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3 authors, including:

J. Corte-Real
Universidade de Évora

Budong Qian
Agriculture and Agri-Food Canada

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REGIONAL CLIMATE CHANGE IN PORTUGAL: PRECIPITATION VARIABILITY ASSOCIATED WITH LARGE-SCALE ATMOSPHERIC CIRCULATION

JOÃO CORTE-REAL*, BUDONG QIAN and HONG XU
ICAT, Faculty of Sciences, University of Lisbon, 1700 Lisboa, Portugal

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ABSTRACT

Four major circulation patterns, associated with daily precipitation in Portugal, are classified from daily sea level pressure fields over the northeastern Atlantic and western Europe, based on the K-means clustering algorithm coupled with principal component analysis. A rainy pattern is clearly identified with a probability of rain of 74.6%, as well as two distinct dry patterns, one prevailing in summer and the other occurring frequently in winter; a blocking-like pattern with a probability of rain of 36.8% has also been identified. These patterns are quasi-stationary, normally persisting for 1 week and sometimes even for 1 month, especially the dry ones; they represent the principal weather regimes associated with precipitation in Portugal.

Interannual variations in monthly precipitation associated with the circulation patterns are also investigated; results show that these variations match fluctuations in the frequencies of occurrence of both the rainy and the dry patterns. The decreasing trend of March monthly rainfall in southern Portugal is closely related to corresponding trends in the frequencies of both the rainy pattern and the summer dry pattern. Long term trends are not significant either in other monthly rainfall sequences or in the frequencies of different circulation patterns. Interannual variations seem, in most months, to be quasi-periodic. Singular spectrum analysis (SSA) is performed on these sequences to detect quasi-periodic oscillations. Relationships between oscillations in rainfall and in frequencies of occurrence of circulation patterns are studied. Results show that four weather circulation patterns or weather regimes are important for investigating regional climate change in Portugal and its relationship with variability of large-scale atmospheric circulation. © 1998 Royal Meteorological Society.

KEY WORDS: regional climate change; circulation pattern; K-means clustering; singular spectrum analysis; precipitation variability; Portugal

1. INTRODUCTION

Variability of precipitation has an essential role in water resources management, which in turn controls agriculture, as well as other economic activities and ultimately social development and behaviour. This is especially clear in southern Portugal where precipitation has displayed large variability on both intra- and inter-annual scales with severe, sometimes disastrous, consequences. A better understanding of the causes of variability of precipitation and associated regime is one of the most important steps, not only in improving long-range and even extended-range forecasting skills, but also in assessing regional impacts of future climate change. It is a well-known fact that for periods longer than a couple of weeks, detailed forecasting is impossible due to climatic system instabilities and nonlinearities that give rise to deterministic chaos. However, chaos does not mean that the behaviour is totally irregular or random on larger time scales, as macroscopic regularities, such as near periodicity, may still significantly contribute to the

* Correspondence to: Institute for Applied Science and Technology, Faculty of Sciences, University of Lisbon, Campo Grande, Edificio ICAT, 1700 Lisboa, Portugal. E-Mail: jcr@fc.ul.pt

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variability of the system (Vautard *et al*., 1992). Furthermore, the regular part of the circulation is easy to predict using empirical models, based on time-series analysis. Thus, many studies have attempted to find long term periodicities in both climatic records and atmospheric circulation (Rampino *et al*., 1987; Burroughs, 1992). It is well established that quasi-periodic oscillations do exist in the climatic system, such as QBO, ENSO and other examples of interannual variability (Philander, 1983, 1990; Labitzke and van Loon, 1990), as well as intra-seasonal low-frequency oscillations, e.g. the Madden-Julian oscillation. It is obvious that intra-seasonal low-frequency oscillations are helpful in long-range and extended-range forecasting (Plaut and Vautard, 1994). In recent decades, numerous studies have focused on describing the spatial structures of atmospheric low-frequency variability by using cross-correlation functions (Wallace and Gutzler, 1981) and empirical orthogonal functions (Barnett and Preisendorfer, 1978; Mo and Ghil, 1987). Recently, study of low-frequency variability has been addressed in terms of temporal behaviour by considering clusters that define recurrent states of the atmosphere or quasi-stationary weather patterns (Mo and Ghil, 1988; Vautard and Legras, 1988; Vautard, 1990). A powerful technique, the multi-channel version of singular spectrum analysis (mcSSA) has been developed and applied to document the most regular coherent space-time patterns of low-frequency variability (Plaut and Vautard, 1994). Vautard (1990) (hereafter V90) has identified four weather regimes: blocking (BL), zonal (ZO), Greenland anticyclone (GA) and Atlantic ridge (AR), over the North Atlantic, from 700 hPa geopotential height observations covering 37 winters. Moreover, Plaut and Vautard (1994) (hereafter PV94) associated these four weather regimes with the 30–35-day oscillation in the North Atlantic. They indicated that conditional probability of occurrence of blocking, 30 days ahead, is enhanced by a factor of two, relative to climatological probability if the phase of the 30–35-day oscillation is known.

Other important issues are the assessment of regional climatic change and the identification of its causes; for instance, Matos *et al*. (1994) document the interesting fact that, in Portugal, March rainfall has been undergoing a reduction in recent decades, especially since the end of the 1960’s. Is this phenomenon related to a global warming trend? What is the cause of the change? All these questions need to be investigated in depth. von Storch *et al*. (1993) designed a downscaling technique to simulate regional scenarios of Iberian rainfall in wintertime. Corte-Real *et al*. (1995b) applied a non-parametric multivariate regression approach, the multivariate adaptive regression splines (MARS) model (Friedman, 1991), to obtain future regional information of precipitation in Portugal from GCM simulated sea-level pressure (SLP). All these downscaling studies are based on monthly mean fields of SLP.

This study aims to identify weather circulation patterns related to precipitation in southern Portugal from daily fields of SLP in the Atlantic–Europe sector, using the objective algorithm of K-means clustering coupled with principal component analysis (PCA), and to help clarify the variability of these patterns as well as their relationship with precipitation in Portugal on an interannual time scale. It is also a primary purpose that the relationships developed should be such that they may be used, with appropriate input from GCM data on daily scale, in the assessment of regional climate change in southern Portugal.

2. DATA AND STRATEGY

Four data sets are used in this study: (i) daily sea level pressure field-series over the Northern Hemisphere, northward of 20°N, defined on longitude–latitude grids with a spacing of 5°, covering the period from January 1946 to August 1992, provided by NCAR, with some gaps being filled by linear interpolation in time (Wang *et al*., 1994); (ii) daily 500 hPa geopotential height field-series from January 1946 to June 1989 over a $5° \times 4°$ longitude–latitude grid covering the Northern Hemisphere poleward of 18°N, taken from the NMC Grid Point Data Set, Version II, 1990, and processed by Corte-Real *et al*. (1995a); (iii) daily rainfall at two stations in Alentejo, southern Portugal, namely Évora and Beja, for the period 1946–1992; (iv) monthly rainfall totals over the period 1951–1990 at 75 stations covering all of Portugal, and over 1901–1994 at Évora and Beja.

In order to identify weather circulation patterns affecting Portugal, especially the southern part of the country, from daily large-scale atmospheric circulation, the K-means clustering algorithm coupled with PCA analysis has been adopted. Wilson *et al*. (1992) compared four methods of classification: K-means clustering, fuzzy clustering, principal components, and principal components coupled with K-means clustering. They found that, in terms of distinguishing the circulation patterns responsible for precipitation events, all methods performed approximately equally well; however, Gong and Richman (1992) showed that principal components coupled with K-means clustering can provide the most separable system of clusters once the total number of clusters is chosen. In this study, an information measure Inf is applied to determine the optimal number of clusters (i.e. weather circulation patterns). Since the primary purpose of this study is to investigate the influences of circulation patterns on precipitation in southern Portugal, the information measure *Inf is* defined as

$$\mathrm{Inf} = \sum_{i=1}^{k} \left| n_{\mathrm{r}_i} - p_{\mathrm{r}} n_i \right|$$

where n_i and n_{r_i} are respectively, the number of days in a specific cluster i and the number of rainy days within that same cluster and p_{r} is the probability of occurrence of rain, for all observations. The optimal number of clusters, k, corresponds to the relatively highest score of Inf*;* it is the number of clusters that best differentiates between precipitation states, i.e. that gives a high probability of rain within some specific clusters but low in all others. Daily rainfall data at Évora are used to calculate the information measure.

PCA analysis was used to condense information in daily sea level pressure fields and to reduce the number of variables during K-means clustering. The objective of the K-means algorithm is to find group definitions and memberships that minimize the total within-cluster sum of squares over all the clusters. The objective function, ϕ, can be represented as

$$\phi = \sum_{k=1}^{K} \sum_{j=1}^{M} \sum_{i=1}^{N_k} (x_{ijk} - \bar{x}_{jk})^2 ,$$

where K is the total number of classes, M is the number of variables used, N_k is the number of samples in the k-th cluster, x_{ijk} is the i-th member of variable j in the k-th cluster, and $\bar{x}_{jk}$ is the mean value of variable j in the k-th cluster. Thus, a sample was assigned to a cluster based on minimizing the Euclidean distance between the vector of its variables and the means of the variables within a cluster. The K-means algorithm proceeds by updating the mean and grouping the data again. This procedure continues until all the samples no longer change clusters. The K-means algorithm is described in more detail by Hartigan (1975) and Hartigan and Wong (1979).

The above procedure was applied to the first 20 principal components (PCs) (explaining 99.1% of total variance) of daily sea level pressure fields over the area including the eastern Atlantic and western Europe (30°W–10°E, 25°–60°N) throughout the period from 1 January 1946 to 31 August 1992. Clustering was attempted using different choices for seeds; in all cases the basic rainy and dry patterns were identified; therefore it was concluded that, for the purpose of this study, it is not important how the seeds are selected to initiate clustering. The information measure indicates four (see Table I) to be the optimal number of clusters or weather circulation patterns; then, the spatial structure of each weather circulation pattern was obtained by composing all the daily fields belonging to the corresponding cluster. These four weather circulation patterns will be discussed in detail in the next section; all of them are actually quasi-stationary, although the persistence of the patterns has not been considered in the classification algorithm.

Table I. Information measure for different number (k) of clusters

k	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Inf	1796	2478	3076	2388	2232	2192	2039	2369	2114	2061	2148	2180	2145	2185

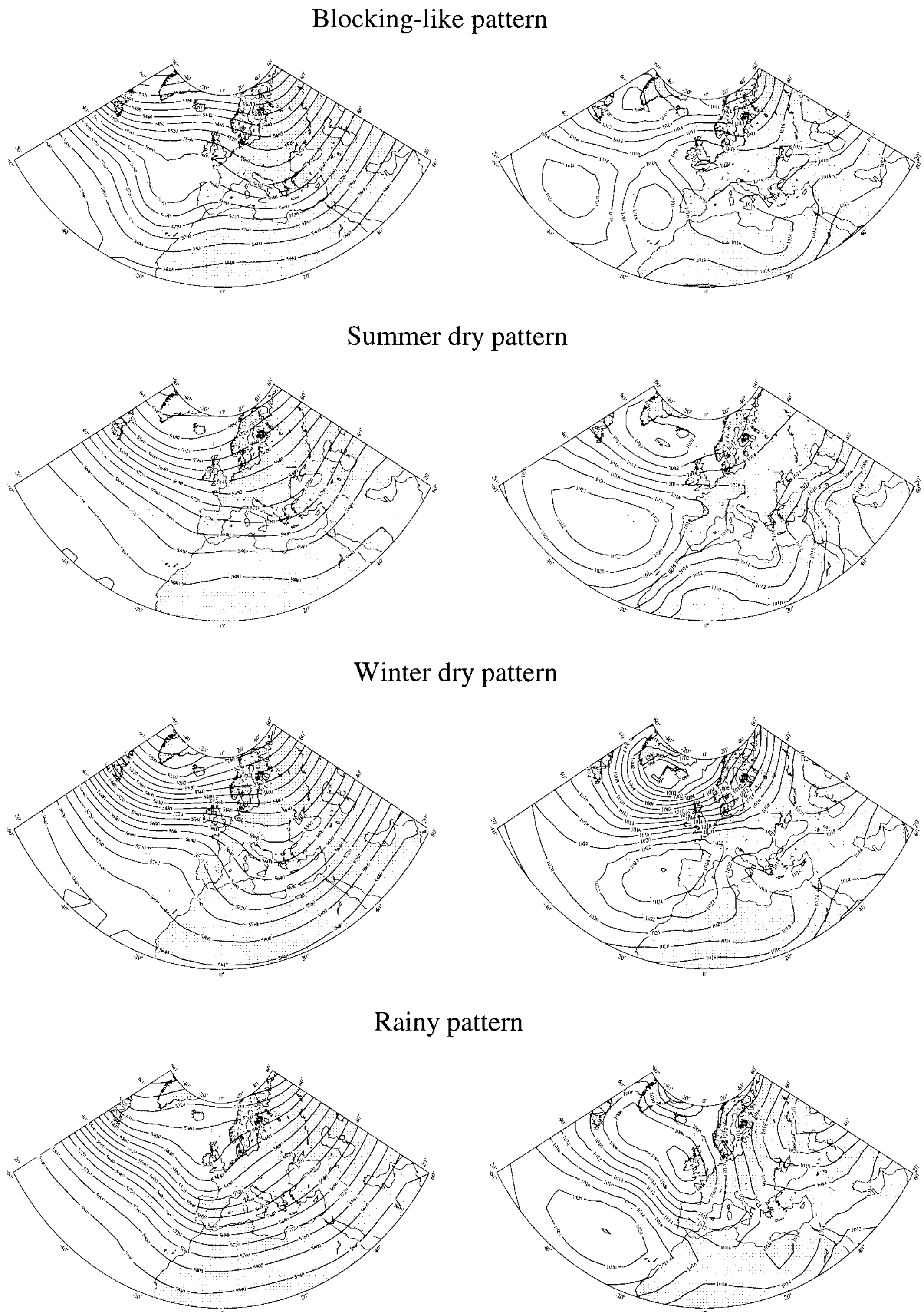


Figure 1. Composites of Z500 (left panel) and SLP (right panel) over Atlantic–Europe corresponding to the four weather circulation patterns identified by K-means clustering

Table II. Main characteristics of weather circulation patterns

Patterns	Character of Z500	Character of SLP	Local character in Portugal
Blocking-like pattern	A weak ridge of high pressure over the Bay of Biscay and British Isles; a trough of low pressure west of Gibraltar	A weak high over western Europe centred at English Channel; a weak depression west of Gibraltar; Azores high and Icelandic low westward of normal positions; weak depression over the Mediterranean Sea	Least frequent pattern (Table III) characterised by weak southerly or south-easterly flow
Summer dry pattern	5880 gpm isohypse extending northward; very weak wave activity over midlatitudes	Strong and northward extended Azores high centred over Azores; weak Icelandic low located over Greenland/Iceland	Most frequent pattern (Table III); circulation is controlled by the Azores high with northerly flow
Winter dry pattern	A ridge of high pressure over the coast of Iberian Peninsula; troughs of low pressure over western Atlantic and Mediterranean Seas; polar jet displaced northward	An anticyclone over mid-latitude eastern Atlantic and southern Europe; a weak depression over eastern Mediterranean; strong Icelandic low with polar fronts from the British Isles to the North Sea	Second driest pattern (Table III); circulation is controlled by an anticyclone with strong northerly flow
Rainy pattern	A deep trough of low pressure extending from the British Isles to the Strait of Gibraltar with a quasimeridional axis	Azores high located south of Azores Isles; a strong Atlantic depression over northern Atlantic centred near the British Isles extending as a pronounced trough to western Mediterranean	Wettest pattern (Table III); strong flow carrying moist maritime air masses along the normal track of Atlantic depressions

Table III. Statistics of different weather circulation patterns and their associated precipitation characteristics at Évora

Weather circulation patterns	Frequency of occurrence (%)	Probability of rain (%)	Mean daily rainfall on a rainy day (mm)	Contribution to total rainfall (%)
Blocking-like	13.1	36.8	5.8	16.3
Summer dry	47.8	13.2	4.1	15.3
Winter dry	22.3	18.8	2.8	7.0
Rainy	16.8	74.6	8.3	61.5
Total	100	27.9	6.1	100

Correlation analysis was applied to detect the relationships between circulation patterns and precipitation in Portugal. Singular spectrum analysis (SSA) is one of the most powerful tools to isolate signals, such as trend and quasi-periodic oscillations, from short and noisy time series (Vautard *et al*., 1992). SSA was applied to the year-to-year series of corresponding monthly values of precipitation and number of days of occurrence of weather circulation patterns for specific months such as January, March, April and October, in order to investigate the interannual quasi-periodic oscillations or trends in the series. The techniques of SSA analysis and reconstruction of the oscillation components can be found in detail in Vautard *et al*. (1992).

3. WEATHER REGIMES RELATED TO PRECIPITATION IN PORTUGAL

Four weather circulation patterns, classified by K-means clustering coupled with PCA, are shown in Figure 1, their characteristics being listed in Table II. All these four patterns are distinct from each other and relate well to precipitation in southern Portugal. Table III shows some statistics of different weather circulation patterns and their associated precipitation characteristics at Évora during the above-mentioned period (January 1946–August 1992). A rainy pattern is distinctly identified with a probability of rain of 74.6%, which is far larger than the climatological probability of rain of only 27.9%; two distinct dry patterns were classified, one prevailing in summer and the other occurring frequently in winter, and named summer dry pattern and winter dry pattern, respectively. A blocking-like pattern was also clustered, although this pattern is not so closely related to precipitation in southern Portugal. Figure 2 shows the seasonal variation of occurrence of each circulation pattern, all patterns displaying the strong signal of the annual cycle. It is interesting that these four patterns are very similar to the four weather regimes identified in V92 over the north Atlantic in winter, from 700 hPa geopotential fields; the blocking-like pattern is similar to BL (blocking) of V92, the summer dry pattern to ZO (zonal), the winter dry pattern to AR (Atlantic ridge) and the rainy pattern to GA (Greenland anticyclone). It implies that the weather circulation patterns classified in this study do in fact represent large-scale circulation regimes. Furthermore, in PV94 the Atlantic weather regimes were related to the 30–35-day oscillation of the lower troposphere (700 hPa level) in the Atlantic sector.

The persistence of weather circulation patterns is considered by calculating the number of cases in which each pattern lasted for a certain number of days on a seasonal basis without any break. The results are shown in Table IV, the letters W, S, S and A in the second row representing winter (December–February), spring (March–May), summer (June–August) and autumn (September–November), respectively. It is clear that all these four patterns are quasi-stationary, although there are some differences from season to season and between patterns. The blocking-like pattern and the rainy pattern can persist for 1–2 weeks but for less than 1 week in summer; the dry patterns can last longer than 1 month, especially the summer dry pattern, which however cannot persist for longer than 1 week in winter; the winter dry pattern, which rarely occurs in summer, cannot last more than 2 days in summer if it does occur. The persistence of these patterns is also seen in Table V as conditional transition probabilities between patterns. Every pattern tends to persist on the following day in each season, except in summer when the summer dry pattern prevails.

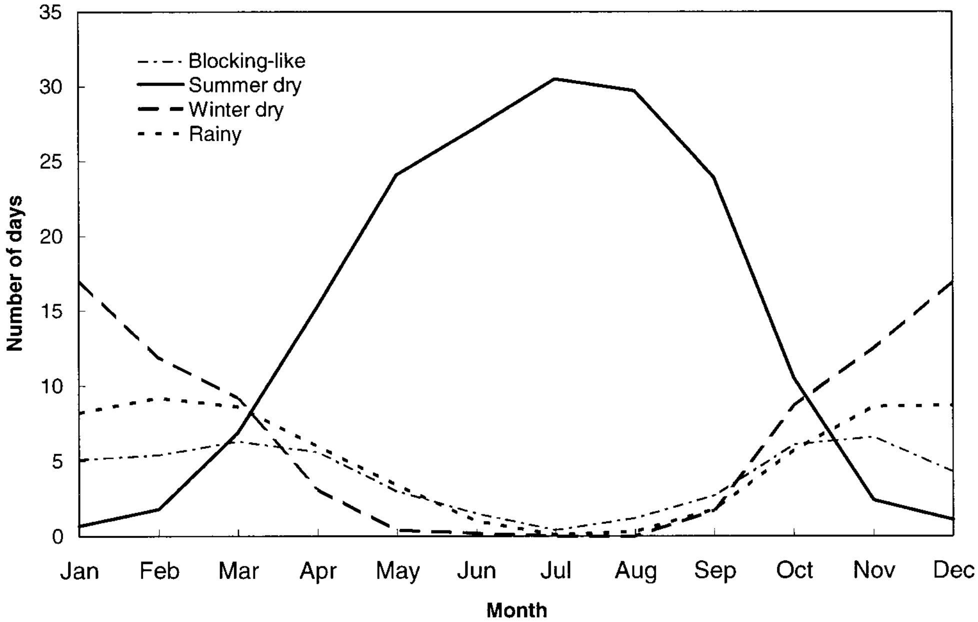


Figure 2. Mean number of days with different patterns in each month (1946–1992)

4. VARIABILITY OF PRECIPITATION ASSOCIATED WITH WEATHER CIRCULATION PATTERNS

As described above, the optimal number of clusters is decided by an information measure calculated from daily precipitation at Évora; however, the four weather regimes relate equally well to precipitation over the entire country. The correlation coefficients between monthly rainfall and monthly frequencies of occurrence of each weather circulation pattern are calculated for each month at 75 stations all over Portugal, in the period from 1951 to 1990. The blocking-like pattern is not important for monthly rainfall over almost all parts of the country, except in the Algarve, the southernmost province of the country, where monthly rainfall is influenced by this pattern from October to January; this is understandable because when a blocking situation occurs the low pressure centre takes a southern track and moves eastward into the Mediterranean through the Strait of Gibraltar. Furthermore, the blocking-like pattern can affect the entire southwest coast. The frequency of occurrence of the summer dry pattern is closely

Table IV. Numbers of consecutive occurrences (persistence) in each season of different weather circulation patterns

Duration (days)	Blocking-like				Summer dry				Winter dry				Rainy			
	W	S	S	A	W	S	S	A	W	S	S	A	W	S	S	A
1	94	104	45	109	76	140	10	131	93	66	7	114	146	153	29	126
2	71	71	12	52	25	72	4	54	72	33	2	62	82	75	6	72
3	41	42	7	37	7	50	3	47	30	26	0	44	46	47	6	35
4	25	18	1	26	2	32	4	29	30	11	0	30	31	30	1	23
5–9	28	34	6	37	2	90	19	54	81	23	0	53	69	31	0	33
10–14	5	3	0	7	0	21	7	15	35	6	0	17	11	6	0	10
15–19	0	0	0	0	0	22	12	4	15	2	0	3	4	0	0	0
20–24	0	0	0	0	0	8	5	0	8	0	0	1	0	0	0	0
25–29	0	0	0	0	0	5	4	0	6	0	0	2	0	0	0	0
≥ 30	0	0	0	0	0	12	48	0	3	0	0	1	0	0	0	0

Table V. Conditional transition probabilities between weather circulation patterns in each season

	Blocking-like	Summer dry	Winter dry	Rainy
Blocking-like	0.60 (winter)	0.03 (winter)	0.14 (winter)	0.22 (winter)
	0.59 (spring)	0.20 (spring)	0.03 (spring)	0.17 (spring)
	0.43 (summer)	0.50 (summer)	0.00 (summer)	0.07 (summer)
	0.62 (autumn)	0.11 (autumn)	0.13 (autumn)	0.15 (autumn)
Summer dry	0.10 (winter)	0.33 (winter)	0.30 (winter)	0.28 (winter)
	0.07 (spring)	0.80 (spring)	0.04 (spring)	0.09 (spring)
	0.02 (summer)	0.97 (summer)	0.00 (summer)	0.01 (summer)
	0.07 (autumn)	0.77 (autumn)	0.09 (autumn)	0.07 (autumn)
Winter dry	0.06 (winter)	0.02 (winter)	0.82 (winter)	0.10 (winter)
	0.08 (spring)	0.07 (spring)	0.68 (spring)	0.07 (spring)
	0.00 (summer)	0.83 (summer)	0.17 (summer)	0.00 (summer)
	0.09 (autumn)	0.13 (autumn)	0.70 (autumn)	0.09 (autumn)
Rainy	0.10 (winter)	0.04 (winter)	0.19 (winter)	0.66 (winter)
	0.09 (spring)	0.26 (spring)	0.07 (spring)	0.58 (spring)
	0.08 (summer)	0.63 (summer)	0.00 (summer)	
	0.10 (autumn)	0.17 (autumn)	0.12 (autumn)	0.60 (autumn)

correlated with monthly rainfall only in May, June and September with negative correlation all over the country. This implies that monthly rainfall in summer is not closely related to large scale circulation and may be affected mainly by local convective systems; however, precipitation in summer is not significant in southern Portugal. The frequency of occurrence of the winter dry pattern is closely related to monthly rainfall all over the country from October to April with negative correlation, significant at the 99.9% confidence level. The rainy pattern is the most important one; its frequency of occurrence correlates well with monthly rainfall throughout the year except during the summer months, although there are some seasonal differences; in effect it is not very important in the Algarve during autumn, being more important in the north-western part of the country. Some results are shown in Figure 3. In this case, it is reasonable to discuss the variability of precipitation in Portugal, associated with these weather circulation patterns, based on precipitation data only at some representative observational stations.

Interannual variability of precipitation is investigated in this study, especially for March. In Matos *et al.* (1994) it is shown that March monthly rainfall has tended to decrease since the 1960's. The relationships between March monthly rainfall and the frequencies of different weather circulation patterns are detected in this study. March marks the beginning of spring. Monthly rainfall in each year should be related to the relative importance of different patterns in the same year, e.g. the monthly rainfall should be higher if the rainy pattern occurs more frequently and the dry patterns less frequently. Furthermore, the frequencies of occurrence of these weather circulation patterns in March should also show trends if monthly rainfall indeed has one. Figure 4 shows the cumulative anomalies of March monthly rainfall and numbers of days with occurrence of the summer dry pattern and the rainy pattern in March, from 1946 to 1992. It is clear that the historical variation of rainfall is consistent with that of the number of days with occurrence of the rainy pattern (correlation coefficient 0.89 for $n = 47$) but opposite to that of the summer dry pattern (correlation coefficient -0.90 for $n = 47$). It can be concluded that the decrease of rainfall since the late 1960's is accompanied by a reduction of the occurrences of the rainy pattern and an increase in those of the summer dry pattern. These trends, which will be discussed later, are so significant that they can be isolated by SSA.

The trends of both rainfall and the frequencies of occurrences of weather circulation patterns are remarkable in March; however, the trends are not significant in other months, and interannual variation seems to be quasi-periodic instead. Figure 5 shows the corresponding cumulative anomalies in January and October. An interesting phenomenon is that, in January, the amplitude of interannual variability is small before the 1970's but large since then.

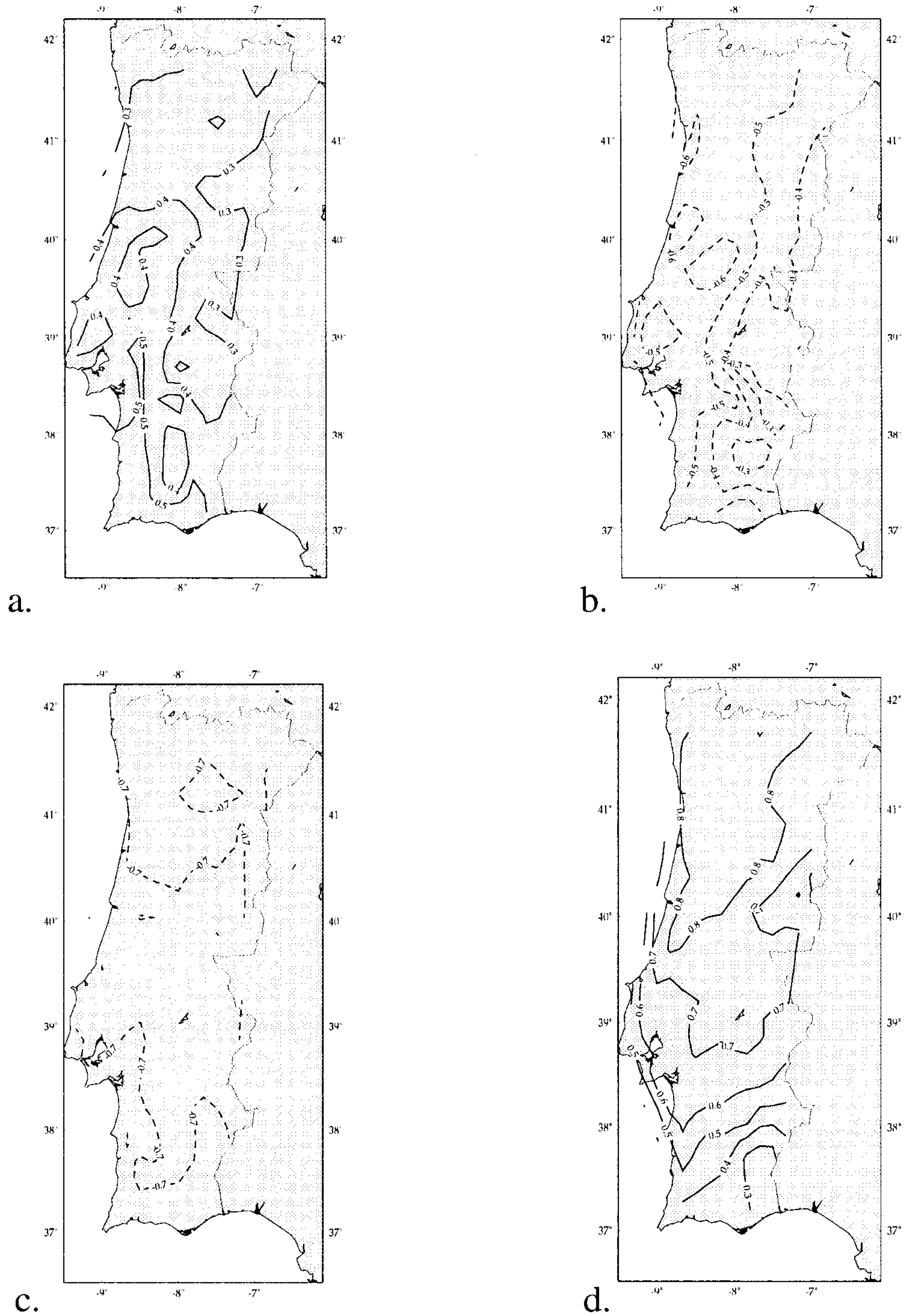


Figure 3. Correlation coefficients between monthly rainfall and frequencies of occurrence of different weather circulation patterns in Portugal. (a) The blocking-like pattern in June; (b) The summer dry pattern in June; (c) The winter dry pattern in December; (d) the rainy pattern in October

In order to study the details of interannual variability, SSA is applied to the year-to-year series of monthly rainfall, respectively for January, March, April and October, at Évora and Beja, as well as to the year-to-year series of the frequencies of occurrence of weather circulation patterns. Unfortunately, the

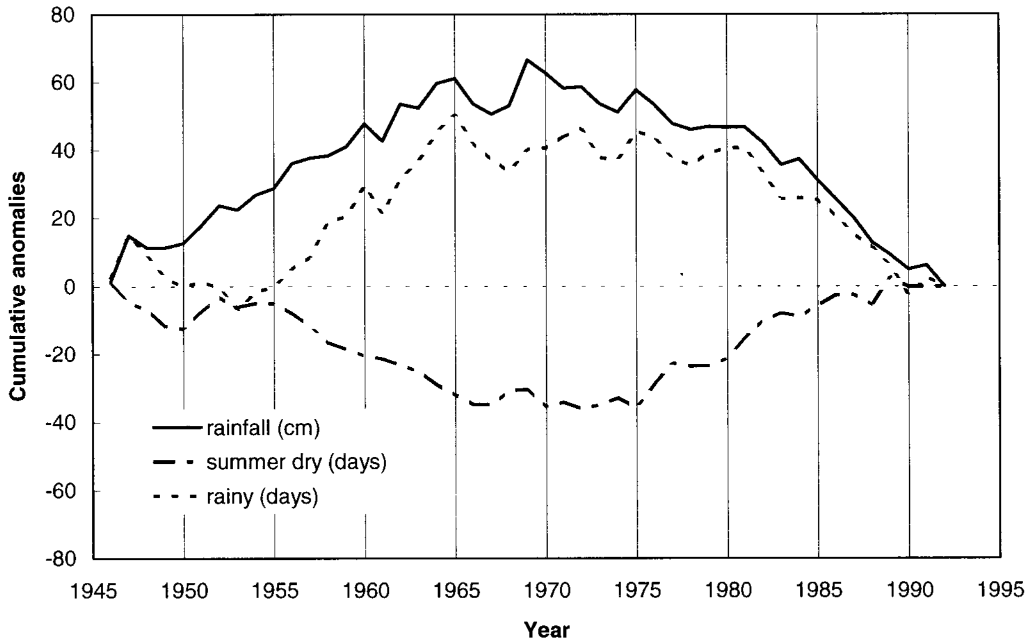
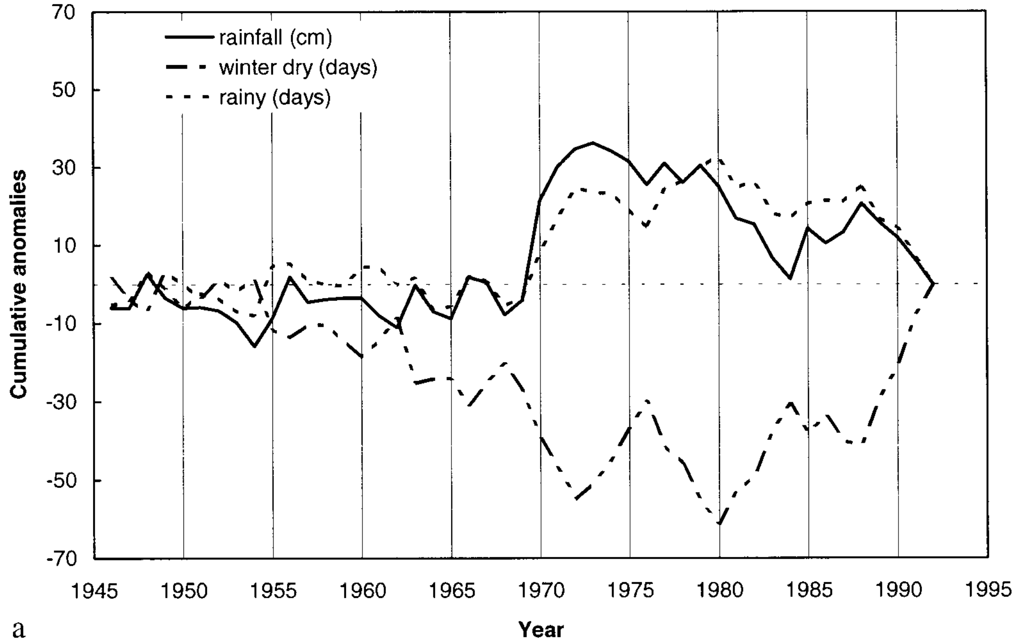


Figure 4. Cumulative anomalies of March monthly rainfall at Évora and number of days with occurrences of two different patterns in March

length of the available time series is too short to enable discussion of long-period oscillations, for example, that characterising interdecadal variability. For the specific months mentioned, oscillations with periods of 2.5–2.6 years, 3.6–3.7 years and 4.9 years are clearly isolated by SSA in both the rainfall series and the corresponding series of frequencies of occurrence of weather circulation patterns. Figure 6 shows some results of spectrum analysis from SSA, which imply that oscillatory pairs are well isolated. These oscillations are detected from many other series all over the world, and may be related to the quasi-biennial oscillation (QBO) and the El Niño/Southern Oscillation (ENSO) (Burroughs, 1992). Besides, an approximately 8-year oscillation is also identified from the rainfall series at Évora and the frequency of occurrence of the winter dry pattern in January. An interesting fact is that trends, isolated from the rainfall series and the series of frequencies of occurrence of both the rainy pattern and the summer dry pattern in March, usually explain a percentage of total variance as high as 20%. It is worth mentioning that while monthly rainfall usually more noticeably relates to the winter dry pattern, its trend in March is really associated with that of the summer dry pattern. Figure 7(a) shows the trends of rainfall at Évora and Beja, as well as frequencies of the rainy pattern and the summer dry pattern in March. It is clear that the same trends in rainfall are isolated at the two stations, and that they match the trend of the rainy pattern but oppose that of the summer dry pattern, although an approximately 5.6-year oscillation is mixed in the trend of the rainy pattern. The same trend is also isolated from the March monthly rainfall series during 1901–1994 (Figure 7(b)), although the variance explained by the trend is slightly smaller than that during 1946–1991. It is worth mentioning that the decrease of rainfall since the late 1960's is fast, a reduction being apparent of about 20 mm of monthly rainfall in about 30 years. The corresponding decrease in the number of days of occurrence of the rainy pattern is about 2.5 days; this would result in a decrease of rainfall of about 20 mm, because mean daily rainfall is 8.3 mm when the rainy pattern occurs. In the same period, the number of days of occurrence of the summer dry pattern has increased by about 2 days. Furthermore, the trend of reduction of occurrence of the rainy pattern is closely related to the variation of the intensity of the North Atlantic Oscillation (NAO). The correlation coefficient is -0.59 between the NAO index (provided by the Climate Prediction Center, NOAA, USA) and the frequency of occurrence of the rainy pattern in March, with confidence level 99.9%. This means that the rainy pattern occurs more frequently when the NAO is weak, and *vice versa*. Figure 8 shows the



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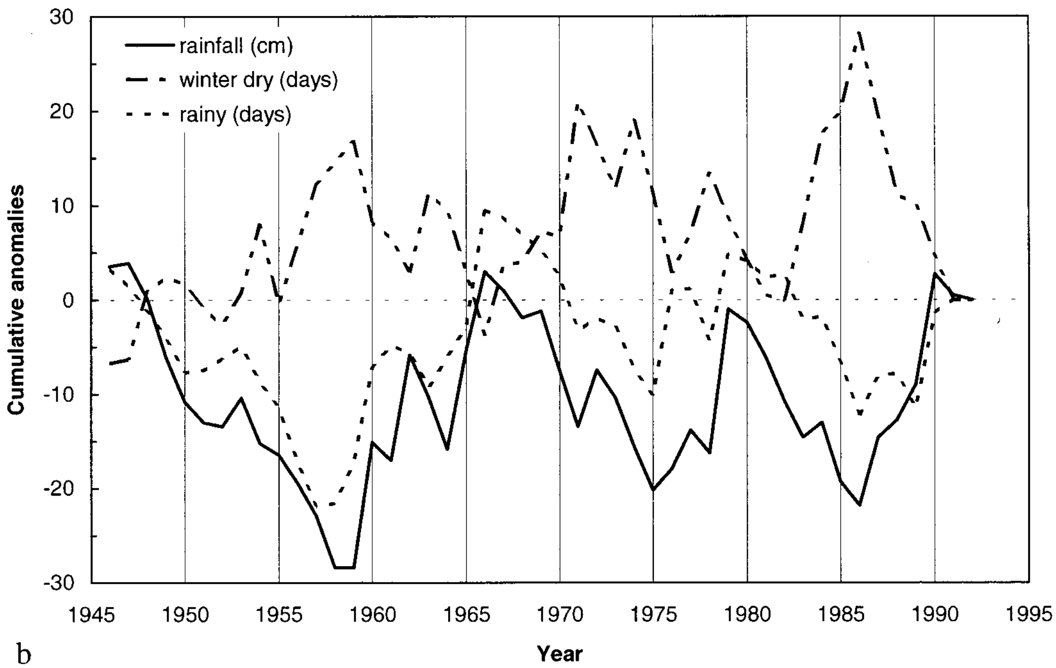


b

Figure 5. As in Figure 4 but for (a) January and (b) October

year-to-year variation of the NAO index in March during the period from 1950 to 1996. A trend of increase is clear in the series, especially since the 1980's. When the NAO gets stronger in March, the Azores high will get stronger also, and depression activities tend to be reduced in the eastern Atlantic west of the Iberian Peninsula. March monthly rainfall also exhibits a 4.9-year oscillation that relates to corresponding variability of the number of days of occurrence of the winter dry pattern (Figure 9(a)).

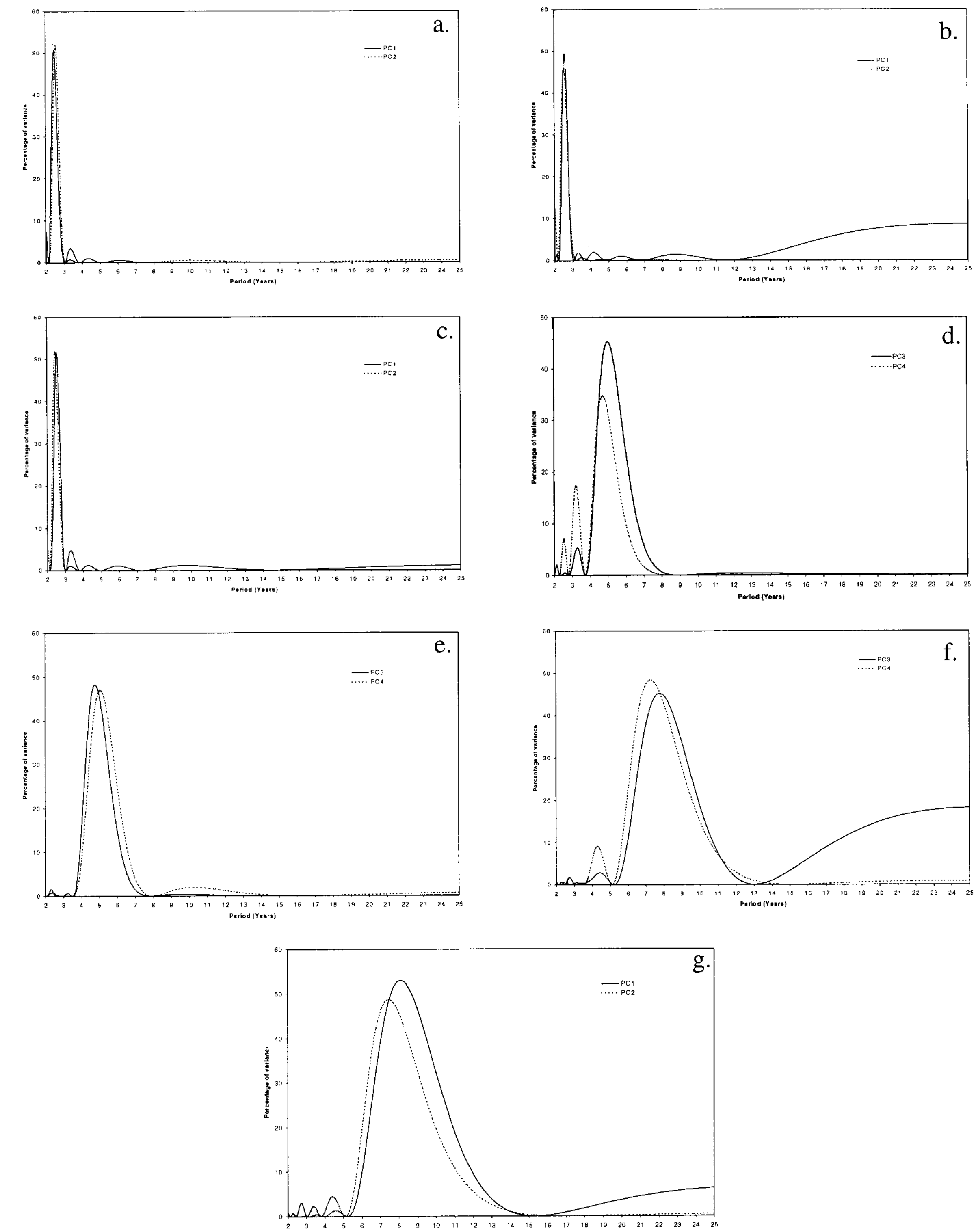
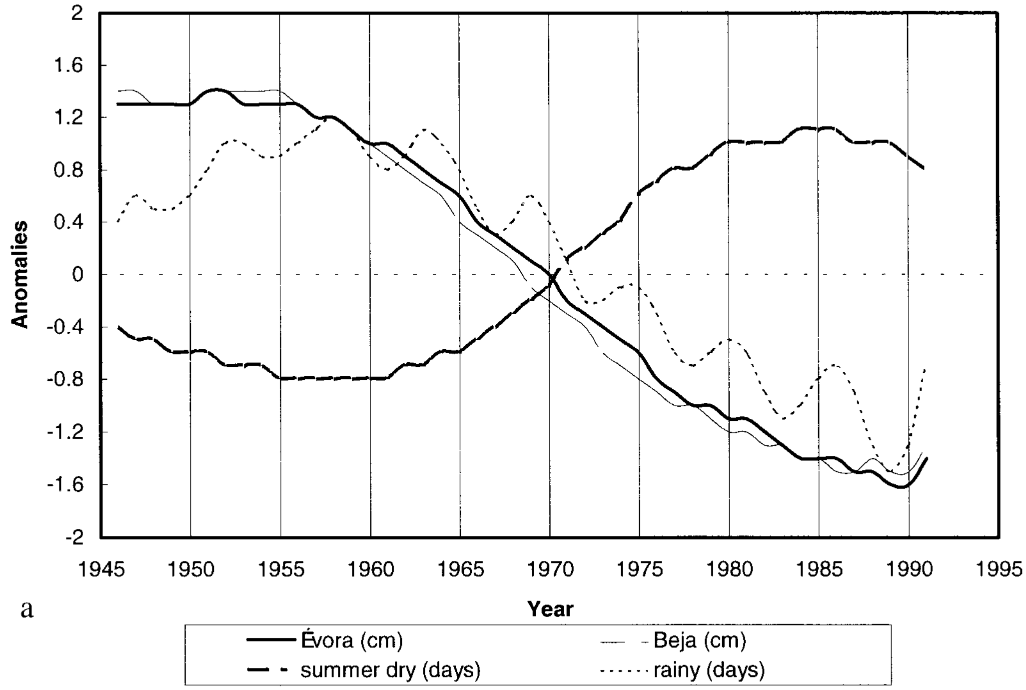


Figure 6. Variance fraction (%) of the indicated pair of PCs of (a) monthly rainfall in April at Évora (b) frequency of occurrence of the rainy pattern in April (c) frequency of occurrence of the winter dry pattern in April (d) monthly rainfall in March at Évora (e) frequency of occurrence of the winter dry pattern in March (f) monthly rainfall in January at Évora (g) frequency of occurrence of the winter dry pattern in January, derived by SSA with a window length of 15 years



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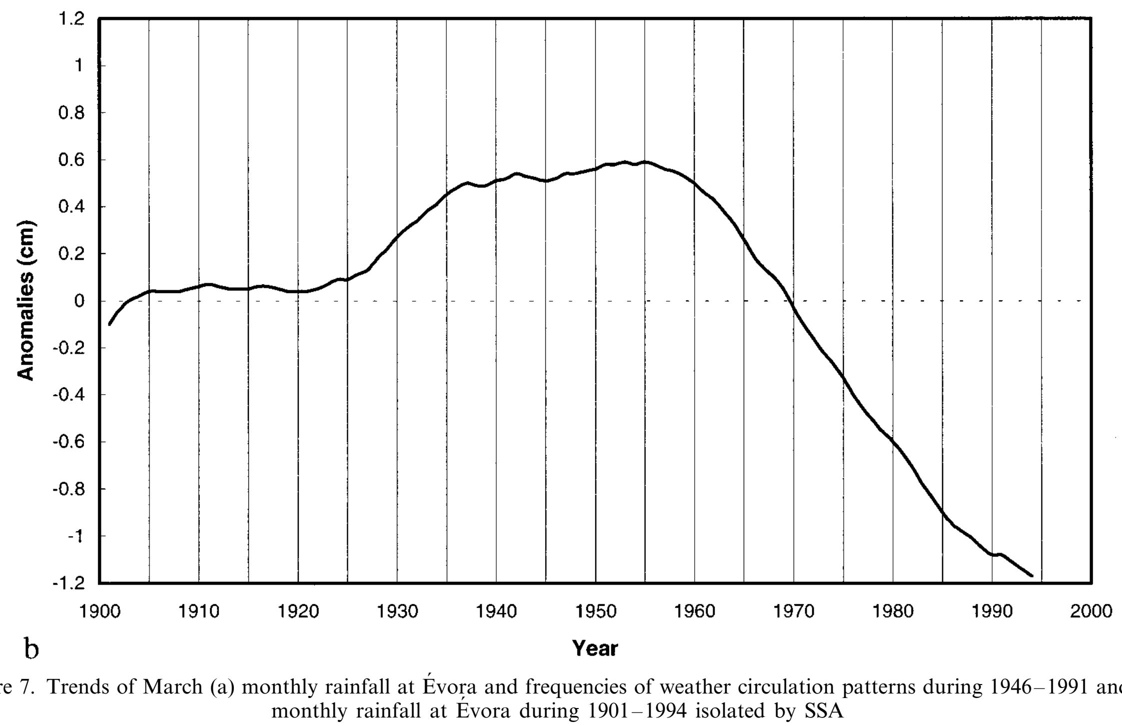


b

Figure 7. Trends of March (a) monthly rainfall at Évora and frequencies of weather circulation patterns during 1946–1991 and (b) monthly rainfall at Évora during 1901–1994 isolated by SSA

An interesting fact is that interannual variability of January monthly rainfall is not so noticeable before the 1970's. Figure 9(b) shows the periodic component of the 7.6-year cycle of rainfall at Évora and the corresponding one of the 7.8-year cycle of the winter dry pattern. It is evident that the amplitudes of both

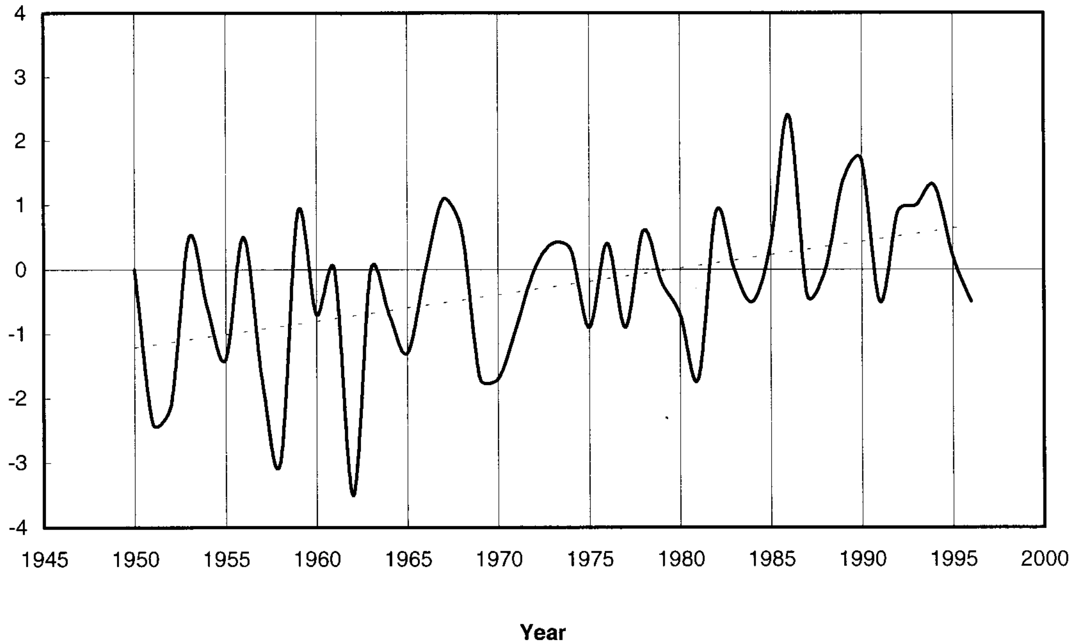
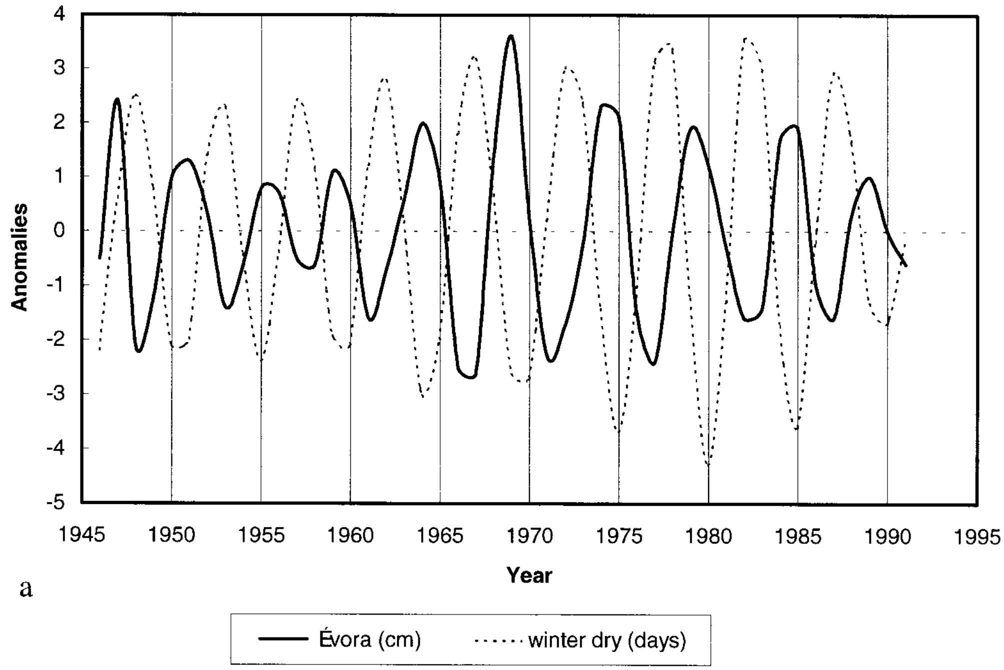


Figure 8. Year-to-year variation of the North Atlantic Oscillation index

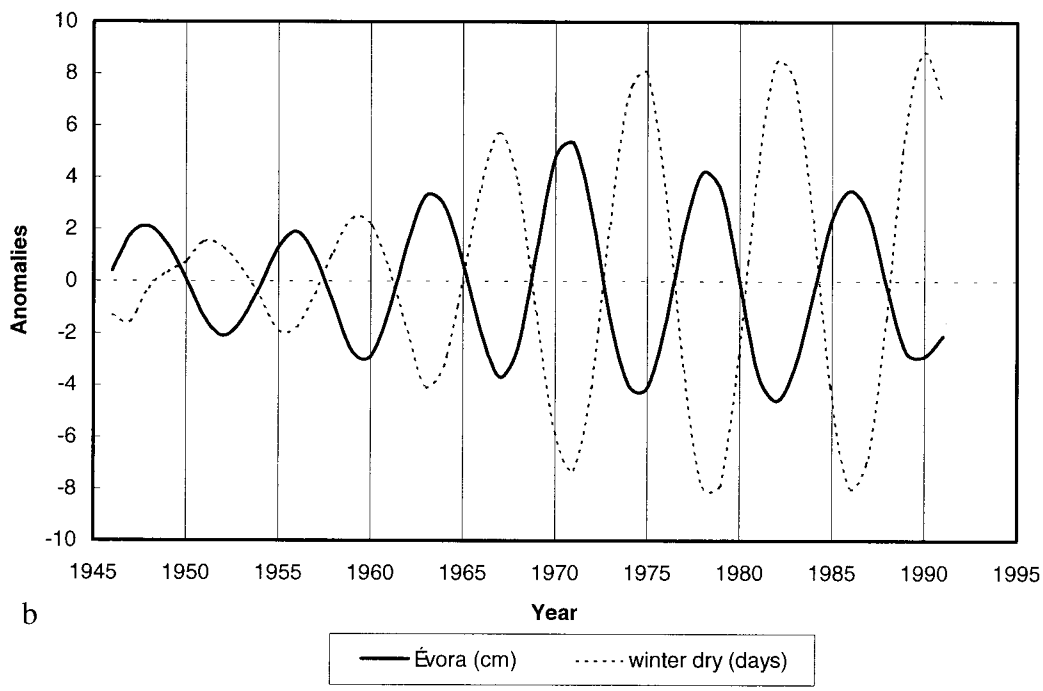
oscillations are small before the 1970's, the small amplitudes of the 7.6-year oscillation being one of the causes for insignificant interannual variability. A biennial oscillation is detected in most cases, although the significance is different. For example, a 2.5–2.6-year cycle is detected in all the analysed series in April, except in the number of days of occurrence of the blocking-like pattern. The variance explained by this oscillation is more than 20% for the two dry patterns and more than 30% for the rainy pattern and monthly rainfall. Figure 10 shows the corresponding components of the 2.5–2.6-year cycle in April. Rainfall at Évora and Beja is in phase with the rainy pattern, but out of phase with dry patterns.

5. CONCLUSIONS

In this study, four quasi-stationary weather circulation patterns, which relate to precipitation in Portugal, are identified from the large-scale atmospheric circulation, by the K-means clustering algorithm coupled with principal component analysis. Interannual variability of monthly rainfall, associated with that of weather circulation patterns, is also investigated by singular spectrum analysis. Except for the trend in March, quasi-biennial oscillations with periods of 2.5–2.6 years, and cycles associated with ENSO are detected. Relationships of comparative oscillations and trends in precipitation and weather circulation patterns are significant. All this means that: first, regional climate change in Portugal, during the past decades, has been associated with variation of large-scale atmospheric circulation; second, the four circulation patterns, classified in this study, represent the main weather regimes in Portugal and relate to large-scale atmospheric circulation on the interannual variability scale. It implies that these four patterns can be applied to validate GCMs by investigating if they can be identified on their daily output. Moreover, these four patterns can be used to assess regional scenarios of climate change in Portugal. These topics will be discussed in a future study.



a



b

Figure 9. Periodic components extracted by SSA of (a) 4.9-year oscillations of March monthly rainfall at Évora and the number of days of occurrence of the winter dry pattern (b) 7.6-year oscillation of January monthly rainfall at Évora and 7.8-year cycle of the number of days of occurrence of the winter dry pattern

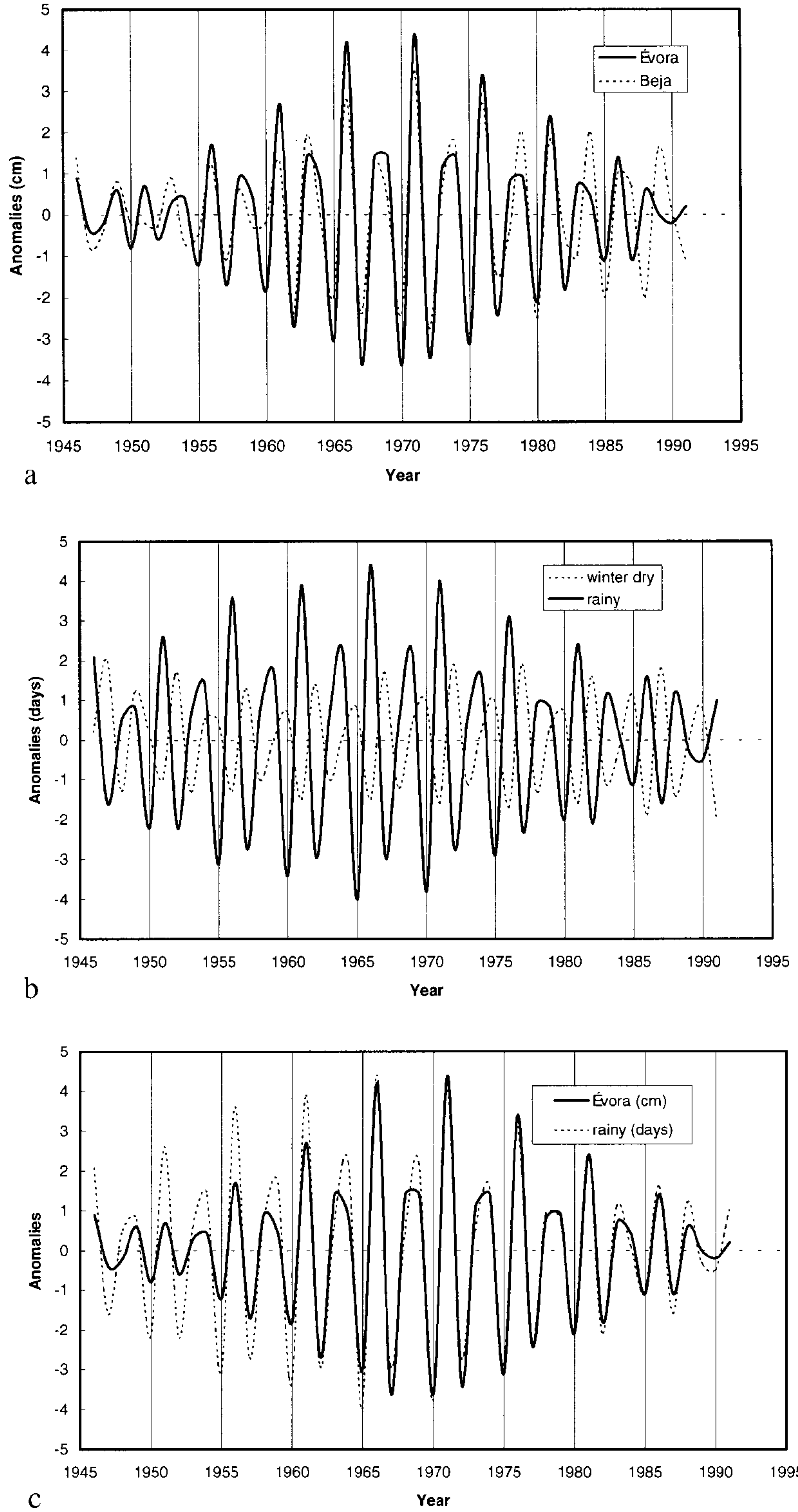


Figure 10. Periodic components extracted by SSA of (a) 2.5-year and 2.6-year cycles of monthly rainfall respectively, at Évora and Beja (b) 2.5-year and 2.6-year cycles of the number of days of occurrence of weather circulation patterns, respectively for the rainy pattern and the winter dry pattern (c) 2.5-year cycles of rainfall at Évora and the occurrence of the rainy pattern in April

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