P3.2 DROUGHT IDENTIFICATION AND DROUGHT INDICES USING ERA-40 REANALYSIS DATA

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1. INTRODUCTION

Drought is a recurring phenomenon that has affected civilization throughout history. It affects natural habitats, ecosystems, and many economic and social sectors. The wide range of economics sectors on which drought has an impact make its effects difficult to quantify. Some numerical standard is needed for comparing measures of drought from region to region, as well as for comparing past drought events. Because of the complexity of drought, no single index has been able to adequately capture the intensity and severity of drought and its potential impacts (Heim, 2002).

Several authors recently used soil moisture as an indicator of weather extremes, namely droughts (Lakshmi *et al.,* 2004; Andreadis *et al.* 2005). To diagnose soil moisture, the European Centre Medium-Range Weather Forecasts reanalysis ERA-40 (Uppala *et al.*, 2005) precipitation, downwelling radiation and near-surface meteorology were used to force the land-surface model TESSEL (Hurk *et al.*, 2000) for the period 1958-2001. Soil moisture output is used for drought identification and to create a drought index. A verification of the concept is performed over the Iberian Peninsula, where the derived drought index is compared to other indices in use for agricultural and hydrological purposes, such as the standardized precipitation index (SPI) (Mckee *et al.*, 1993) and the Palmer drought severity index (PDSI) (Palmer, 1965).

2. METHODS

The use of ERA-40 soil moisture analysis values for drought applications is limited by the systematic attenuation of the seasonal cycle and damping of interannual variability (Viterbo and Betts, 1999; Ferranti and Viterbo, 2006); this can be primarily attributed to the soil moisture analysis increments (Mahfouf *et al.*, 2000; Uppala *et al.*, 2005); For these reasons, we have used the ERA-40 land-surface model in offline mode.

Precipitation is the primary factor controlling the formation and the persistence of drought conditions (Lloyd-Hughes and Saunders, 2002), requiring an evaluation of ERA-40 precipitation with observations. The general evaluation of ERA-40 precipitation is described by Uppala *et al.*(2005) and references therein, but the performance over the Iberian Peninsula is not documented.

Delworth and Manabe (1988; 1993) using a general circulation model for the climatic system, proposed that the temporal evolution of soil moisture could be described as a first order Markov process. Vinnikov *et al. (*1996) showed that the temporal evolution of soil moisture can be represented by a combination of a first-order Markov process with white noise. An approximation for the empirically estimated autocorrelation functions is presented by Vinnikov *et al. (*1996):

$$r(t)=\begin{Bmatrix} 1 & \text{if } t=0 \\ r_0 \exp\left(-\dfrac{t}{T}\right) & \text{if } t\neq 0 \end{Bmatrix}, \qquad (1)$$

where t is the temporal lag, T is the temporal scale of autocorrelation for soil moisture, representing the decay time scale in the absence of precipitation forcing. The parameters r_0 and T can be estimated from the empirical autocorrelation function. The decay time scales of soil moisture were used to identify zones over Iberia susceptible to long periods of drought. In addition, drought spatial patterns over Iberia were studied with principal components analysis.

Soil moisture output, from TESSEL in offline mode, is used for drought identification and to create a drought index. The normalized total depth soil moisture (NSM) is simply the difference of soil moisture from the mean for a specified time period divided by the standard deviation, where the mean and standard deviation are determined from the entire record. Considering $\theta_{i,j}$ the total depth soil moisture in a determined point for month i and year j, with $i=1,...,12$ and $j=1,...,n$ – where n is number of years in the record – the normalized total depth soil moisture $\chi_{i,j}$ is calculated by:

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$$\chi_{i,j} = \frac{\theta_{i,j} - \bar{\theta}_i}{s_i}$$
$$\bar{\theta}_i = \frac{1}{n}\sum_{j=1}^{n}\theta_{i,j} \qquad (2)$$
$$s_i = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(\theta_{i,j} - \theta_i\right)^2}$$

where $\bar{\theta}_i$ and $\bar{s}_i$ correspond to the monthly mean and standard deviation, respectively.

3. RESULTS

The correlation between NSM and SPI was used to compare the coherency between precipitation and soil moisture temporal evolution. SPI was evaluated for time scales of 1, 3, 6 and 12 months using ERA-40 precipitation. Figure 1 represents the monthly maximum correlation between NSM (from ERA-40 and offline simulations) and SPI, averaged over Iberia. The temporal evolution of soil moisture, in the offline model, shows a good agreement with precipitation, unlike ERA-40 soil moisture that presents an annual cycle and lower values for the correlation. The poor correlation of ERA-40 NSM with SPI, especially during summer, results from the analysis increments in soil moisture used during the reanalysis (Mahfouf *et al.*, 2000).

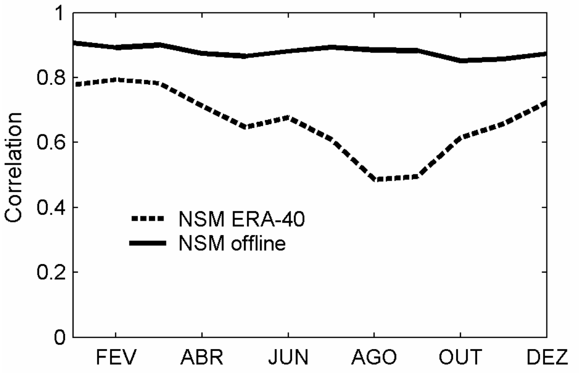

Fig. 1. Maximum monthly correlation between SPI at time scales of 1, 3, 6 and 12 months and NSM averaged over Iberia. Solid line, correlation with offline model NSM; dashed line, correlation with ERA-40 NSM.

Figure 2 displays the comparison between ERA-40 monthly precipitation and observations in the centre and South of Portugal between 1958 and 2001. The scatter plot shows a systematic sub-estimation in the order of 30%, which is reinforced by the mean annual cycle. Despite a dry bias in the rainy season, ERA-40 monthly precipitation explained variance is of the order of 90% (correlation between observations and ERA-40 is about 0.9), and the 1, 3, 6 and 12 months SPI are very similar to those from observations (correlations between SPI calculated from observations and ERA-40 monthly precipitation vary between 0.82 and 0.88 for time scales of 1, 3, 6 and 12 months).

NSM was compared with SPI, at several time scales (calculated from monthly observed precipitation), and with PDSI (from Dai *et al.*, 2004) for the ERA-40 period in the centre and South of Portugal. The correlation between NSM and SPI is highest for 12 months time scale and about 0.8; and the correlation between NSM and PDSI is about 0.8. In figure 3 are represented times series of NSM, SPI-12 and PDSI for South of Portugal. The three indices showed are in agreement for the 44-year period, and the drought periods indicated are in conformity with the historical records for South of Portugal. The high degree of coherency between the three indices for the 44-year period studied is an indication that NSM can be used as a robust drought indicator.

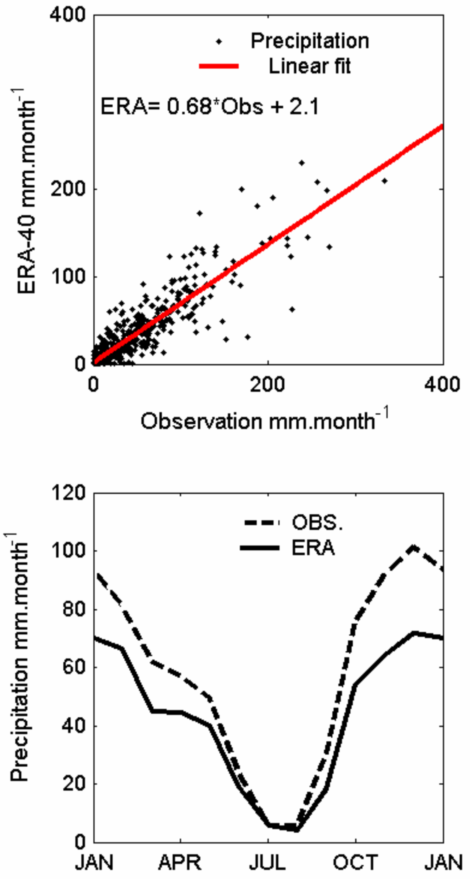

Fig. 2. Aggregated observed monthly precipitation versus ERA-40 montlhy precipitation in the nearest point and linear fit (top); mean annual cycle of monthly precipitation for observations and ERA-40 (bottom). The data represents the centre and South of Portugal between 1958 and 2001 (21 stations and 6 ERA-40 grid points).

To identify the characteristic time scales of soil moisture, the NSM was correlated with SPI at several time scales; the maximum value was retained and represented in figure 4. All the values of correlation are greater than 0.7, and we observe a spatial distribution of the characteristic time scales with lower values in the northeast increasing to southwest.

Figure 5 presents the decay times of NSM calculated by eq (1). The values vary between 1 and 20 months and have a similar spatial distribution when compared with figure 4. In northeast Iberia, where precipitation is abundant throughout the year, decay times are reduced, corresponding to soil moisture anomalies quickly attenuated, and shorter drought periods. In contrast, in southwest Iberia the characteristic soil moisture decay times reach values of 20 months. This result emphasizes the importance of precipitation in modelling the drought, since scattered and reduced precipitation leads to slower recovery from a drought event.

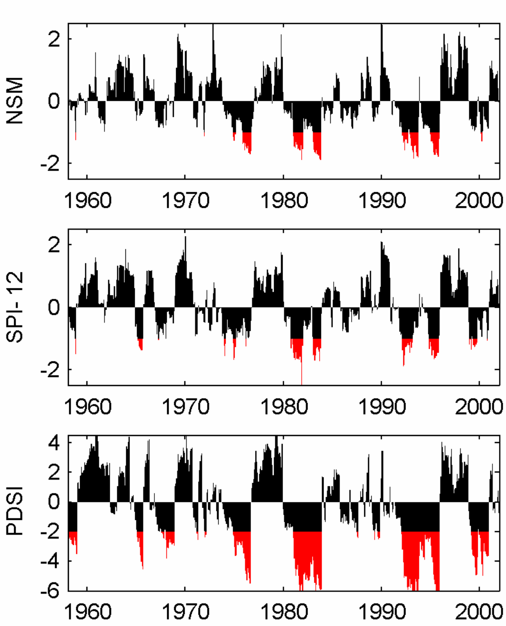

Fig. 3. Temporal series of NSM (top), SPI at 12 months time scale (middle) and PDSI (bottom), representing south Portugal. NSM is the mean over 4 ERA-40 grid points; SPI-12 was calculated using observed precipitation in 16 stations; and PDSI was taken from Dai *et al.*, 2004, one grid point. Red zones indicate values inferior to -1 for NSM and SPI-12 and -2 for PDSI.

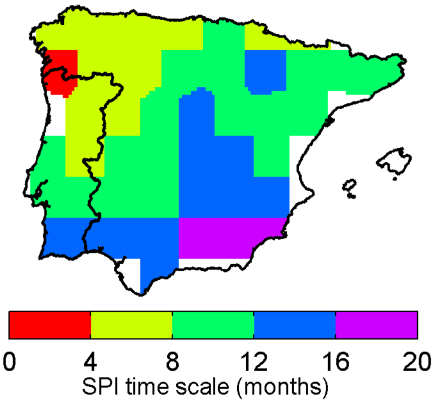

Fig. 4 SPI time scale for which the correlation with NSM is maximum.

Principal component analysis of NSM was used to identify the spatial patterns of drought over Iberia. The empirical orthogonal functions (EOFs) were rotated using the Varimax (Kaiser, 1958) criterion, an approach common in climatological works (Richman, 1986; White *et al.*, 1991). Vicente-Serrano (2006) used the same method to analyse spatial patterns of drought over Iberia using SPI as drought index. After the rotation, the first 4 EOFs explained 86.2% of the total variance. The spatial classifications were based on the general patterns returned by the EOFs, by aggregating the grid points through a maximum factor loadings criterion. Figure 6 represents the 4 zones over Iberia where the first 4 EOFs have maximum loadings. This analysis allows the treatment of each zone separately using the corresponding principal component (PC), and also has the advantage that each PC is uncorrelated with the others. The spatial patterns are related with the typical decay times of NSM, and highlight the need for a regional analysis of drought events.

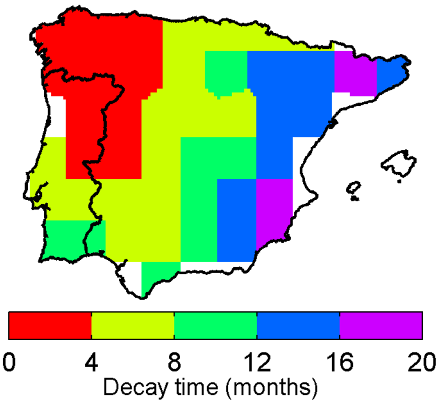

Fig. 5 – NSM decay times as given in eq (1) for the temporal autocorrelation.

4. DISCUSSION

Since precipitation is the major drought atmospheric forcing, a validation of ERA-40 precipitation fields against observations was conducted over the centre and South of Portugal. Despite a dry bias in the rainy season, ERA-40 monthly precipitation explained variance is of the order of 90%, and the 1, 3, 6 and 12-months SPI are very similar to those from observations.

Normalized total depth soil moisture is used as a drought index and compared with the SPI, at several time scales, and the PDSI. The high degree of coherency between the three indices

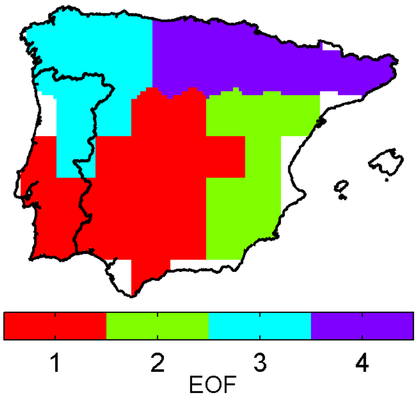

Fig. 6 – Division of Iberia according to the loadings of the rotated EOFs of NSM.

for the 44-year period studied is an indication that NSM can be used as a robust drought indicator. Besides the identification of major drought periods and their intensity, soil moisture was applied to the study of drought spatial and temporal patterns over Iberia. The temporal evolution of soil moisture is related to the accumulated precipitation at various time scales, demonstrated with the correlations of NSM and SPI. PDSI and NSM are related since both indexes are associated with the surface hydrological budget. Soil moisture relaxation times were used to identify areas with longer drought periods (due to scarcer annual precipitation values) where NSM is related to SPI at longer time scales. Drought spatial patterns over Iberia were established from principal components analysis. The spatial heterogeneity of precipitation is the main issue in the spatial analysis of drought.

The approach to drought analysis used here can be applied to other areas with realistic time variability of ERA-40 precipitation, with no particular model calibration. Forcing from a future near-real time continuation of ERA-40 could be used as a tool in the monitoring of drought situations. Robust early identification of an impending drought could be used to support drought mitigation actions.

Acknowledgements. This research was funded by FCT under Grant VAST(POCTI/CTA/46573 /2002), co-financed by the EU under Program FEDER.

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