainfall variability, the normalized precipitation anomaly series (R and PCI) are used. The normalization procedure proposed by Kraus (1977) and later used by several researchers (Salinger *et al.*, 1995; Türkes, 1996) is adopted. In this case, the mean instead of the S.D. is used as the normalization reference. This deviation from the original method does not produce differences in non-parametric trend analysis (in both cases, the series are divided by constant values). Conversion to the original normalized precipitation anomalies can easily be obtained by multiplying the coefficient of variation of the series.

Thus, the normalized precipitation anomalies (AR and APCI) for a given station s and for a given year y is expressed as the ratio of each value to the mean for the reference period.

$$\mathrm{AR}_{sy} = (R_{sy} - \bar{R}_s)/\bar{R}_s;\ \mathrm{APCI}_{sy} = (\mathrm{PCI}_{sy} - \overline{\mathrm{PCI}_s})/\overline{\mathrm{PCI}_s}$$

We use the absolute value of these anomaly series ($|\mathrm{AR}|$ and $|\mathrm{APCI}|$) to detect changes in the amplitude of interannual variability of both elements.

2.3.2. Statistical procedure. In rainfall change detection, the moving average or running mean is a conventional procedure used for climate stability or long-term trend description (Sneyers, 1992). This procedure offers a valuable way of filtering out year-to-year variations to reveal more persistent trends (Wheeler and Martín-Vide, 1992; Salinger *et al.*, 1995). Thus, prior to trend analysis, the datasets were smoothed using a 9-year moving average.

Linear regression is probably the most commonly used technique for assessing relationships between two variables (Gregory, 1978; Lanzante, 1996). However, trends in climatic series are rarely linear. Moreover, linear regression assumes normality and homogeneity of variance throughout the series (Clark and Hosking, 1986), and may be adversely affected by outliers. Non-parametric statistics are usually much less affected by the presence of outliers and other forms of non-normality (Lanzante, 1996), and they represent a measure of monotonic dependence whether linear or not (Davis, 1986; Rossi *et al.*, 1992).

Two non-parametric statistics were proposed by Sneyers (1992) to test for trends: Mann–Kendall's test and Spearman's test. Both measures are based on rank correlation. Spearman's rank correlation test was chosen in this study to detect significant trends at a 95% significance level (Loureiro and Coutinho, 1995; Suppiah and Hennessy, 1998). Here, a 95% significance level was used.

2.4. Spatial analysis. Cramér–von Mises statistic test

Specifically, the test statistic is calculated as the squared difference between the two cumulative distribution functions summed over all sampling locations (Syrjala, 1996).

For the Cramér–von Mises test, data must be selected at random in space. For a true generalization of the test, the random variable of interest would be the localization of the tested stations. When locations cannot be sampled at random (such as meteorological stations), the generalization of the Cramér–von Mises test must be modified (Syrjala, 1996). For this reason, in such a case the random variable is the observed sign of the trend in each station, not the location itself.

In comparing distributions of signs, this approach requires that all populations of signs must be sampled over all locations. To do this, each location is categorized by the presence or absence of each of the three signs. Thus, for each population of signs ('+','−' or '*o*'), the value of the location was either 1 or 0. Therefore, if a given location for a given element had a significant positive trend, it was categorized as 1 in the positive population ('+') and as 0 in the negative ('−') and zero ('*o*') populations.

This test was specifically designed to be insensitive to differences in the total number of trends in the study area, but sensitive to differences in the distributions, given the respective number of locations with a given trend. Thus, in each pairwise comparison ('+' versus '−'; '+' versus '*o*'; '−' versus '*o*'), the two distributions compared must be normalized in order to remove the effect of differing population sizes.

In examining the difference between the spatial distribution, the test statistic is based on the differences between two cumulative distribution functions. In this way, following the normalization procedure, the magnitude of the increment of the cumulative distribution function of each population of signs is proportional to the total number of stations with this sign. The sum of the increments in the cumulative distribution function for each population of signs is 1.

2.4.1. Unidimensional test application. Under the unidimensional model of application of this test, the cumulative step on unidimensional gradients must be made. In this way, it is possible to compare the spatial distribution of the trends along different univariant gradients that may be annual average rainfall, pressure gradients, altitude, different erosion risk, fire activity, etc. Thus, for a given cumulative direction, the statistic test indicates if the compared population of signs ('+' versus '−'; '+' versus '*o*'; '−' versus '*o*') overlap along this gradient. For example, if the distribution of trends is analysed in the annual rainfall mean gradient, the test inquires about the distribution of the trends along the gradient, and it is possible to identify if rainfall changes are occurring in the same way in the different mean rainfall areas.

Under this unidimensional model, the statistic is invariable with respect to the initial point of accumulation; in addition, for each pairwise comparison, only one statistic is obtained for each cumulative direction. If significance is obtained, results can be interpreted by using the trend distribution maps and the variable used as the gradient.

2.4.2. Bidimensional test application. To characterize the geographical distribution of trends, the cumulative distribution across a two-dimensional (2D) sample space can be calculated. Zimmerman (1993) proposed a solution assuming a Cartesian coordinate system superimposed on a rectangle. In this case, there is no corner that one would naturally define as the origin of the coordinate system, but the statistic is not invariant with this respect. Zimmerman proposed calculating the statistic Ψ four times, one with each corner of the rectangle defined as the origin, and making the cumulative step in a diagonal (bidimensional) way. Later, Zimmerman proposed averaging the four bidimensional statistics to obtain a single test statistic. This averaged approach provides a general description of the spatial distribution of the trends.

This paper suggests an alternative analysis. If the coordinate system agrees with the latitudinal–longitudinal directions, four unidimensional statistics (Ψ_1, Ψ_2, Ψ_3 and Ψ_4) that will indicate the distribution of the trend signs along four different geographic directions (Figure 3) can be calculated: two of them (Ψ_1, Ψ_2) for a longitudinal gradient (making the cumulative step from east to west) and the other two for a latitudinal one (Ψ_3, Ψ_4) (making the cumulative step from north to south).

2.4.3. General procedure. For a given gradient, data are collected for the three populations of signs at all (K) rain-gauge stations. Observations must be made for each population of signs at each station as follows: let (x_k) be the position of the kth rain-gauge station, $\{k = 1, \ldots, K\}$. Let $d_i(x_k)$ be the categorized trend sign (1 or 0) at the kth rain-gauge station of the ith population (i = '+', '−' or '*o*').

The question being evaluated is whether the data $\{d_i(x_k)$: $k = 1, \ldots, k$; $i = +, -$ or $o\}$ indicate a difference in the underlying normalized distribution of the two populations or whether the data may reasonably represent simply random variations drawn from a single, common underlying distribution.

This approach, rather than comparing the two distributions directly, identifies whether there is an attraction, a repulsion or independence between each pairwise population of signs under the study region

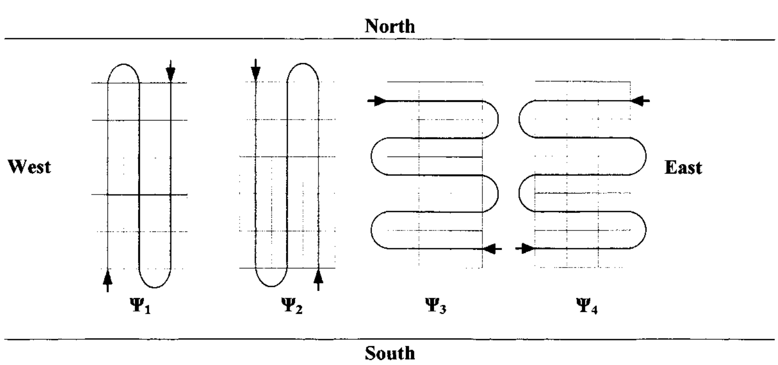

Figure 3. Cumulative criterion used in the geographical characterization of rainfall trends. Ψ_1 and Ψ_2 are related to spatial distribution of trends in an east–west (or coastal–inland) gradient, whereas Ψ_3 and Ψ_4 are related to a north–south gradient

(Upton and Fingleton, 1985). The null hypothesis is that across the study area, the normalized distributions of signs are the same. The alternative hypothesis is that there is some unspecified difference in the underlying normalized distributions.

To conduct this test, which is independent of the population size, the observed categorized trend in each location is normalized, dividing it by the sum of all observations for that population. Thus

$$\Phi_i(x_k) = \frac{d_i(x_k)}{D_i}$$

defines the normalized density observations where

$$D_i = \sum_{k=1}^{k} d_i(x_k).$$

The value of the cumulative distribution function at the location (x_k) for the ith population, denoted by $\Gamma_i(x_k)$, is the sum of all normalized observations, $\Phi_i(x_k)$, whose locations (x) are such that $x \leq x_k$. Thus, the cumulative distribution function for the ith population at the kth sampling location can be defined as

$$\Gamma_i(x_k) = \sum_{\forall x \leq x_k} \Phi(x).$$

Following the Cramér–von Mises analogue, a statistic to test the null hypothesis is the square of the difference between each pairwise cumulative distribution functions, taken over all locations:

$$\Psi_{(+\text{ versus } o)} = \sum_{k=1}^{K} [\Gamma_{(+)}(x_k) - \Gamma_{(o)}(x_k)]^2.$$

$$\Psi_{(+\text{ versus } -)} = \sum_{k=1}^{K} [\Gamma_{(+)}(x_k) - \Gamma_{(-)}(x_k)]^2.$$

$$\Psi_{(o\text{ versus } -)} = \sum_{k=1}^{K} [\Gamma_{(o)}(x_k) - \Gamma_{(-)}(x_k)]^2.$$

In the 2D model, for each pairwise comparison of signs, four different statistics can be obtained (Ψ_1, Ψ_2, Ψ_3 and Ψ_4).

The test is carried out using empirical distribution functions only and, therefore, there is no need to make any assumption about the underlying distribution of the populations. The level of significance of the test statistic Ψ can be determined using the methodology of a randomized test (Edgington, 1980; Underwood, 1997).

For a given set of data with K rain-gauge stations, in which p, o and n are the number of stations with positive, zero and negative trends, respectively, where $K = p + o + n$, the distribution of the statistic can be determined by calculating its value for all $K!/p!\cdot o!\cdot n!$ pairwise combinations.

The level of significance of a specific statistic Ψ is determined from its position in the ordered set of test statistic values from all $K!/p!\cdot o!\cdot n!$ combinations. In this case, the number of stations, K, is too large to compute all possible combinations (e.g. with 97 locations more than 1.5E + 44 combinations can be obtained), so instead a large number of randomly selected combinations can be used to approximate the distribution of the test statistic Ψ; hence, the level of significance of the observed value (Syrjala, 1996). In this study, 1000 combinations of the data are examined, i.e. the observed combination plus 999 pseudo-random combinations. The p value is thus calculated as the proportion of the 1000 test statistic values that were greater than or equal to the observed test statistic. A copy of the *QuickBasic* program written to randomize the process is available from the authors upon request.

2.4.4. Unidimensional characterization of rainfall trends in the region of Valencia. We compare the spatial distribution of rainfall trends along different univariant gradients in the region of Valencia. The selected unidimensional gradient for trends in annual rainfall (R) and rainfall variability ($|\text{AR}|$) is the mean annual rainfall ($\bar{R}$). For trends in monthly rainfall concentration (PCI) and its interannual variability (|APCI|), the selected unidimensional gradient is the PCI mean value ($\overline{\text{PCI}}$).

A detailed example of the calculations used to estimate each pairwise Cramér–von Mises statistic is shown in Table I. In this sample case, the cumulation criterion used is the mean annual precipitation ($\bar{R}$) over the period 1961–1990. In the case of the pairwise comparison between positive and zero locations, 100 of the pseudo-random test statistic values were greater than or equal to the observed test statistic $\Psi = 4.14$, yielding a value of $p = 0.101$ and indicating that the observed difference between the distribution of positive and negative trends along the mean annual rainfall gradient was not statistically significant. In the two other pairwise comparisons (+ versus −) and (*o* versus −), 0 and 8 pseudo-random test statistic values were greater than or equal to the observed test statistics $\Psi = 11.18$ and $\Psi = 3.43$, yielding values of $p = 0.001$ and 0.009, respectively.

2.4.5. Geographical characterization of rainfall trends in the region of Valencia. For each of the four pluviometric trends analysed (*R*, |AR|, PCI and |APCI|), differences in the spatial distribution of the trend signs across geographical gradients were tested for. Given that the coordinate system agrees with latitude–longitudinal gradients, each of the four individual statistics is related to different geographic directions: from coastal to inland stations and from northern to southern stations.

Once the importance of this change was determined, linear models and kriging methods to illustrate the spatial distribution of the magnitude changes were used.

3. RESULTS

3.1. Rainfall characteristics in the region of Valencia

Annual mean precipitation ($\bar{R}$) for the WMO normal period 1961–1990 showed high spatial variation (Figure 4(a)), with values ranging from < 300 mm in southern areas to > 800 mm in the northern aspect of the Cabo de Sant Antoni. In this area, mountains act as a barrier for Mediterranean fronts (humid and warm) coming from the sea (Camarasa, 1993). These mountain ranges contribute to activating precipitation and provide a trigger mechanism for potentially unstable air masses reaching the coast (Millán *et al.*, 1995).

The CVR shows that interannual variability was high in the whole area, with values ranging from 28% to more than 46% (Figure 4(b)). This complex spatial pattern indicates that local factors (such as local topography) may be responsible for this variability. The western Mediterranean has the world's highest density of cyclogenesis (Petterssen, 1956) and convective cells of small extension (from 10 to 50 km^2) produce rainfall that is highly variable, both in space and in time (Sharon, 1972; Yair and Lavee, 1985). Areas with coefficients of variation higher than 30% are likely to have more frequent and severe droughts and floods (Türkes, 1996).

Intraannual distribution of rainfall amounts was highly variable in space and time (Figure 5(a)). The most irregular intraannual rainfall distribution ($\overline{\text{PCI}} > 22$) was mainly concentrated in the coastal area. These features can be explained by the fact that extreme events, which mainly occur in autumn, are still a consequence of perturbations generated in the Mediterranean Sea with effects that are mostly felt in coastal areas (Camarasa, 1993; Lana *et al.*, 1995; Millán *et al.*, 1995). The coastal relief in the Cabo de Sant Antoni may encourage more vigorous convective processes, and it is in this area that the highest irregularity is observed. In contrast, intraannual variability is lower inland ($\overline{\text{PCI}} < 20$). This may result from less intense convective processes during the autumn and a higher influence of Atlantic fronts in winter and spring.

Interannual variability in the monthly distribution of rainfall is high (Figure 5(b)). The coefficients of variation of PCI ranged from 40% to more than 85%. Again, local factors seem to play a relevant role. Higher differences occur mainly in coastal areas, where convective processes are more frequent (Camarasa, 1993) and torrential rainfall (> 200 mm/day) occurs with return periods lower than 10 years (De Luís *et al.*, 1998). Thus, for a given year, high variability seems to be associated with torrential autumnal episodes (De Luís *et al.*, unpublished).

Table I. A detailed example of Cramér–von Mises statistic calculation for distribution of trends in annual rainfall amount (R) in the mean annual rainfall ($\bar{R}$) gradient

Station name	K	$\bar{R}$	Trend	d_i			Φ_I			Γ_i			Pairwise comparison		
				$D_{(+)}=11$ $d_{(+)}$	$D_{(o)}=42$ $d(o)$	$D_{(-)}=44$ $d(_{-})$	$\Phi_{(+)}$	$\Phi_{(o)}$	$\Phi_{(-)}$	$\Gamma_{(+)}$	$\Gamma_{(o)}$	$\Gamma_{(-)}$	(+ versus o) $[\Gamma_{(+)}-\Gamma_{(o)}]^2$	(+ versus −) $[\Gamma_{(+)}-\Gamma_{(-)}]^2$	(o versus −) $[\Gamma_{(o)}-\Gamma_{(-)}]^2$
Tárbena	1	828	−	0	0	1	0/11	0/42	1/44	0/11	0/42	1/44	0	0.0005	0.0005
Fontilles	2	819	−	0	0	1	0/11	0/42	1/44	0/11	0/42	2/44	0	0.0021	0.0021
Pego	3	796	−	0	0	1	0/11	0/42	1/44	0/11	0/42	3/44	0	0.0046	0.0046
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Mira	48	516	o	0	1	0	0/11	1/42	0/44	3/11	18/42	27/44	0.0243	0.1162	0.0342
Villar del Arz.	49	515	−	0	0	1	0/11	0/42	1/44	3/11	18/42	28/44	0.0243	0.1322	0.0432
Càlig	50	511	o	0	1	0	0/11	1/42	0/44	3/11	19/42	28/44	0.0323	0.1322	0.0338
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Orihuela	95	293	o	0	1	0	0/11	1/42	0/44	10/11	41/42	44/44	0.0045	0.0083	0.0006
Elche	96	236	o	0	1	0	0/11	1/42	0/44	10/11	42/42	44/44	0.0083	0.0083	0
Torrevieja	97	233	+	1	0	0	1/11	0/42	0/44	11/11	42/42	44/44	0	0	0
Ψ													$\Psi_{(+\ \text{versus}\ o)}$ 4.14	$\Psi_{(+\ \text{versus}\ -)}$ 11.18	$\Psi_{(o\ \text{versus}\ -)}$ 3.43

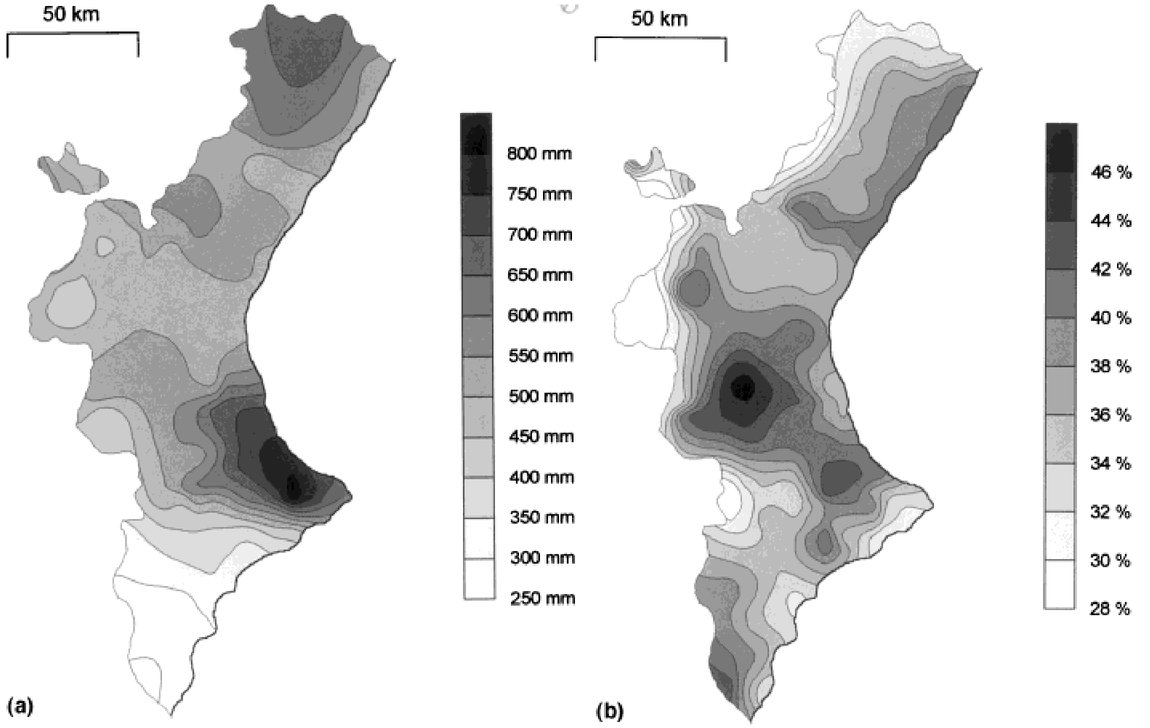

Figure 4. Annual rainfall in the region of Valencia (1961–1990). (a) Mean annual rainfall ($\bar{R}$) distribution in the region of Valencia (1961–1990). (b) Spatial distribution of interannual variability of annual rainfall (CVR)

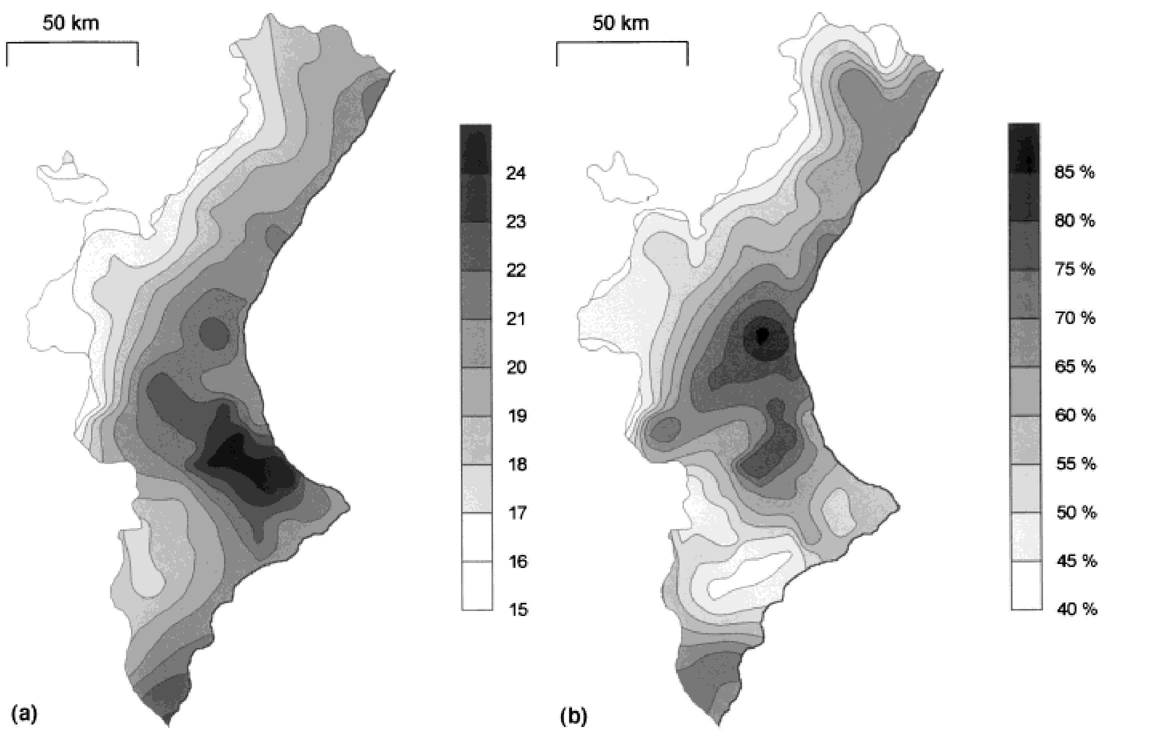

Figure 5. Monthly Precipitation Concentration Index (PCI) in the region of Valencia (1961–1990). (a) Mean monthly $\overline{\text{PCI}}$. (b) Spatial distribution of interannual variability of Precipitation Concentration Index (CVPCI)

3.2. Trends in rainfall elements

3.2.1. Annual rainfall amount (R). We observe a significant increase in annual rainfall amounts in 11 meteorological stations. Forty-two showed no trend, while a significant decrease occurred on 44 occasions. Spatial analysis applied to this data indicates that these locations are not randomly distributed across the region.

Spatial analyses in the unidimensional model (i.e. in a mean annual rainfall gradient ($\Psi_{\bar{R}}$)) indicate that negative stations showed a different spatial distribution when they are compared with positive or zero stations. In contrast, positive and zero stations seemed to overlap along this gradient. Statistic $\Psi_{\bar{R}}$ for each pairwise comparison and significance levels are shown in Table II. To identify these differences in the spatial distribution, the observed trends distribution (Figure 6(a)) and the observed mean annual rainfall distribution map (Figure 4(a)) were used. The more humid areas ($\bar{R} > 550$ mm) were mainly characterized

Table II. Annual rainfall amount (R)

Pairwise comparison	Geographical model								Univariate model	
	Coast–inland				North–south				($\bar{R}$)	
	Ψ_1	P	Ψ_2	P	Ψ_3	P	Ψ_4	P	$\Psi_{\bar{R}}$	P
+ versus *o*	1.81	0.383	3.10	0.187	3.72	0.130	3.34	0.163	4.14	0.101
+ versus −	2.75	0.220	2.91	1.186	5.88	0.038	5.77	0.041	11.2	0.001
o versus −	0.53	0.523	0.47	0.569	0.48	0.561	0.54	0.513	3.43	0.009

Spatial analysis of trends in univariate and geographical mode. For each gradient and pairwise comparison, the value of the Cramér–von Mises statistic and the level of significance are shown.

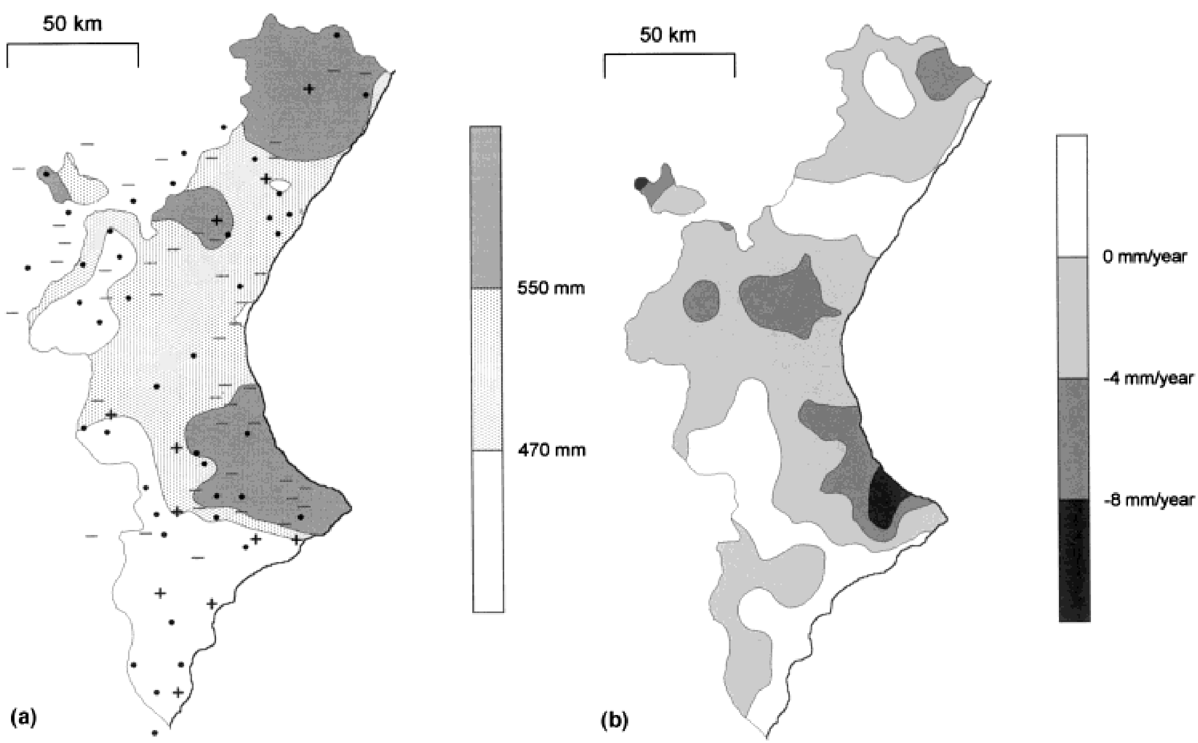

Figure 6. Observed trends in annual rainfall (R). (a) Locations of stations showing increasing (+), decreasing (−) and non-significant (●) trends (Spearman test, $p < 0.05$) are shown. Superimposed, smoothed distribution of mean annual rainfall ($\bar{R}$) in the region of Valencia over WMO normal period 1961–1990. (b) Annual rate of change of annual rainfall (R) along WMO normal period 1961–1990. Values in mm/year

by stations with a significant decrease in annual rainfall. In contrast, positive trends were mainly located in more arid areas ($\bar{R} < 470$ mm). Non-significant differences between positive and zero stations indicate that both are overlapping in space. As can be seen, more arid areas are not purely positive areas, as positive and null stations can be found. Areas with mean rainfall around 500 mm were characterized by negative or null trends (Table III).

Other statistics $\Psi_{(1-4)}$ obtained to test for geographical distribution of trends are shown in Table II. Significant differences were obtained between positive and negative stations in the north–south gradient. Again, these differences were mainly the result of a concentration of positive stations in more arid areas. It must be noted that the test is independent of the number of stations with a given sign. Thus, this concentration of positive signs in more arid areas does not necessarily mean that this sign dominates.

The magnitude of observed changes can be estimated using maps obtained from linear model analysis (Figure 6(b)). In more humid areas, where a significant decrease in annual rainfall amount was detected, this change occurred at a rate ranging from 4 to 12 mm/year. In dry zones, non-significant decreases occurring at a rate around 2–4 mm/year were observed. Positive and negative rates of change were observed in more arid areas.

3.2.2. Annual rainfall variability (|AR|). Positive signs in |AR| trends were distributed in a different way from negative ($p = 0.002$) and zeros ($p = 0.008$) along the mean annual rainfall gradient (Table IV; Figure 7(a)). Positive trends were mainly located in more humid areas, whereas drier trends were mainly characterized by non-significant trends. More arid areas showed higher local variability (Table V). Rates of changes of |AR| ranged from 0% to 4% in more humid areas in which significance has been detected (Figure 7(b)).

Table III. Trends in annual rainfall amount (R) during the period 1961–1990 in the region of Valencia related to mean annual rainfall ($\bar{R}$)

Annual rainfall (R)	Number of stations	% positives (n)	% null (n)	% negatives (n)
Whole region of Valencia	97	11 (11)	43 (42)	45 (44)
More arid zones ($\bar{R} < 470$ mm)	32	25 (8)	50 (16)	25 (8)
Dry zones ($470 \leq \bar{R} \leq 550$ mm)	33	3 (1)	52 (17)	45 (15)
More humid zones ($\bar{R} > 550$ mm)	32	6 (2)	28 (9)	66 (21)

3.2.3. Monthly Precipitation Concentration Index (PCI) trends. Trends in rainfall concentration were heterogeneously distributed along $\overline{\text{PCI}}$ and geographical gradients (Table VI). A clear distinction could be made between high, medium and low $\overline{\text{PCI}}$ areas (Figures 5(a) and 8(a)). For this gradient, positive, negative and zero trends did not overlap (Table VI). Thus, a highly significant increase in rainfall concentration (75%

Table IV. Absolute value of annual rainfall anomalies (|AR|)

Pairwise comparison	Geographical model								Univariate model	
	Coast–inland				North–south				($\bar{R}$)	
	Ψ_1	P	Ψ_2	P	Ψ_3	P	Ψ_4	P	$\Psi_{\bar{R}}$	P
+ versus *o*	3.08	0.014	2.55	0.030	1.00	0.239	0.87	0.296	13.6	0.008
+ versus −	0.77	0.946	0.91	0.902	1.74	0.639	1.08	0.855	19.8	0.002
o versus −	2.00	0.569	3.77	0.261	2.30	0.500	1.22	0.791	7.90	0.063

Spatial analysis of trends in univariate and geographical mode. For each gradient and pairwise comparison, the value of the Cramér–von Mises statistic and the level of significance are shown.

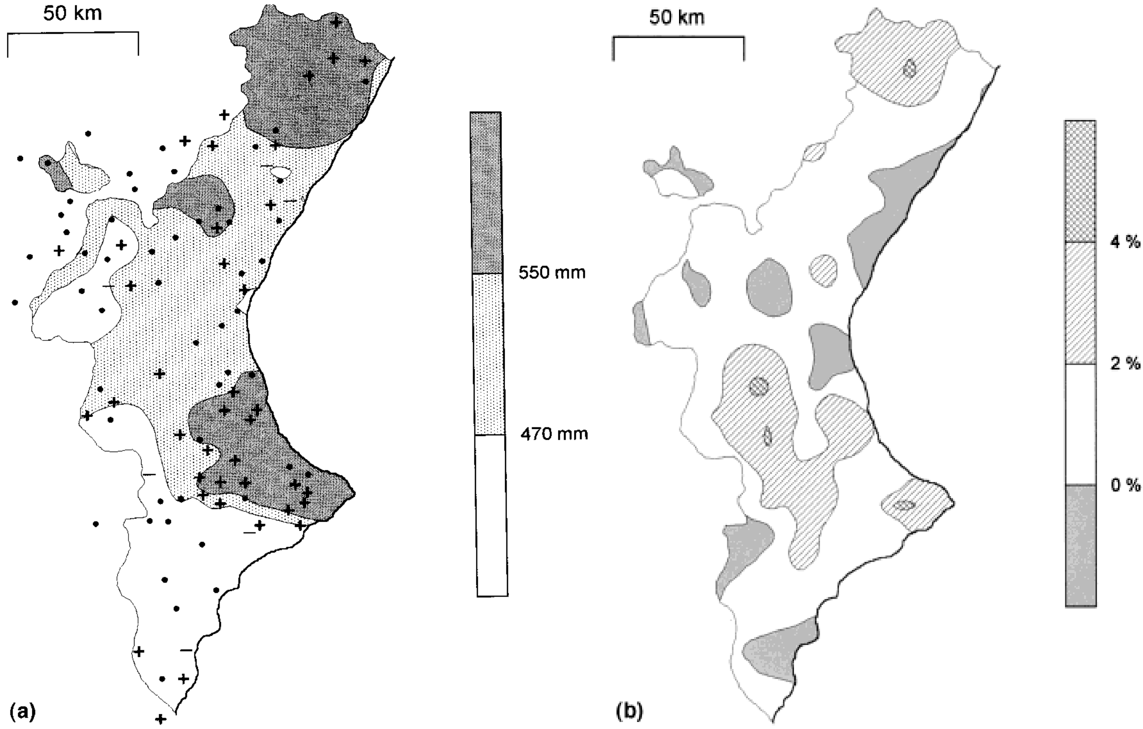

Figure 7. Observed trends in the absolute value of annual rainfall anomalies (|AR|). (a) Locations of stations showing increasing (+), decreasing (−) and non-significant (●) trends (Spearman test, $p < 0.05$) are shown. Superimposed, smoothed distribution of mean annual rainfall ($\bar{R}$) in the region of Valencia over WMO normal period 1961–1990. (b) Annual rate of change of the absolute values of annual rainfall anomalies (|AR|) through WMO normal period 1961–1990. Values expressed as annual percentage of change

Table V. Trend direction for the absolute value of annual rainfall anomalies (|AR|) during the period 1961–1990 in the region of Valencia related to mean annual rainfall ($\bar{R}$)

Annual rainfall anomalies (|AR|) (R)	Number of stations	% positives (n)	% null (n)	% negatives (n)
Whole region of Valencia	97	40 (39)	54 (52)	6 (6)
More arid zones ($\bar{R} < 470$ mm)	32	31 (10)	53 (17)	16 (5)
Dry zones ($470 \leq \bar{R} \leq 550$ mm)	33	33 (11)	64 (21)	3 (1)
More humid zones ($\bar{R} > 550$ mm)	32	56 (18)	44 (14)	0 (0)

Table VI. Monthly Precipitation Concentration Index (PCI)

Pairwise comparison	Geographical model								Univariate model	
	Coast–inland				North–south				($\overline{PCI}$)	
	Ψ_1	P	Ψ_2	P	Ψ_3	P	Ψ_4	P	Ψ_{PCI}	P
+ versus *o*	6.82.	0.001	9.20	0.001	1.48	0.128	1.14	0.205	4.84	0.001
+ versus −	16.3	0.001	15.3	0.001	6.41	0.010	6.98	0.009	22.3	0.001
o versus −	3.21	0.085	1.60	0.303	6.30	0.010	7.90	0.004	7.72	0.004

Spatial analysis of trends in univariate and geographical mode. For each gradient and pairwise comparison, the value of the Cramér–von Mises statistic and the level of significance are shown.

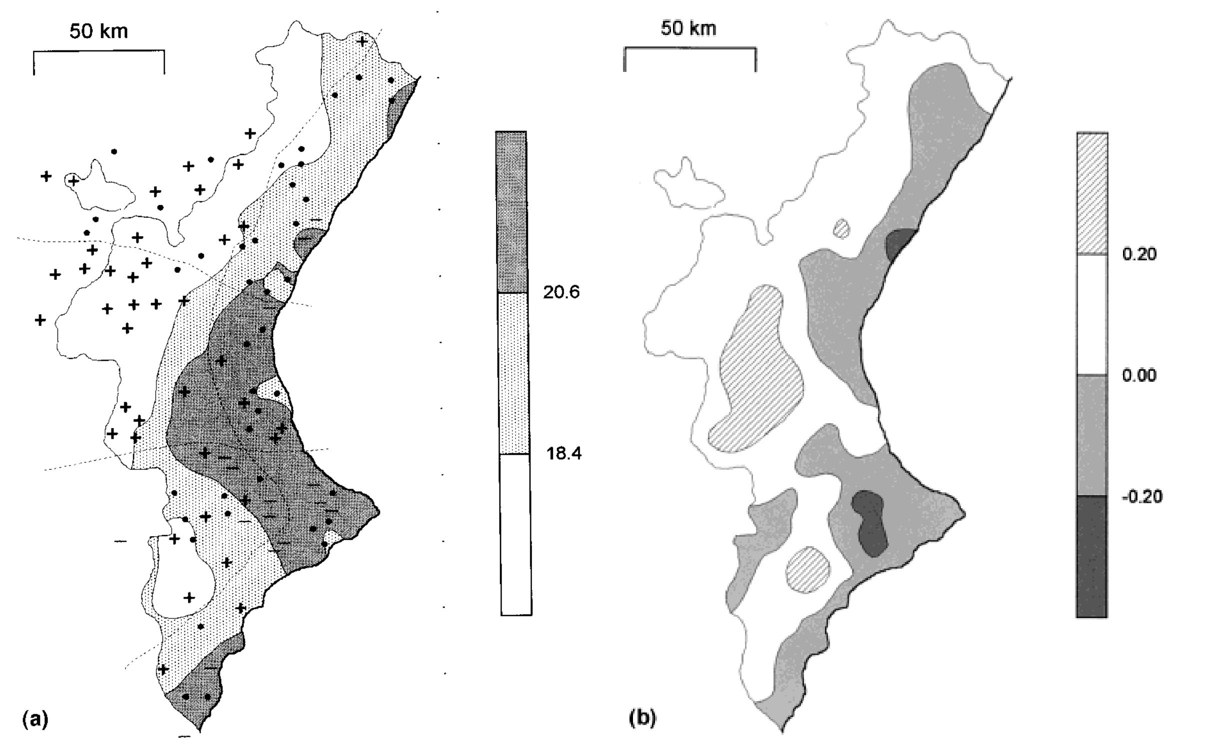

Figure 8. Observed trends in monthly Precipitation Concentration Index (PCI). (a) Location of stations showing increasing (+), decreasing (−) and non-significant (●) trends (Spearman test, $p < 0.05$) are shown. Superimposed, smoothed distribution of Precipitation Concentration Index ($\overline{PCI}$) in the region of Valencia over WMO normal period 1961–1990 and arbitrary defined geographical areas with contrast rainfall concentration evolution. (b) Annual rate of change of monthly Precipitation Concentration Index (PCI) along WMO normal period 1961–1990

Table VII. Trend direction for the monthly Precipitation Concentration Index (PCI) during the period 1961–1990 in the region of Valencia related to (a) $\overline{PCI}$ and (b) geographical gradient

Monthly PCI	Number of stations	% positives (*n*)	% null (*n*)	% negatives (*n*)
Whole region of Valencia	97	41 (40)	42 (41)	16 (16)
(a)				
Lower $\overline{PCI}$ zones ($\overline{PCI} < 18.4$)	32	75 (24)	25 (8)	0 (0)
Medium $\overline{PCI}$ zones ($18.4 \leq \overline{PCI} \leq 20.5$)	33	27 (9)	64 (21)	9 (3)
Higher $\overline{PCI}$ zones ($\overline{PCI} > 20.5$)	32	22 (7)	37 (12)	41 (13)
(b)				
Inland				
North	17	65 (11)	35 (6)	0 (0)
Centre	18	94 (17)	6 (1)	0 (0)
South	18	33 (6)	33 (6)	33 (6)
Coastal				
North	17	0 (0)	88 (15)	12 (2)
Centre	11	36 (4)	55 (6)	9 (1)
South	16	12 (2)	44 (7)	44 (7)

of stations) was located in areas characterized by lower $\overline{PCI}$ values. On the contrary, in areas with higher $\overline{PCI}$, negative trends dominated (41%) (Table VII(a)). Non-significant trends were common in areas with moderate rainfall concentration (64%).

The bivariate model defines a more complex pattern. A distinction can be made between coast and inland zones ($\Psi_{(1-2)}$). In these gradients, positive trends show a different spatial distribution when compared with null and negative stations, while negative and null stations overlap. Positive stations are mainly located in inland zones whereas negative and null trends are located in coastal areas.

Along the north–south gradient ($\Psi_{(3-4)}$), negative stations show a different spatial pattern when compared with positive or null trends, whereas positive and zero trends overlap. This bivariate distinction in spatial distribution of trends indicates that a more complex spatial pattern can be defined. Positive trends are dominating in inland zones, but their relative importance varies in the north–south direction. In the same way, zero and negative stations are dominant in coastal zones, but with differences in the north–south direction.

A detailed description of intraannual changes can be found in Table VII(b). The general pattern of positive trends in inland zones was especially true in central areas (94%), while in northern (65%) and southern (33%) areas, this dominance decreased. In coastal zones, a complex pattern could be observed. Dominance of zero and negative trends did not occur along the whole north–south gradient. Dominance of zero stations was particularly evident in northern areas (88%). The magnitude of these changes is shown in Figure 8(b).

3.2.4. Interannual variability of rainfall concentration (|APCI|). Trends in PCI variability (Figure 9(a)) seem to be distributed homogeneously across the region of Valencia. A predominance of zero trends, with local positive and negative ones, is the common pattern. No significant differences across the region (Table VIII) indicate that local factors are responsible for the significant changes found, and no areas with homogeneous trends can be defined (Table IX). The magnitude of the changes is shown in Figure 9(b). Monthly variability increased or decreased at rates ranging from 0.2 to −0.2%/year, but these values are only significant at local scales.

4. DISCUSSION

At a regional scale, negative and non-significant trends in annual rainfall seem to be occurring, associated with increased or unchanged monthly rainfall concentration. Thus, the decrease in rainfall totals found in some stations seems to be coupled with a gradually more heterogeneous monthly distribution of rainfall. The amplitude of annual rainfall anomalies appears to remain constant or to increase from 1961 to 1990, while no clear temporal pattern is observed in the amplitude of monthly concentration anomalies.

These results are in agreement with GCM predictions for western Mediterranean areas (Houghton *et al.*, 1996; Palutikof, 1996). However, local variations seem to be significant in this area. Using the

Table VIII. Absolute value of Precipitation Concentration Index (PCI) anomalies (|APCI|)

Pairwise comparison	Geographical model								Univariate model	
	Coast–inland				North–south				($\overline{PCI}$)	
	Ψ_1	P	Ψ_2	P	Ψ_3	P	Ψ_4	P	Ψ_{PCI}	P
+ versus *o*	0.42	0.729	0.37	0.775	0.66	0.480	1.07	0.268	1.11	0.252
+ versus −	1.02	0.580	2.73	0.158	3.44	0.104	3.77	0.083	0.43	0.918
o versus −	1.22	0.375	2.62	0.114	1.90	0.195	1.92	0.191	0.58	0.721

Spatial analysis of trends in univariate and geographical mode. For each gradient and pairwise comparison, the value of the Cramér–von Mises statistic and the level of significance are shown.

Figure 9. Observed trends in the absolute value of PCI anomalies. (a) Location of stations showing increasing (+), decreasing (−) and non-significant (●) trends (Spearman test, $p < 0.05$) are shown. Superimposed, smoothed distribution of Precipitation Concentration Index (PCI) in the region of Valencia over WMO normal period 1961–1990. (b) Annual rate of change of absolute value of PCI anomalies (|APCI|) through WMO normal period 1961–1990. Values expressed as annual percentage of change

precipitation series of Gibraltar and Tarifa (Southern Iberian Peninsula), Wheeler and Martín-Vide (1992) found a gradual decrease in rainfall amounts. In contrast, Piñol *et al.* (1998) found no significant trend in average precipitation for a similar period in Roquetes (east Spain). Rambal and Hoff (1998) found no significant trend in annual rainfall in Montpellier (south France) and a significant decline in annual precipitation in Seville (south Spain). Romero *et al.* (1998) also noted the spatial variability of annual rainfall in this area. These authors referred to a significant decrease in annual totals and changes in seasonal distribution in western and northern Andalucia and northern Catalonia, but they did not observe significant changes in areas mainly reliant on Mediterranean dynamics (the region of Valencia especially). This study indicates that spatial heterogeneity in rainfall trends in the region of Valencia may preclude the identification of a significant regional trend. At local scales, however, coherent areas with a common significant trend can be defined.

Spatial analysis applied to rainfall trends is a useful tool for identifying areas with similar rainfall evolution. Cramér–von Mises type tests offer a good approach for defining gradients or directions in which significant changes are occurring. Non-parametric tests for trend analysis offer a better approach to the study of rainfall evolution and the proposed test can be a good option for evaluating the spatial

Table IX. Trend direction for absolute value of Precipitation Concentration Index (PCI) anomalies (|APCI|) during the period 1961–1990 in the region of Valencia

Monthly |APCI|	Number of stations	% positives (*n*)	% null (*n*)	% negatives (*n*)
Whole region of Valencia	97	26 (25)	58 (56)	16 (16)

distribution of temporal trends. This study focuses on geographical and averaged rainfall gradients. Other gradients can be used for other purposes.

In the region of Valencia, a spatial pattern of rainfall trends has been found in areas with different rainfall-dependent problems, such as soil erosion, fire risk, desertification and floods. Decreases in rainfall amount and increases in rainfall variability are occurring in dry inland areas, where most forest and woodland areas are located (Generalitat Valenciana, 1996). Changes in rainfall, together with land-use changes, may be partly responsible for the decrease in fire return time and the increase in the surface area affected by wildfire in this region. In Spain, the annual area burned has increased by 600% from 1960 to 1990 (Prieto, 1993). In vast areas of the region of Valencia, wildfire return time is very short (Vallejo, 1997) and 600000 ha of a total of 900000 ha covered by forest and woodlands have been burned in the last 20 years (Generalitat Valenciana, 1996; Vallejo, 1997). In this context, wildfire and desertification processes seem to be fostered by a synergistic interaction between climate (Piñol *et al*., 1998; Rambal and Hoff, 1998; Stocks *et al*., 1998) and land-use changes (Moreno, 1998; Puigdefábregas and Mendizabal, 1998).

Rainfall concentration is another relevant factor affecting erosivity and desertification (González-Hidalgo, 1996). Stormy rainfall may promote sediment yield transport and, thus, it may strongly affect the sustainability of Mediterranean ecosystems, particularly if they are affected by other disturbances such as wildfires (Pérez-Trejo, 1992, 1994; Albaladejo, 1995; De Luís *et al*., 2000).

Our results show strong indications of increased rainfall concentration in inland areas with higher fire risk. A detailed study on trends in the seasonal distribution of rainfall is much needed to assess fully the potential effects of changes in rainfall pattern on ecosystem dynamics.

In the more humid and torrential rain areas (near Cabo de San Antonio), a significant decrease in rainfall amount associated with a significant increase in interannual variability was detected. This is one of the most densely populated areas in the region of Valencia, and tourist activities and intensive agriculture demand high quantities of water. Extremely heavy rainfall and floods are common features too. If rainfall trends are maintained in the future, they may adversely affect the availability of water resources and economic activities.

The significant increase of internal variability indicates that there is a greater contrast from year to year in annual rainfall values. It suggests that if the trend is not reversed, resources availability may become more unpredictable and drought and flood sequence may worsen.

The general pattern of decrease in annual rainfall amount and the increase in interannual variability is not observed in the more arid areas. These areas show great local variability and changes are locally dependent.

Empirical studies do not provide information on the causal factors of detected trends. In particular, from this study, it is not possible to establish whether the detected trends are the result of global warming (in which case it might expect to persist in the future) or of natural short-term variability. The agreement between the GCM predictions and the observed trends, however, might suggest that this trend could be linked to global warming. The authors are aware that a 30-year normal period is not enough to encompass fully any climatic variability signal. Therefore, the observed changes should be considered with caution.

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