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Local patterns and trends of the Standard Precipitation Index in southern Portugal (1940–1999)

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Abstract. This paper analyzes the yearly changes in precipitation from 1940 to 1999 on local and regional scales over the southern region of continental Portugal, which has large areas threatened by desertification. The Standard Precipitation Index (SPI) time series with the 12-month time scale is calculated for 43 meteorological stations. A geostatistical approach is used to evaluate the temporal dynamics of the spatial patterns of precipitation. The spatial homogeneity of the SPI is evaluated for each decade. Afterwards, a geostatistical simulation algorithm (direct sequential simulation) is used to produce 100 equiprobable maps of the SPI for each year. This gridded data set (6000 maps with 800 m $\times$ 800 m grid cells) is then used to produce yearly scenarios of the SPI from 1940 to 1999, and uncertainty evaluations of the produced scenarios. The linear trend of SPI values over the sixty years period is calculated at each grid cell of the scenarios' maps using a nonparametric estimator. Wilcoxon-Mann-Whitney one-sided tests are used to compare the local median of the SPI in 1940/1969 with its median in 1970/1999. Results show that moderate drought conditions occur frequently over the study region, except in the northwest coast. Severe drought frequency patterns are found in areas of the centre and southeast regions. A significant trend towards drying occurs in the centre region and in the northeast. Considering the amount of water consumption and irrigation already required in some municipalities, water shortage due to drought is a viable threat in most of the Alentejo region if those local trends persist.

1 Introduction

The spatial, seasonal and inter-annual variability of rainfall follows a complex pattern in Mediterranean regions, such as the south of Portugal. These areas are subject not only to droughts, but also to flooding and erosion phenomena caused by intensive rainfall. Extreme precipitation events such as these have been raising concern about the risks of land degradation and desertification (Lázaro et al., 2001; Costa et al., 2008). Furthermore, the susceptibility map of desertification of Portugal's National Action Programme to Combat Desertification shows that, under the mean climatic regime evaluated, the south of the country has extensive areas highly vulnerable to desertification (Rosário, 2004). Accordingly, research on the extent of dryness and space-time patterns of extreme precipitation is an important contribution to evaluate desertification dynamics in this region.

The Standard Precipitation Index (SPI) was proposed by McKee et al. (1993) to quantify precipitation deficits/surpluses on a variety of time scales (usually between 1-month and 24-month sums). Because of the fact that the SPI is normalized, wetter and drier climates can be represented in the same way, and wet periods can also be monitored using the SPI. Those time scales reflect different aspects of the hydrological cycle. Soil moisture conditions respond to precipitation anomalies on a relatively short scale (2–3 months), stream flow may be described by SPIs with time scales of 2–6 months, while ground water and reservoir storage reflect longer-term precipitation anomalies (Lloyd-Hughes and Saunders, 2002). Hence, the different time scales for which the index is computed address the various types of drought: the shorter seasons for agricultural and meteorological drought, the longer seasons for hydrological drought (Heim, 2000).

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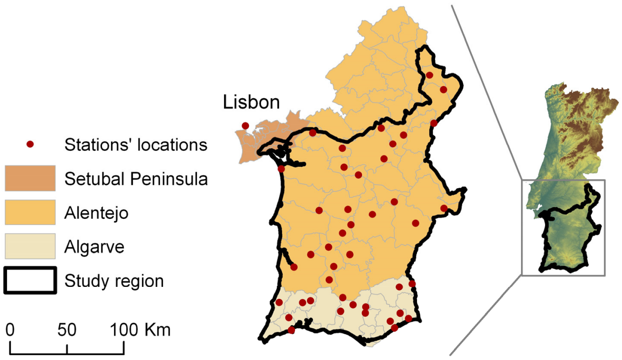

Fig. 1. Study region in the south of Portugal and meteorological stations' locations.

The SPI has been widely used for drought analysis in many countries/regions such as America (Logan et al., 2010), Africa (Ntale and Gan, 2003) and Europe (Lloyd-Hughes and Saunders, 2002; Vicente-Serrano, 2006). Advantages and weaknesses of the SPI are discussed by Lloyd-Hughes and Saunders (2002) and Logan et al. (2010). A few studies show the appropriateness of using the SPI to characterize droughts in Alentejo (Paulo et al., 2003; Paulo and Pereira, 2006), which is a region located in the central portion of the study domain (Fig. 1). Other studies analyzing the SPI in southern regions of Portugal focus on the stochastic properties of the time series for predicting drought class transitions using Markov chains and log-linear models in a few monitoring stations scattered over the region (Paulo et al., 2005; Moreira et al., 2006).

This study aims at analyzing yearly changes in SPI time series from 1940 to 1999 on local and regional scales over the southern region of continental Portugal. The 12-month SPI is calculated for 43 rainfall stations and a stochastic geostatistical approach is used to produce a set of equally probable yearly precipitation scenarios for the region. Changes in the spatial patterns of the SPI are analyzed, and uncertainty is assessed.

2 Data and methods

2.1 Study region and precipitation data

The study domain (Fig. 1) is defined by the southern river basins of continental Portugal, such as the Guadiana River that holds the largest Portuguese dam (Alqueva). In the northeast part it includes the Setúbal peninsula, the centre corresponds to the Alentejo region, and the southern region is named Algarve. The climate regime, typically Mediterranean, is characterized by a dry and very hot summer and a very irregular distribution of precipitation, both in time and space, with very intense flood peaks and frequent drought periods. The heaviest and most frequent extreme precipitation events occur in the Algarve region (Costa et al., 2008, Fragoso and Gomes, 2008). The Alentejo area is mainly an agro-silvo-pastoral region and the most affected by scarce precipitation, little runoff and water availability (Paulo et al., 2003; Santo et al., 2005).

Each of the 43 monitoring stations used (Fig. 1) has records of at least 30 years of daily precipitation amounts during the period from 1940 to 1999. Most of them were extracted from the National System of Water Resources Information (SNIRH – Sistema Nacional de Informação de Recursos Hídricos) database (http://snirh.inag.pt, access: January 2004), and three of them (Beja, Lisboa Geofísica and Tavira) were compiled from the European Climate Assessment (ECA) dataset (http://eca.knmi.nl, access: January 2004). Each station series data was previously quality controlled and comprehensively studied for homogeneity (Costa and Soares, 2009a, 2009b). Although the Lisboa Geofísica station is located outside the study region (Lisbon in Fig. 1), its data were also used in order to improve the SPI estimates over the northeast part of the study area.

2.2 SPI calculation

The SPI is computed by fitting a probability density function to the frequency distribution of precipitation summed over the desired time scale. This is performed separately for each period/month and for each location in space. Each probability density function is then transformed into the standardized normal distribution (z-distribution). In this study the SPI was calculated on the 12-month time scale (for the end of December) which reflects long-term precipitation patterns.

Lloyd-Hughes and Saunders (2002) describe in detail the calculation of SPI, which is outlined here. Those authors also tested the standardization procedure (probability transformation) assuming normal, log–normal, and gamma statistics for precipitation, and concluded that the gamma distribution provides the best model for describing monthly precipitation over most of Europe, especially at the 12-month scale. Similarly to Paulo et al. (2005) and Moreira et al. (2006), the two-parameter gamma distribution was used to compute the SPI for stations located in the south of continental Portugal. The probability density function is defined as

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \qquad \text{for } x > 0, \tag{1}$$

where $\alpha > 0$ and $\beta > 0$ are the shape and scale parameters, respectively, x is the amount of precipitation, and Γ is the gamma function. The α and β parameters of the gamma probability density function are estimated for each station, for each time scale of interest (12 months), and for each month of the year. The approximation of Thom (1958) for the maximum likelihood solution is used to optimally estimate α and β. The resulting parameters are then used to find the cumulative probability, denoted $G(x)$, of an observed precipitation event for the given month and time scale for the

Table 1. Classification scale for the SPI values and corresponding event probabilities (McKee et al., 1993; Lloyd-Hughes and Saunders, 2002).

Class	Description of state	SPI values	Probability (%)
1	Extreme drought	SPI ≤ -2	2.3
2	Severe drought	$-2 <$ SPI $\leq -1{,}5$	4.4
3	Moderate drought	$-1.5 <$ SPI ≤ -1	9.2
4	Near normal	$-1 <$ SPI <1	68.2
5	Moderately wet	$1 \leq$ SPI <1.5	9.2
6	Severely wet	$1.5 \leq$ SPI <2	4.4
7	Extremely wet	SPI ≥ 2	2.3

Table 2. Parameters of the exponential variogram models for the 12-month SPI, by decade.

Decade	a–Range (km)	C–Sill
1940/49	75	0.3475
1950/59	75	0.3231
1960/69	75	0.2505
1970/79	75	0.2191
1980/89	75	0.2369
1990/99	75	0.2418

station in question. Since the gamma distribution is undefined at $x=0$, and the precipitation distribution may contain zeros within the time scale considered, the cumulative probability becomes:

$$H(x)=1+(1-q)G(x) \tag{2}$$

where q is the probability of zero precipitation. The cumulative probability distribution $H(x)$ is then transformed into the standard normal distribution to generate the SPI values. Positive SPI values reflect wet conditions while negative values indicate a drier climate. State definitions are given in Table 1.

In this study, the SPI time series were computed using the program files from the National Drought Mitigation Center (http://www.drought.unl.edu/monitor/, access: 27 October 2009).

2.3 Geostatistical simulation

Geostatistical conditional simulation methods generate a set of equiprobable realizations of the spatial distribution of an attribute, conditional to the observed data, which allow the characterization of the space-time uncertainty of the physical phenomena. The Direct Sequential Simulation (DSS) algorithm proposed by Soares (2001) reproduces both the spatial covariance structure and the histogram of the original variable. Durão et al. (2009, 2010) analyzed the spatial and temporal patterns of extreme precipitation indices in southern regions of Portugal using DSS, while Costa et al. (2008, 2010) used direct sequential cosimulation (coDSS) to map a flood indicator and the extreme precipitation frequency in southern Portugal using elevation as auxiliary information. The geostatistical simulation approach used in this study is similar to that of Durão et al. (2010). However, instead of treating time as an additional dimension of the 2D space domain, the DSS algorithm was applied to each year without considering the previous years' values. Otherwise, it would misrepresent the SPI values meaning: the 12-month SPI provides a comparison of the precipitation for 12 consecutive months with the same 12 consecutive months for all the years included in the historical record. The geostatistical procedures used can be summarized as follows.

Let $z(u_\alpha,\, t_i)$: $\alpha=1,\ldots,\, n$; $i=1,\ldots,\, T$ be the set of SPI values measured at n locations u_α and in t_i time instants (years). The n monitoring stations do not have to be all informed at the same T time instants (i.e., a number of values can be missing). This data set corresponds to realizations of a spatiotemporal random variable $Z(u,t)$ that can take a series of values at any location in space u and instant in time t according to a probability distribution. The DSS algorithm was applied in order to obtain a set of $m=100$ equally probable realizations of $Z(u,t)$ at all 800 m $\times$ 800 m grid cells of each instant in time t_i $(T=60)$:

$$z^s(u_\alpha,t_i): s=1,\ldots,m; \alpha=1,\ldots,N; i=1,\ldots,T \tag{3}$$

where $N=74683$ is the total number of grid nodes to be simulated for each year from 1940 to 1999.

Costa et al. (2008) suggested that a different space-time semivariogram model should be used for each decade in order to account for possible long-term trends, or fluctuations, in precipitation. In fact, based on the spatial range parameter of the semivariogram models, Costa et al. (2008, 2010) and Durão et al. (2009, 2010) concluded that the spatial patterns of extreme precipitation became more homogenous over the last decades of the twentieth century in the south of Portugal. Hence, in this study, the DSS algorithm also used a different exponential semivariogram model for each decade. The exponential model $\gamma(h)$ approaches the sill (C) asymptotically, with a representing the practical range (distance at which the semivariance reaches 95% of the sill value):

$$\gamma(h)=C\left(1-e^{(-3h/a)}\right),\ h\neq 0. \tag{4}$$

The spatial variability was assumed identical in all directions (i.e. isotropic) within each decade. However, unlike those previous studies, the spatial decorrelation distance (i.e. the spatial range parameter) of the SPI values was found to be equal to 75 km throughout the decades (Table 2).

The space-time scenario for a given year t_0 corresponds to the average of the local histograms that were computed for all grid cells u_α:

$$z^M(u_\alpha, t_0) = \frac{1}{m}\sum_{s=1}^{m} z^s(u_\alpha, t_0)\ , \alpha = 1, ..., N. \tag{5}$$

Similarly, the uncertainty of the space-time scenario for a given year t_0 was evaluated by the standard deviation, the variance and the coefficient of variation of the local histograms.

2.4 Trend assessment

The nonparametric estimator of the slope proposed by Sen (1968), and based on the Kendall's rank correlation, has been widely used to compute linear trends in hydrometeorological series (e.g., de Lima et al., 2010). The yearly trend map corresponds to the Sen's slope estimates computed at each grid cell u_α:

$$b(u_\alpha) = \text{Median}\left[\frac{z^M(u_\alpha, t_j) - z^M(u_\alpha, t_i)}{(t_j - t_i)}\right], \tag{6}$$
$$\forall t_i < t_j\ , \alpha = 1, ..., N$$

where $z^M(u_\alpha, t_j)$ and $z^M(u_\alpha, t_i)$ are data points of the space-time scenario (Eq. 5) measured at years t_j and t_i, respectively.

To assess local changes in precipitation patterns, Wilcoxon-Mann-Whitney one-sided tests were applied to the SPI values, at each grid cell, to compare the median of the SPI values in 1940/1969 with their median in 1970/1999. The p-values of each test were estimated using Monte Carlo simulations with 10 000 samples. This nonparametric test was preferred over the usual t-test because of the small sample sizes of each sub-period.

3 Results and discussion

For illustration purposes, two scenarios of the SPI are shown in Fig. 2, as well as their spatial uncertainty measured by the standard deviation (STD). Negative values of the SPI indicate higher dryness (Table 1). The scenarios show that the inland areas and the southeast region are affected by drought in many years. The extreme drought episodes of 1948/49 and 1980/81 that affected Portugal's territory (Trigo and DaCamara, 2000) were also captured by the SPI scenarios. Moderate drought conditions occur more frequently over the study region, except in the northwest coast.

As expected, regions where the SPI shows greater spatial variability correspond to regions less densely sampled. Only a few stations are located at medium (>400 m) and high elevations, thus greater uncertainty would be expected at those regions. However, the spatial variability in the mountainous regions of the south is often small, because the SPI is not

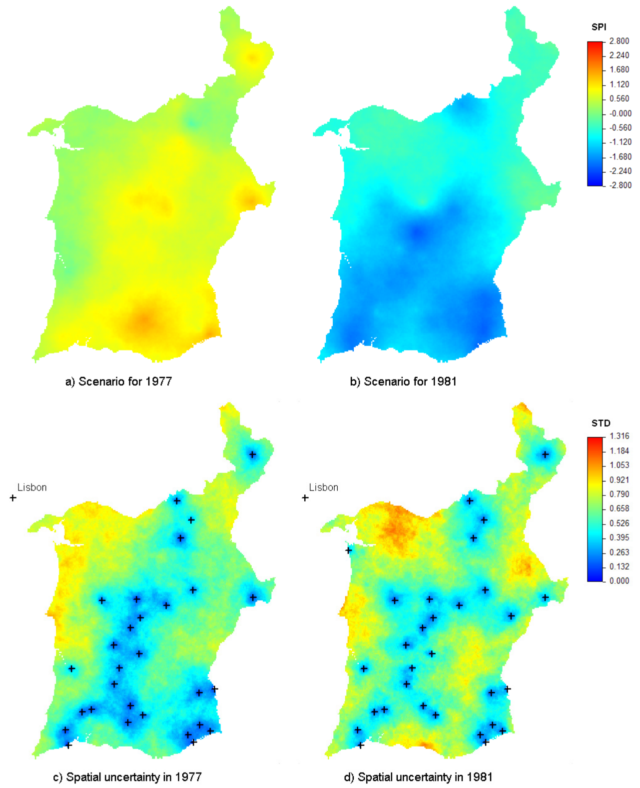

Fig. 2. Scenarios for the 12-month SPI and their corresponding spatial uncertainty measured by the standard-deviation in 1977 (left), and 1981 (right).

affected adversely by topography (Lloyd-Hughes and Saunders, 2002).

Nonparametric estimates of the SPI trend slope were computed at each grid cell of the 1940–1999 space-time scenarios. The local trend map (Fig. 3) shows a pattern of negative trend signals over most of the study region, which indicates an increasing trend in dry conditions through time. The local trend magnitude is especially high in the centre of the region (Odemira, Aljustrel and Castro-Verde municipalities) and in the northeast within the region analyzed. These results may be considered consistent with those of Costa and Soares (2009a) for the Aridity Intensity Index (AII), which is a numerical indicator of the degree of dryness of the climate at a given location. These authors verified that the AII had significant trends towards drier climatic conditions in many stations located in the south of Portugal during the 1955–1999 period. Mourato et al. (2010) also found an increase of dry years in the northeast area and a decrease in wet years with the consequent increase of normal years in the southeast sector of Alentejo, during the period 1931–2006, as a result of changes in the precipitation regimes. Furthermore, Moreira et al. (2006) analyzed 12-month SPI drought class transitions using log-linear models and verified that there were significant differences when comparing the 1955/56 to 1976/77

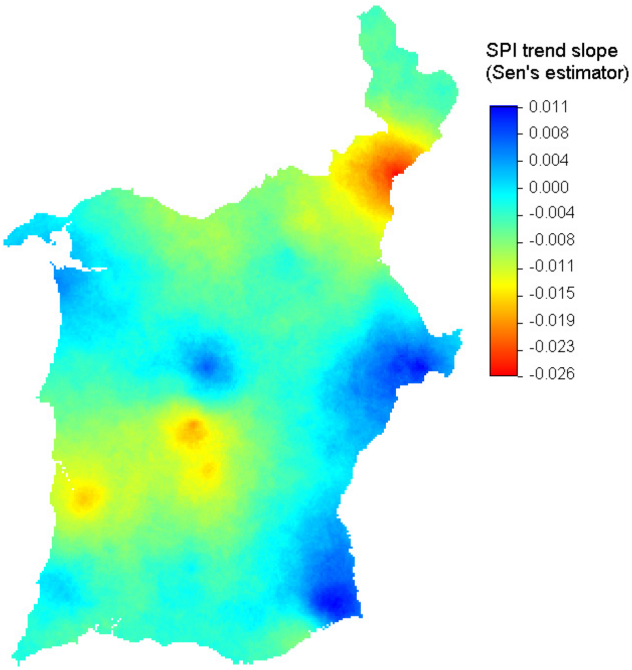

Fig. 3. Local trends in the 12-month SPI.

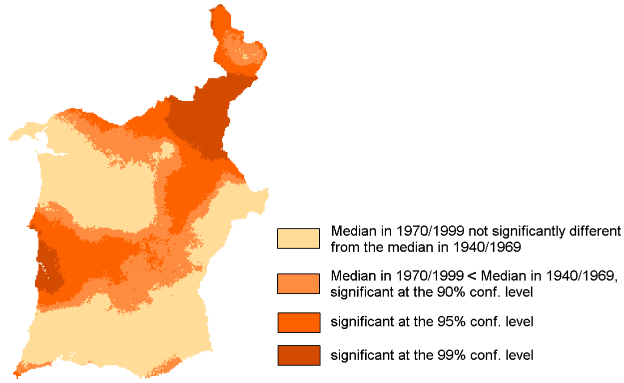

Fig. 4. Wilcoxon-Mann-Whitney tests results for the 12-month SPI.

period with the last period of 1977/78 to 1998/99. If only these two periods were compared, one could conclude that drought frequency and severity were aggravating in the Alentejo region. However, looking at the whole study period from September 1932 to September 1999, the results of Moreira et al. (2006) indicate that the last period may correspond to a cycle that could be related to a long-term natural variability.

Similarly, the Wilcoxon-Mann-Whitney tests (Fig. 4) indicate a significant increase in dryness and drought conditions in most of the Alentejo region when comparing the first thirty years of SPI data (1940–1969 period) with the data from the last thirty years of the twentieth century (1970–1999 period). These results are also consistent with the local trend map (Fig. 3) as changes in the SPI median are statistically significant in the centre of the region and in the northeast area. The local trend map (Fig. 3) also shows a trend towards wetter conditions in a few areas, particularly in the west of the Alentejo region. However, this local trend may not be significant because the SPI median in 1970–1999 is not significantly greater than the SPI median in 1940–1969 in the whole study region (Fig. 4). Additionally, if a non-linear trend occurred at those locations, the nonparametric trend estimator may have not significantly captured the trend signal.

4 Conclusions

This study evaluates spatial and temporal dynamics in precipitation in southern Portugal, from 1940 to 1999, through the analysis of local patterns in the Standard Precipitation Index. The SPI has been computed for the 12-month time scale, which mainly addresses hydrological droughts (Heim, 2000; Lloyd-Hughes and Saunders, 2002). The hydrological component of droughts is very important given the high dependence of many socio-economic activities on surface water resources (e.g., agriculture, hydropower generation, and domestic supply).

The increasing precipitation trend found in the west, along the Guadiana river, may not be significant. The Guadiana supplies the Alqueva reservoir and irrigation water for much of the western region, but recent studies project decreases in the Guadiana stream flow (Kilsby et al., 2007). Hence, it is unclear if that trend signifies an increase in water availability. On the other hand, results show that a significant trend towards drying occurs in most of the Alentejo region, particularly in the centre and in the northeast. Hence it is very important for water resources and agriculture management to propose adaptation and mitigation measures if these local trends become persistent.

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