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# Assessing drought cycles in SPI time series using a Fourier analysis

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## Assessing drought cycles using Fourier analysis

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Abstract

In this study, drought in Portugal was assessed using 74 time series of Standardized Precipitation Index (SPI) with a 12 month time scale and 66 years length. A clustering analysis on the SPI Principal Components loadings was performed in order to find regions where SPI drought characteristics are similar. A Fourier analysis was then applied to the SPI time series included in each cluster to investigate the existence of cycles that could represent the return periods of droughts. The most frequent and significant cycles that compound the time series in each of the three clusters were therefore identified and analysed. Results show that droughts periodicities vary among the three clusters identified. The results point to a cycle with 6 years return period of droughts occurrence across the country and a cycle with 9.4 years period of droughts with very high presence in central and southern Portugal. Both these cycles are likely showing influences of the North Atlantic Oscillation on the occurrence and severity of droughts in Portugal.

## 1 Introduction

The cyclicity of climatic and earth surface processes such as precipitation, streamflow and droughts is object of a variety of studies aimed at better understanding their variability. Some of these studies refer to the reconstruction of past climate series or with the analysis of past drought information. This is the case of a study that used reconstructed drought time series from historical data (1502–1899) relative to the south-eastern Mexico, which found cycles of several periodicities likely related with the El Niño Southern Oscillation (ENSO) and solar activity (Mendoza et al., 2006). This is also the case of another study that, using historical data of Sicily from 1565 to 1915, identified several periodicities of drought events, some of them likely connected to solar cycles (Piervitali and Colacino, 2001). However, most of studies refer to recent time series of precipitation, streamflow and drought indices.

## Assessing drought cycles using Fourier analysis

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Assessing drought cycles using Fourier analysis

E. Moreira et al.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



Research used to find cyclicity of processes adopts a variety of methods including various approaches to the Fourier analysis (Rodrigo et al., 2000; Yadava and Ramesh, 2007) also called spectral analysis (Bordi et al., 2004a, b; Mitra et al., 2006; Telesca et al., 2012) and another approach, the wavelet transform analysis (Labat, 2006; Prokoph, 2012; Li et al., 2013). Research generally aims at finding a better explanation of time and space variability of the processes and relating the detected cycles with the periodicity of sea surface temperature, the solar cycles or teleconnection patterns.

Studies with annual or monsoon precipitation data series often identified cycles of around 11 years which were related with solar activity cycles (Mazzarella and Palumbo, 1992; Mitra et al., 2006; Yadara and Ramesh, 2007; Chattopadhyay and Chattopadhyay, 2011). Studies on solar cycles are reported by Tsiropoula (2003) and Hathaway (2010). The cycle of solar activity is characterized by the rise and fall in the number and surface area of sunspots ranging between 9 and 13 years and averaging 11 years (Hathaway, 2010). Studies on streamflow periodicity could also be related to solar cycles (Prokoph et al., 2012). A streamflow periodicity study has shown interannual 4 to 5 y, 14 y and multidecadal 25 and 50 y oscillations for Europe (Labat, 2006). The influence of North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) was considered specially taking into consideration the study by Lucero and Rodriguez (2002) showing that the European rainfall variability exhibits a 20 to 22 year NAO related bidecadal component of NAO. Gámiz-Fortis et al. (2011) studied streamflow variability in the Ebro basin and found that respective oscillation have different periodicity among the sub-regions considered.

Rodríguez-Puebla et al. (1999) used 50 years series of 3 month cumulated precipitation in the Iberian Peninsula and applied Principal Components Analysis (PCA). They detected that NAO was the major source of interannual variability in winter precipitation and observed that the time series of precipitation and the NAO had a common peak at about 8 years while showing a significant coherence. An analysis of rainfall variability on decadal and centennial scales relative to southern Spain found an alternation

## Assessing drought cycles using Fourier analysis

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



of wet and dry periods, with various decades of duration (Rodrigo et al., 2000). This study also reported various periodicities in data series that allowed authors to identify NAO among the most possible causal mechanisms in the region. The precipitation variability study by Lucero and Rodriguez (2002) has shown both decadal and bidecadal oscillations averaging respectively 12 years and 20 to 22 years. A main conclusion of the study is that “the first principal component of the transformed bidecadal component of annual rainfall anomalies attains its positive (negative) peak about 3 years before the bidecadal component of NAO reaches its negative (positive) peak” (Lucero and Rodriguez, 2002). Various studies later demonstrated the influence of NAO on precipitation and droughts (e.g., Trigo et al., 2004; Pires and Perdigão, 2007; Bierkens and Van Beek, 2009; Sousa et al., 2011).

Bordi et al. (2004a) using PCA applied to SPI-24 for the Elba basin and Sicily found significant peaks for periodicities of 9.6 year for Sicily and 12.0–9.6 year for Elbe basin. However, significant relations with NAO or ENSO were not found. In addition, other relevant peaks were close to the 11 year solar cycle. Telesca et al., 2012 used the SPI with various time scales of 1 up to 48 months, and applied a spectral analysis to each of local time series in the Ebro basin, Spain. For the SPI-12, 24 the 3.1 year, 4.1 year, the 5.3 year, the 8.8 year and the 17.6 year cycles are common to most locations. The 3–5 years band was considered as related to NAO (Telesca et al., 2012).

Bordi et al. (2004b) characterized droughts with SPI-24 and studied their variability with PCA in Eastern China. The application of a spectral analysis to a principal component led to detect peaks characterizing the interdecadal, decadal, and interannual variability. A broad band peak was found for the interannual time scale of 4.0–3.7 years suggesting a link with ENSO. The other peaks lie near 6.9–8 up to 16 years and near 24 years. The precipitation study by Liang et al. (2011) applied to NW China identified significant periods of 2.3 and 3.3 years on a regional scale, which authors related with ENSO. Liu et al. (2013) used the PDSI for studying the variability of dryness/wetness conditions across Qinghai Province, Northwest China and detected a 3–5 year significant periodical oscillation in the PDSI series of the source region of the Yangtze

## Assessing drought cycles using Fourier analysis

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



River and 5–7 year and 8–10 year periods in Qaidam Basin. Thus they observed that the periodicity of PDSI series varied spatially throughout the Qinghai Province. Tong et al. (2006) also observed that the ENSO changes and wetness/dryness variation were significantly correlated at 5.04 year and 10–12 years periods. Li et al. (2013) used clustering to define drought sub-regions with SPI and observed also that distinctive temporal evolution patterns of droughts occurred for each sub-region. The cycles varied from 2–3 years to 5–7 years.

The various studies reported above show that cyclicity is found for precipitation, streamflow and droughts, different methodological approaches lead to coherent results, cycles relate well with those of NAO, AO and ENSO as well as with solar cycles, and that detected cyclicity varies among sub-regions when PCA and cluster analysis identify those inside the region under study.

Results of a former study with loglinear models applied to droughts in southern Portugal have shown the existence of a long-term periodicity that could reflect the natural variability of the climate (Moreira et al., 2006). These long-term periodicity was expressed by the alternation between long periods with high and low frequency of severe and extreme droughts. A recent study using ANOVA-like inference coupled with loglinear models applied to 10 long series across Portugal also suggested a cyclic behaviour of droughts with periodicity ranging from 26 to 30 years, mostly for the sites in central and southern Portugal (Moreira et al., 2012). These studies suggested the interest in using the Fourier analysis to detect the various cycles that contribute to the variability of droughts. Moreover, since that cyclicity changes from a region to another, we also considered the use of PCA and cluster analysis to identify possible regions within the country (Bordi et al., 2004a, b, 2006; Raziei et al., 2009; Santos et al., 2010; Telesca et al., 2012). Recently, Martins et al. (2012) used PCA applied to the SPI with 12 months time scale (SPI-12) to draw the spatial patterns of precipitation and drought in Portugal. This approach could then be combined with the Fourier analysis and verify if the cycles would change with the considered region. The Fourier analysis, also called spectral analysis, uses the Fourier decomposition of time series and the periodogram

device (Pollock, 1999; Bloomfield, 2000) with the aim of find cycles within a given series. As referred before, various applications in hydrology and climatology studies are reported.

Considering the review presented before and previous studies also referred above, assuming that conjugating the techniques of Fourier analysis applied to the SPI-12 time series with the cluster analysis applied to the PCA loadings of SPI-12, the objectives of this study are to assess the cyclic behaviour of droughts throughout Portugal, to detect the most representative cycles in each region and to identify the possibly related driving forces that determine the periods characterizing the detected cycles. Although similar approaches were applied by Santos et al. (2010) and Telesca at al. (2013), in our approach the Fourier analysis is applied individually to each SPI-12 time series and an analysis of frequency on the significant cycles found inside each region is performed in the following. Furthermore, a correspondence is searched between the minima of the sinusoidal functions and the moderate, severe and extreme drought events.

## 2 Data, SPI and clustering

The data consists of monthly precipitation time series from 1941 to 2006 (66 years) of 74 sites across Portugal (Fig. 1). Data quality was assessed using the Kendall autocorrelation test, the Mann–Kendall trend test and the homogeneity tests of Mann–Whitney for the mean and the variance (Helsel and Hirsch, 1984). To estimate missing values of monthly precipitation, maintenance of variance extension techniques were applied (Hirsch, 1992; Vogel and Stedinger, 1985). Precipitation based drought indices are the first indicators of droughts, since hydrological droughts may emerge several months after a meteorological drought has been initiated (Wilhite and Buchanan-Smith, 2005). The Standardized Precipitation Index, SPI (McKee et al., 1993, 1995), which is often used for identification of drought events and to evaluate their severity through well-defined drought classes, is adopted in this study following results obtained in previous

## Assessing drought cycles using Fourier analysis

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



studies characterizing droughts in Portugal (Paulo and Pereira, 2006; Santos et al., 2010; Martins et al., 2012).

The SPI is widely used because it is standardized and therefore allows a reliable comparison between different locations and climates (Mishra and Singh, 2010). It may be computed on shorter or longer time scales, which reflect different lags in the response of the water cycle to precipitation anomalies (Steinemann et al., 2005). In addition, due to its standardization, its range of variation is independent of the aggregation time scale of reference, as well as on the particular location and climate. The 12 month time scale, as well as larger time scales, identifies anomalous dry and wet periods of relatively long duration and relates well with impacts of drought on the hydrologic regimes and water resources of a region (Vicente-Serrano, 2006), or to effects of fluctuation in rainfall over short intervals (Mishra and Singh, 2010).

Shorter time scales of less than 6 months are more useful to detect agricultural droughts and longer ones, > 24 months, may be useful to consider impacts on groundwater resources. For the Portuguese conditions, where a dry summer period of near 6 months occurs, droughts impacting the hydrologic regime are better assessed when using the 12 month time scale (Paulo and Pereira, 2006; Santos et al., 2010). Hence, former studies on drought variability and drought class transitions were performed with the SPI 12 month (Moreira et al., 2006, 2012; Martins et al., 2012). Therefore, time series of SPI with a 12 month time scale (SPI-12) were computed from the 74 monthly precipitation time series. The respective monthly drought classes were then computed based on Table 1. Since the inter-annual variability is well studied in the referred references and is not the focus of this analysis, only the December values of the SPI-12 time series were used for the application of the Fourier analysis. The December values contain the information for the entire year as it includes the sum of the precedent 12 months of the year.

In order to identify regions with the same spatial and temporal patterns of droughts, a Principal Component Analysis (PCA) on the SPI-12 was performed and followed by a K-Means clustering of the PC loadings provided by the PCA. The adoption of PCA

## Assessing drought cycles using Fourier analysis

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Assessing drought cycles using Fourier analysis

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



and cluster analysis is justified by the need of taking into consideration the spatial variability of the periodicity that droughts may assume. The PCA is a method commonly used in studies of climate and is often applied to drought indices and precipitation to identify their patterns (Bordi et al., 2004a, b, 2006; Raziei et al., 2009; Santos et al., 2010). This method allows reducing the original dimensionality of the data through forming new uncorrelated variables that are linear combinations of the original ones and explain a large portion of the total variance (Sharma, 1996). Here, the PCA was applied in the S-mode (Richman, 1986), using the 74 SPI-12 time series in order to capture the drought variability which shows the co-variability between stations considering its time variability (Martins et al., 2012). Furthermore, to identify regions with different drought variability, the Varimax Rotation was used (Raziei et al., 2009).

The loadings obtained from the PCA, which represent the correlation between the original data and the principal components series, were then submitted to a Cluster Analysis. This classification method is used to detect the variables that are more similar with each other and categorize them together in different clusters (Sharma, 1996). From various types of methods, the K-means clustering was used herein since this method is suitable for climate data and also eases comparing the results with previous studies that used the same method (Santos et al., 2010).

### 3 Fourier analysis of time series

Regular or near regular cycles are often encountered in nature. The Fourier analysis methodology explained below can be referred as a method aimed to uncover hidden periodicities and, in particular, to extract regular cyclical components from the time series when the quantity of data is not excessively large. The Fourier analysis is a method based upon the Fourier decomposition of a series, which is a matter of explaining the series entirely as a composition of sinusoidal functions. This originates in the idea that, over a finite interval, any analytic function can be approximated, to whatever degree of

accuracy is desired, by taking a weighted sum of sine and cosine functions (Pollock, 1999).

Let  $m = n/2$  if  $n$  is even or  $m = (n - 1)/2$  if  $n$  is odd, with  $n$  the number of observations in a time series. The general model for a cyclic fluctuation would include the frequencies,  $\omega_j = (2\pi j)/n$ ,  $j = 0, \dots, m$  which are equally spaced in the interval  $[0, \pi]$  and takes the form

$$y_t = \sum_{j=0}^m \{\alpha_{j,1} \sin(\omega_j t) + \alpha_{j,2} \cos(\omega_j t)\} + e_t$$

where  $t$  represents time,  $\alpha_{j,1}$  and  $\alpha_{j,2}$ ,  $j = 0, \dots, m$  are estimable parameters and  $e_t$ ,  $t = 1, \dots, n$  are independent and identically distributed random variables with null mean value and variance  $\sigma^2$ , representing the residual element which is called the white noise process (Pollock, 1999).

The factor  $\theta_j = \sqrt{\alpha_{j,1}^2 + \alpha_{j,2}^2}$ ,  $j = 0, \dots, m$ , is the amplitude of the  $j$ th periodic component and indicates the importance of that component within the sum. The parameters  $\alpha_{j,1}$  and  $\alpha_{j,2}$ ,  $j = 0, \dots, m$  are estimated using the least squares method and the expressions for their estimators are given by (Pollock, 1999)

$$\begin{aligned} \tilde{\alpha}_{0,2} &= \frac{\sum_{t=1}^n y_t}{n}; & \tilde{\alpha}_{j,1} &= \frac{2 \sum_{t=1}^n \sin(\omega_j t) y_t}{n}; \\ \tilde{\alpha}_{j,2} &= \frac{2 \sum_{t=1}^n \cos(\omega_j t) y_t}{n}, & j &= 1, \dots, m. \end{aligned}$$

Then an estimator for  $\theta_j$ ,  $\tilde{\theta}_j$ , can be obtained and a statistic to test the significance of the  $j$ th periodic component is given by (Fisher, 1929; Nowroozi, 1967)

$$g_j = \frac{\tilde{\theta}_j^2}{\sum_{i=1}^m \tilde{\theta}_i^2}, \quad j = 1, \dots, m.$$

**Assessing drought cycles using Fourier analysis**

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The total sample variance is given by  $\sum_{j=1}^m \frac{\tilde{\theta}_j^2}{2}$  and the proportion of that variance which is attributable to the periodical component at frequency  $\omega_j$  is  $\frac{\tilde{\theta}_j^2}{2}$ .

In order to provide a graphical representation of the sample variance decomposition, the elements of the total variance must be scaled by a factor of  $n$ . The graph of the

function  $I_j = \frac{n \tilde{\theta}_j^2}{2}$  is known as the classical periodogram (Pollock, 1999). The graphic representation of  $I_j$  for  $j = 1, \dots, m$  (Fig. 2), allows to detect the existence of relevant periodic components of the time series, as well as the importance of each one. The wavelength, i.e., the period in time units of the  $j$ th periodic component, is given by  $\rho_j = n/j$ .

In the current study, the number of observations is  $n = 66$  in all locations, thus  $m = 33$ . For each of the studied time series, the  $I_j$  for  $j = 1, \dots, m$  was calculated and graphically represented in order to visualize the highest peaks, which correspond to the leading periodic components of the time series. The observation of several high peaks indicates the existence of several periodic components with different periods. However in general, few of those peaks represent a strong periodical signal that cannot be assigned to statistical fluctuations in a merely white noise process.

The assessment of the statistical significance of a peak involves testing the null hypothesis,  $H_0$ , that the observed time series are purely white noise against the alternative,  $H_1$ , stating that a periodic signal is present there. The statistical distribution of the periodogram is well known for the even-sampling case, which corresponds to equally spaced observations (Scargle, 1982). The most important result is that if the observations in the time series are pure Gaussian noise the  $I_j$ ,  $j = 1, \dots, m$  are independent and exponentially distributed. In this situation, it is reliable to use the false alarm probability to assess the statistical significance of the highest peaks in the periodogram, which states that if  $Z = \max(I_j), j = 1, \dots, m$  is a maximum value of the periodogram, then the probability for  $Z$  being over the set of the  $m$  periodogram values is given by

$$\Pr(Z > z) = 1 - [1 - \exp(-z)]^m.$$

**Assessing drought cycles using Fourier analysis**

E. Moreira et al.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



So, a threshold  $z_0$  can be used for detecting if a peak is significant, which is defined as

$$z_0 = -\ln \left[ 1 - (1 - p_0)^{(1/m)} \right]$$

where  $p_0$  is the false alarm probability, a fixed small value usually selected between 0.01 and 0.1 (Scargle, 1982). For instance, in “Reguengos” time series the highest peak is attained for  $j = 11$  ( $I_{11} = 9.05$ ), which corresponds to a periodic component with 6 years period (Fig. 2). Choosing a false alarm probability of 0.1, with the number of periodical components  $m = 33$ , the value  $z_0$  obtained is 5.75, which allows concluding that the peak is significant. In this time series, two other peaks are significant, those for  $j = 2$  and  $j = 7$  corresponding to sinusoidal waves with 33 and 9.4 years period (Fig. 2). If one considers a false alarm probability of 0.01 instead of 0.1, then only the peak for  $j = 11$  with 6 years period can be considered significant.

The fitted sinusoidal function of 6 years period is presented in Fig. 2 simultaneously with the “Reguengos” time series and obviously has the best goodness of fit to the time series among all other periodic components,  $R^2 = 0.14$  (grey line). For a better goodness of fit between the sinusoidal wave and the time series, the cycles corresponding to the significant peaks in the periodogram can be summed up, thus  $j = 2 + 7 + 11$ , to build a general model for a non-regular cyclic fluctuation. In Fig. 2, the wave resulting of summing up the significant cycles with period 6, 9.4 and 33 years (black line) is also represented. Some improvement of the goodness of fit is then obtained, with  $R^2 = 0.33$ .

## 4 Results and discussion

### 4.1 Droughts regionalization

From the PCA two principal components were retained, based on the North’s rule of thumb (North et al., 1982), which were submitted to the Varimax rotation. The first component, with the highest loading in the North explains 46 % of the total variance

## Assessing drought cycles using Fourier analysis

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



and the second one 37.3%, representing the South. Both components explain 83.2% of the total variance (Martins et al., 2012).

The K-means clustering of the loadings of these two principal components shows three significantly different regions within Portugal regarding drought variability, separating the North from the Middle and the South (Fig. 1). The identified clusters are consistent with the results found by Santos et al. (2010), although using different time-series with different lengths. The specific characteristics of the station of Cabo da Roca (represented with \* in Fig. 1) makes it closer to the drought variability of cluster three relative to the second cluster; for that reason the analysis was performed including that station in the southern cluster.

The most frequent drought class, i.e., the statistical mode in each month for each of the 3 clusters were computed to provide a global overview on the temporal evolution of the drought classes in each of the corresponding regions (Fig. 3). A drought event is considered a sequence of years with drought class 3 or higher where the interval between droughts do not exceed 2 years. Thus, considering this, when observing Fig. 3, it can be noticed that during the entire 66 years time period there are 13 groups of droughts events in cluster 1; if considering just the classes 4 and 5, this number decreases to 9. For cluster 2, the number of droughts events of classes 3 to 5 is 11 and just for both classes 4 and 5 is only 6. Lastly, for cluster 3 the number of events of the classes 3 or higher is 10 and those, if considering just classes 4 and 5, become 8. These results do not show a clear tendency, as one moves from north to south, regarding the severity and frequency of droughts, but if paying attention only to the extreme droughts we can see that there are more events in the central and southern, 4 and 3 against just 1 in the northern region.

From the observation of the 3 clusters in Fig. 3, one may see that the minimum time interval between groups of severe and extreme drought occurrences is about 4 years and the maximum time without severe droughts is approximately 27 years. This large period of 27 years without severe and extreme droughts, which is observed in the first half of the studied period, could indicate a trend towards drought aggravation. However,

## Assessing drought cycles using Fourier analysis

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



as reported by Moreira et al. (2012) using 10 time series with around 100 years length, there was no evidence of a trend for aggravation. Differently, for most sites, results pointed to the occurrence of large cycles such that a long period with more frequent and severe droughts is followed by another long period where droughts are less frequent and severe.

## 4.2 Fourier analysis

The periodograms of each time series were computed and the significance of the cycles were analysed using the false alarm probability considering the 0.05 significance level, i.e., only the peaks above 95 % of confidence level were considered significant.

The results referring to the periods of the cycles corresponding to the significant peaks recorded in the periodograms of all time series are compiled in Table 2, grouped by clusters. The counts per period and per cluster are resumed in this Table as well as the corresponding frequency relative to the number of series included in each of the 3 clusters expressed as percentage. Several cycles are grouped in the same column when there is a large similarity of related periodicities, thus it is advisable to group them in order to simplify the reading of the results. These cycles with small differences of periods may actually be variations of the same cycle.

Considering the country total, the most frequent cycles are those with periods of 6 year (66) and 9.4 year (29) (Table 2 counts total). When analysing the counts by cluster, because clusters have different number of series, the frequency in percent for each cluster was computed (Table 2). In cluster 1, the most frequent cycles ordered by frequency are 6 year (84.4 %) and 4.7; 4.4 year (43.8 %). In cluster 2, they are 6 year (90 %) and 9.4 (50 %) and in cluster 3 they are: 6 (100 %) and 9.4 (100 %). The inter-decadal cycles with periods of 33 year are present in all regions but with 22, 16.5 and 13.2 year are only present in the northern region (cluster 1). Just three of the significant cycles found in the SPI-12 time series have frequencies sufficiently high in the full country or in each of the 3 clusters to be noted: first, the cycle with period 6 years with very high frequency (84–100 %) in the 3 clusters; second, the cycle with period 9.4 years

## Assessing drought cycles using Fourier analysis

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Assessing drought cycles using Fourier analysis

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



with very high frequency (100 %) in the cluster 3 and median frequency (50 %) in the cluster 2; third, the cycle with periods 4.7; 4.4 year moderately frequent (44 %) in the cluster 1. These results show that the cyclicity of droughts varies among regions. Summarizing, the cycle of 6 year period has very strong presence in the whole country whereas the cycle with 9.4 year period as a stronger presence in the southern rather than in the central/southern region of Portugal. The cycle of 4.7; 4.4 year period is inexistent in central and southern regions and it only appears in the northern cluster. Against our expectations the large cycles with more than 20 years period have low frequency in all clusters. The reasons for that, may lie on the technique associate with the length of time series. For instance, the large cycles of 33 years are frequent mainly in cluster 2 and 3, but most of them were not found significant in the periodogram. This can be the result of using rather small time series with the small length of the studied time series (66 years) when looking for cycles with periods of about 30 years.

Looking to the results from a point of view of inference, since the number of time series included in cluster 1 and 2 is large, (32 and 30 stations), each one can be considered as a random sample respectively of northern and central regions. Thus, an estimative for the probability of the return period of droughts to be 6 years in cluster 1, is  $27/32 = 84.4\%$  and in cluster 2, that probability will be  $27/30 = 90\%$  (counts from Table 2). However in cluster 3, the probability of 100 % for both the return period of droughts to be 6 years and 9.4 years is likely overestimated. The number of time series in the sample is only 12 and their spatial distribution is not the best. Thus the sample may not be representative of the population, even accounting that cluster 3 is smaller. However, as regards to the country total, a reliable estimative for the probability of the return period of droughts to be 6 years is  $66/74 = 89.2\%$ .

In Figs. 4–6, the time series relative to each of the 3 clusters are shown with superposing the most frequent waves: one of 4.7 years period in cluster 1, another of 6 years period in clusters 1, 2 and 3, and a wave of 9.4 years period in cluster 2 and 3. A correspondence between the minima of the waves and the SPI upper borders for moderate drought (−1) and for severe or extreme drought (−1.5) is established through



**Assessing drought cycles using Fourier analysis**

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



obtained by Sousa et al. (2011) that show the influence of NAO on drought (and wetness) variability in the Mediterranean area. Moreover, these authors used the PDSI as drought index, that corresponds well with the SPI-12 (Paulo and Pereira, 2006). That hypothesis is also compatible with the assumptions of Trigo et al. (2004) relative to the influence of NAO on the precipitation in Portugal. However, these authors assumed multidecadal cycles, which were also observed in this study. Labat (2006) also assumed NAO influences on European surface water regimes in terms of multidecadal periods. Nevertheless, in agreement with conclusions by Santos et al. (2010), periodicity of more than 10 years, more frequent in the northern region, are difficult to relate with NAO. This is also concluded by Küçük et al. (2009) for Turkey. Following the results reported by Tsiropoula (2003) and Hathaway (2010), these multidecadal cycles may relate with solar cycles.

## 5 Conclusions

The application of the Fourier analysis to the December values of SPI-12 time series combined with the cluster analysis of the SPI-12 time series PCA loadings allowed assessing the significant and most frequent cycles in each region identified by clusters and relating them to their characteristics in terms of SPI information. These techniques are also useful in long term drought prediction as they may give an idea about the return of a new drought event after  $x$  years of the occurrence of the last one.

In our point of view, the simplicity of the approach used compared to other, is an advantage since it produces additional statistical information which allows a better understanding and interpretation of the drought periodicity results.

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From the analysis 3 cycles emerged: the cycle with a 6 years period compatible with NAO influences, doubtless the most frequent across the country, with a good agreement with the range time of the drought events occurred in each region. The cycle of 9.4 years, also likely related with the NAO, loses importance from south to north, where it is almost non-existent. Finally the cycle with a small period of 4.7/4.4 years is fairly frequent in the northern region but is not significant in the central and southern. These results point to northern and southern Portugal having different climatic influences that cause the strong presence of cycles with periodicities in the range 6–10 years in the time series of central/southern region. Further studies to improve the understanding of teleconnections between drought indices and large scale atmospheric circulation indices for Portugal and the Mediterranean are needed. A better knowledge of related processes may contribute to improve predictability of droughts and related risk management.

*Acknowledgements.* This work was partially supported by the Fundação para a Ciência e a Tecnologia (Portuguese Foundation for Science and Technology) through the project PEst-OE/MAT/UI0297/2014 (Centro de Matemática e Aplicações), FCT, UNL and the project PTDC/GEO-MET/3476/2012 – Predictability assessment and hybridization of seasonal drought forecasts in western Europe.

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## Assessing drought cycles using Fourier analysis

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Assessing drought cycles using Fourier analysis

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## Assessing drought cycles using Fourier analysis

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## Assessing drought cycles using Fourier analysis

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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**Assessing drought cycles using Fourier analysis**

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## Assessing drought cycles using Fourier analysis

E. Moreira et al.

**Table 1.** SPI drought class classification (McKee et al., 1993).

Code	Drought classes	SPI values	Time in category (%)
1	Non-drought	$SPI \geq 0$	
2	Near normal	$-1 < SPI < 0$	34.1
3	Moderate	$-1.5 < SPI \leq -1$	9.2
4	Severe	$-2 < SPI \leq -1.5$	4.4
5	Extreme	$SPI \leq -2$	2.3

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Assessing drought cycles using Fourier analysis

E. Moreira et al.

**Table 2.** The counts per cycle and per cluster and its frequency (%) relative to the number of series included in each cluster (just the significant cycles of the periodograms).

Counts	Nr. series per cluster	Period in years									
		33	22	16.5	13.2	9.4	6	4.7; 4.4	3.5; 3.3	2.4	
cluster 1	32	3	2	1	1	2	27	14	0	1	
cluster 2	30	5	0	0	0	15	27	0	2	1	
cluster 3	12	2	0	0	0	12	12	0	3	1	
Total	74	10	2	1	1	29	66	14	5	3	
Frequency		33	22	16.5	13.2	9.4	6	4.7; 4.4	3.5; 3.3	2.4	
cluster 1		9.4 %	6.3 %	3.1 %	3.1 %	6.3 %	84.4 %	43.8 %	0.0 %	3.1 %	
cluster 2		16.7 %	0.0 %	0.0 %	0.0 %	50.0 %	90.0 %	0.0 %	6.7 %	3.3 %	
cluster 3		16.7 %	0.0 %	0.0 %	0.0 %	100.0 %	100.0 %	0.0 %	25.0 %	8.3 %	
Total		13.5 %	2.7 %	1.4 %	1.4 %	39.2 %	89.2 %	18.9 %	6.8 %	4.1 %	

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

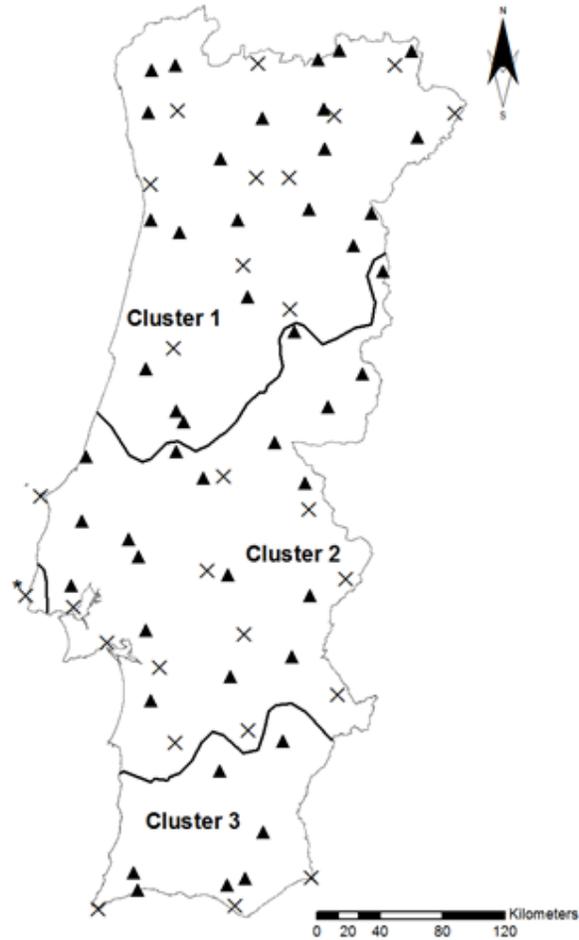
Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Fig. 1.** Spatial distribution of the meteorological stations (x) and rainfall stations (▲) used in the study and delimitation of drought clusters; (\* Station included in cluster 3).

**Assessing drought cycles using Fourier analysis**

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

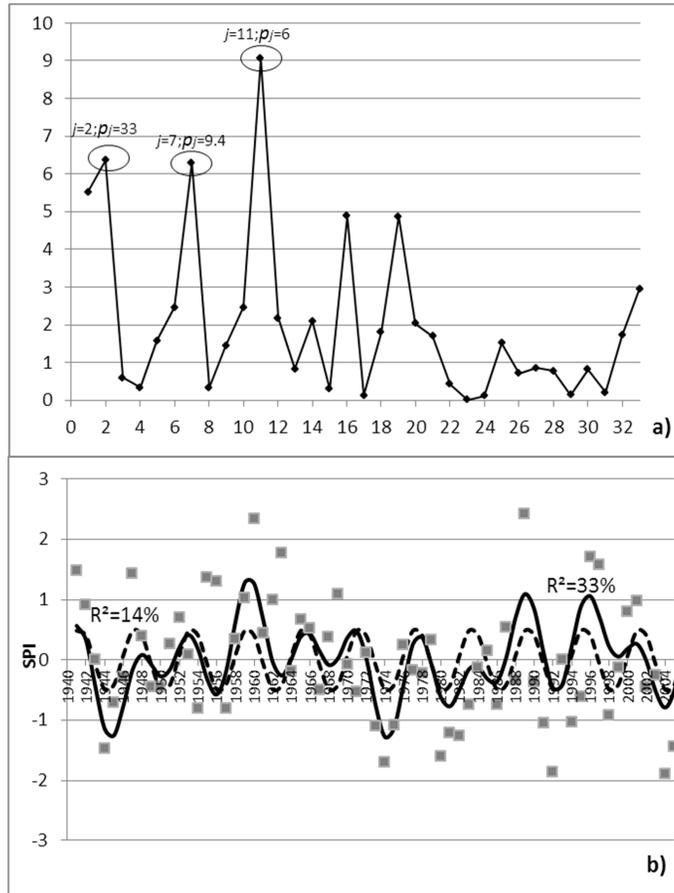
Printer-friendly Version

Interactive Discussion

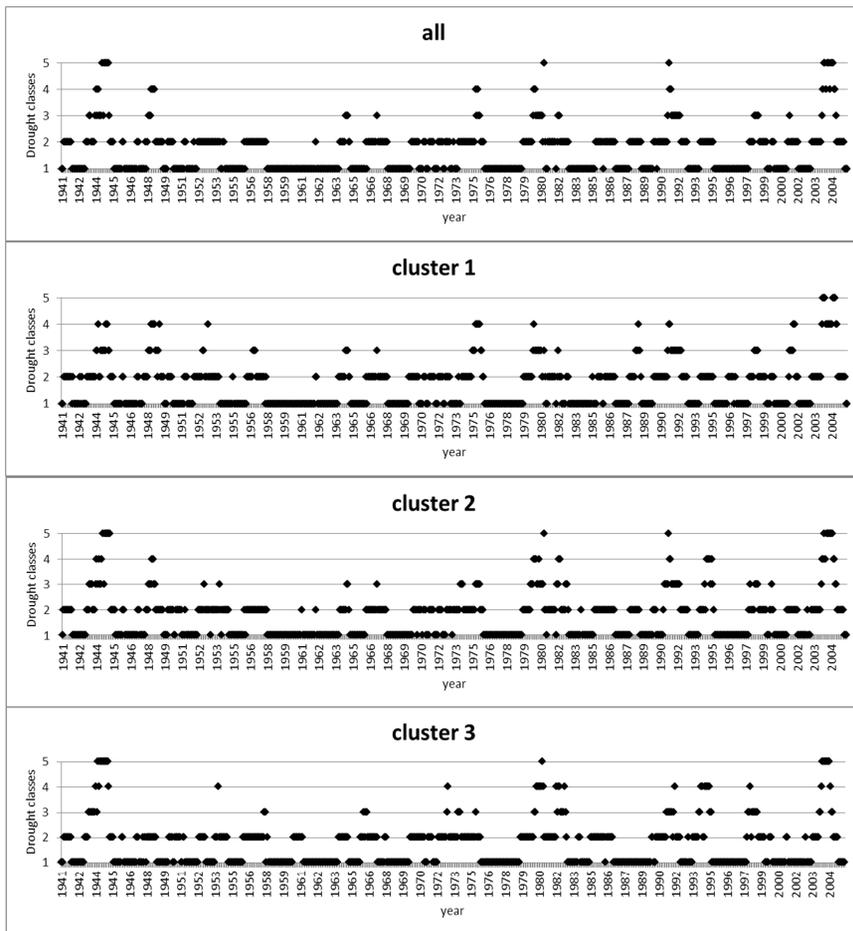


## Assessing drought cycles using Fourier analysis

E. Moreira et al.



**Fig. 2.** “Reguengos”: **(a)** graph of  $I_j$ ,  $j = 1, \dots, 33$ ; **(b)** time series (grey dots) vs. fitted sinusoidal wave of 6 years period (dashed line) vs. fitted model resulting of summing up the waves with period 6, 9.4 and 33 years (black line).



**Fig. 3.** The most frequent drought class by month in Portugal (all), cluster 1, cluster 2 and cluster 3 (1 – non drought, 2 – near normal, 3 – moderate, 4 – severe, 5 – extreme).

## Assessing drought cycles using Fourier analysis

E. Moreira et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

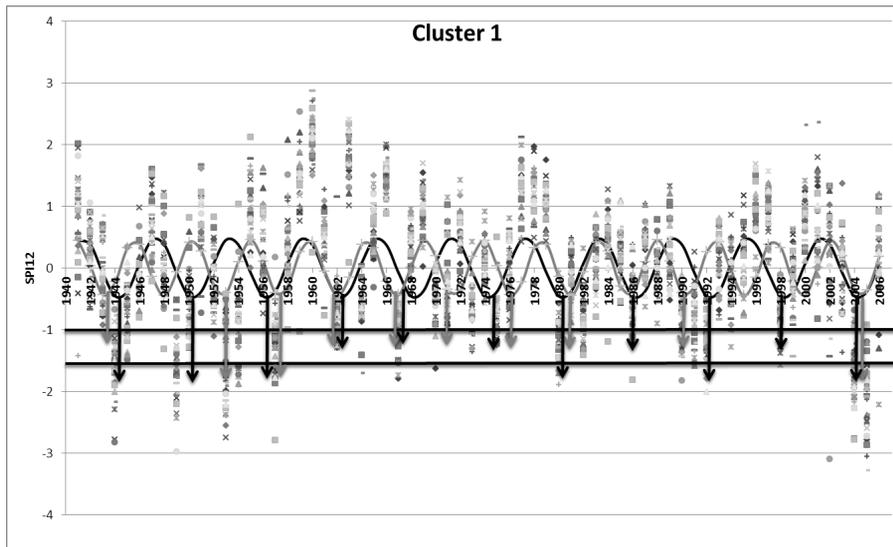
Printer-friendly Version

Interactive Discussion



## Assessing drought cycles using Fourier analysis

E. Moreira et al.



**Fig. 4.** SPI-12 time series for northern Portugal (cluster 1) + waves of period 4.7 years (grey line) and 6 years (black line).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

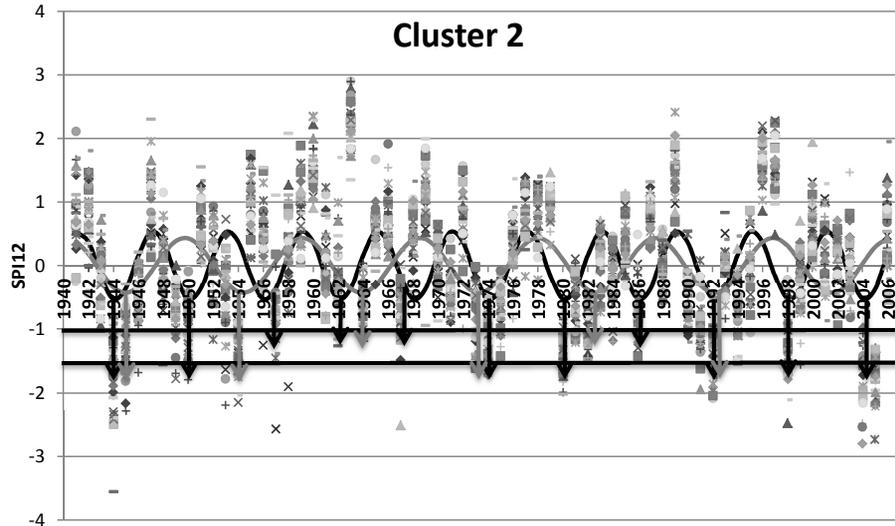
Printer-friendly Version

Interactive Discussion



## Assessing drought cycles using Fourier analysis

E. Moreira et al.



**Fig. 5.** SPI-12 time series for central/southern Portugal (cluster 2) + waves of period 6 (black line) and 9.4 years (grey line).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

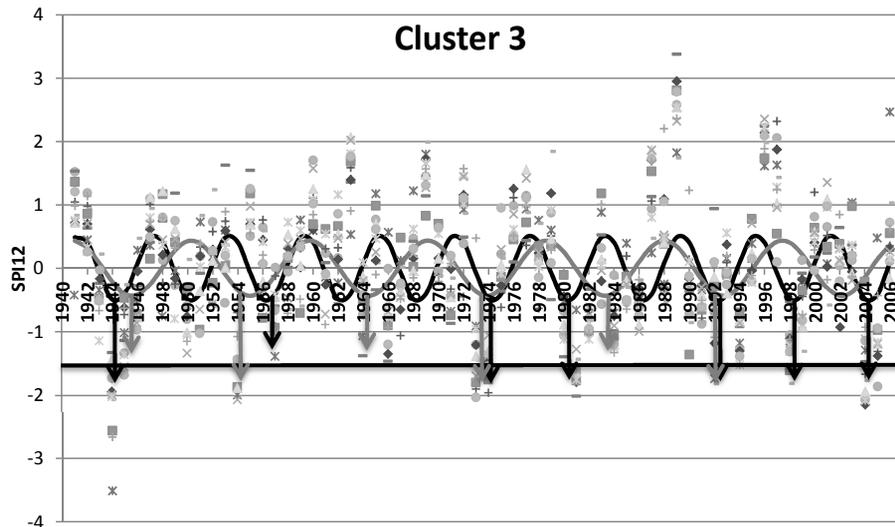
Printer-friendly Version

Interactive Discussion



## Assessing drought cycles using Fourier analysis

E. Moreira et al.



**Fig. 6.** SPI-12 time series for southern Portugal (cluster 3) + waves of period 6 (black line) and 9.4 years (grey line).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

