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SPATIAL AND TEMPORAL PATTERNS OF PRECIPITATION IN SPAIN FOR THE PERIOD 1880–1992

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ABSTRACT

The longest series of precipitation records in Spain are analysed using the principal component analysis (PCA) method. EOF analysis was used to spatially summarise the rainfall data and to enable clarification of the role of the dominant circulation regimes affecting the region. Three significant EOFs have been obtained in general, except for summer, when four EOFs are found. The first EOF is associated with Andalusia and the Spanish interior, the second and third EOFs with the Mediterranean and Cantabric coasts, alternatively, depending on the season. The analysis of the principal components series using a moving average and the Mann–Kendall test, shows significant long term decreases in precipitation for the Mediterranean and interior regions (at least in some seasons), and an increase in precipitation for the Northern coastal region. More of these changes can be related to variations in the large scale circulation features over Western Europe and North Atlantic. The results are also compared with GCM outputs. © 1998 Royal Meteorological Society.

KEY WORDS: Spanish precipitation regime; PCA; circulation patterns; climatic change

1. INTRODUCTION

Climate change research is often focused on analysing trends in global average temperature and making assessments of the most likely trends in the future. This is because temperature is the weather variable that can be most confidently predicted at this time. However, a most critical need is to investigate whether global warming will cause changes in regional precipitation, and some authors have underlined the need for researching precipitation variability (Shuttleworth, 1996).

Recent predictions from general climate models have suggested a global increase in precipitation as a possible effect of the climate change due to the increase of greenhouse gases (IPCC, 1996).

However, this increase is not uniform in space or time. In fact, there are areas and seasons where a decrease in precipitation is expected. For example, these models suggest for the Northern Hemisphere, a winter increase and a summer decrease of precipitation in the mid-latitudes and a general decrease in the subtropical areas. Although these models can simulate the large atmospheric features in a realistic manner, and being adequate to predict global scale changes, the regional estimates are less accurately resolved. Different models give different estimations (IPCC, 1996), in particular for southern Europe. This point addresses the necessity to improve our knowledge on linkages between the large and regional scales, and the ability to identify which features of the regional climate can have important implications for hydrological resources under various climate change scenarios.

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On the other hand, in order to assess the significance of any projected climatic change, the historical records of the variability must be examined to see the predicted conditions from a wider perspective (Bradley *et al.*, 1987). Therefore, the main aim of this paper is to study the long term variation of the precipitation in Spain, a country situated in a meteorologically complex area, between the mid-latitudes and the northern subtropics, between two great seas, the Atlantic Ocean and the Mediterranean Sea, and two continents, Africa and Europe. The climate literature on precipitation fluctuations in southern Europe is scarce: there have been some studies conducted in the Meditarranean area (Maheras, 1988; Maheras *et al.*, 1992), but the database used in these studies are limited in space and time. There have been also some studies of rainfall changes in Italy (Palmieri *et al.*, 1991) and in the Balkans (Maheras and Koliva-Machera, 1990; Amanatidis *et al.*, 1993). Furthermore, Spain is located in the circumpolar vortex border (Capel Molina, 1981) and its climate is closely linked with the atmospheric circulation. The climate response of this area is also very interesting due to the current problems provoked by the droughts and other extreme events, and by the unclear predictions of the models in the Mediterranean area (IPCC, 1996). Extreme events are considered by some authors (Katz and Brown, 1992; Shuttleworth, 1996) as a good indicator of climatic change.

The identification of spatial scales associated with temporal scales of the climatic features is a prerequisite to establish over which regions it is possible to study the common climatic evolution (Gazdil and Yoski, 1983). Principal component analysis (PCA) is a multivariate technique which allows one to obtain patterns of the simultaneous variations of a field or a variable. This is specially useful if one wants to study this evolution in an area where several factors converge, as is the case for Spain, where, besides geographical position, it is orographically complex. EOF analysis was used to spatially summarise the rainfall data and enable clarification of the role of the dominant circulation regimes affecting the region. This paper attempts to identify coherent regions with similar behaviour, to detect and quantify possible changes in the last century, and link them with possible causes.

2. DATA

The database used in this study comprises annual and seasonal total amounts of precipitation for 40 Spanish localities, covering the Iberian Peninsular area and Baleares Islands (see Figure 1). They were selected from a set of 65, supplied by the *Instituto Nacional de Meteorologia* (INM), having met quality criteria.

Most of the stations have not changed their position, but the metadata relative to methods and instruments is known for only a few. The absolute homogeneity of the records was evaluated using the Thom and Bartlett tests (Mitchell, 1966; Thom, 1966). These methods were also used to check the relative homogeneity, analysing the ratio series obtained for neighbouring locations (Bradley *et al.*, 1985; Rhoades and Salinger, 1993). Only the station of Avila possessed an inhomogeneity problem. For its correction, the data from Segovia, a locality very closed to Avila and with a similar altitude have been used, following the Bradley *et al.* (1985) scheme.

Table I summarises these series, their temporal coverage, the altitude of each locality, and some statistical parameters. At least 60% of the series have data from 1880 (89% have data from 1901) and 30 series (75%) have data until 1992 (90% if we consider the series with data until 1988). When just a single monthly value was found to be missing, the data gap was replaced by the average of all the values for the same month.

3. METHOD

In order to extract the general behaviour of all series, principal component analysis was applied (PCA) (Preisendorfer, 1988). Briefly, given p variables (anomalies) of length n corresponding, for example, to p locations, $u_x = (t)$, $x = 1, \ldots, p$; $t = 1, \ldots, n$, the method consists of the diagonalisation of the covari-

Table I. Locations used in this paper, their altitude and statistical parameters

Station	Altitude (m a.s.l.)	Period	Average (mm)	Standard dev. (mm)	Minimum (mm)	Maximum (mm)	Q_{25} (mm)	Q_{75} (mm)	Skewness	Kurtosis
Huelva	26	1903–1992	477	153	161	911	363	582	0.4	−0.2
Córdoba	91	1901–1992	639	217	255	1297	478	751	0.9	0.7
Sevilla (T)	8	1871–1992	561	179	159	1063	431	657	0.6	0.1
Jerez	27	1912–1992	618	177	316	1132	496	704	0.7	0.1
Almería	7	1911–1991	210	80	63	552	153	246	1.3	3.2
San Fernando	30	1840–1989	611	195	300	1273	465	713	1.0	1.1
Jaen	510	1863–1983	619	182	240	1116	490	715	0.7	0.2
Málaga	53	1878–1990	520	173	196	1154	387	598	1.1	2.2
Mallorca	6	1869–1988	454	116	163	777	387	526	0.1	0.0
Menorca	82	1880–1991	616	138	275	971	529	699	0.2	0.0
Barcelona	94	1850–1988	582	157	272	1049	462	656	0.7	0.4
Gerona	94	1906–1992	802	234	420	1626	612	954	1.0	1.6
La Coruña	67	1877–1992	908	219	359	1399	758	1043	-0.1	−0.3
Santiago	260	1859–1988	1637	397	616	3169	1428	1853	0.5	1.7
Soria	1080	1865–1992	555	121	281	869	471	632	0.4	−0.2
Burgos	854	1862–1991	536	117	303	871	455	608	0.5	0.1
Palencia	750	1913–1988	395	98	225	627	329	464	0.6	−0.2
Valladolid	735	1859–1992	389	107	140	729	317	457	0.4	0.3
Avila	1130	1911–1992	365	84	200	678	314	392	1.2	3.0
Segovia	1005	1901–1992	491	124	292	1035	397	555	1.2	3.1
Zamora	667	1909–1992	342	117	155	666	257	409	0.9	0.5
Salamanca	782	1859–1985	367	109	122	684	288	430	0.5	0.3
Madrid	667	1853–1992	432	104	240	747	360	505	0.7	0.3
Toledo	540	1908–1982	370	82	191	575	312	422	0.2	−0.2
Cáceres	459	1907–1983	504	143	254	1008	400	616	0.7	0.7
Ciudad Real	629	1866–1992	409	126	54	857	352	465	0.3	2.2
Badajoz	195	1864–1991	486	150	183	1117	377	567	1.1	2.1
San Sebastián	259	1878–1992	1465	310	670	3011	1259	1665	0.9	4.4
Santander	65	1912–1992	1211	196	812	1732	1062	1372	0.1	−0.3
Gijón	10	1913–1992	990	160	698	1470	904	1082	0.7	1.1
Murcia	66	1862–1984	316	112	99	765	238	358	0.9	1.4
Alicante	82	1856–1992	357	130	122	673	272	438	0.6	−0.1
Cuenca	945	1908–1992	552	142	265	984	456	641	0.6	0.4
Valencia	11	1859–1992	455	178	154	1289	334	554	1.3	3.3
Castellón	25	1911–1975	440	161	220	1026	332	538	1.2	2.0
Reinosa	855	1910–1992	989	205	550	1644	849	1101	0.5	0.8
Vitoria	550	1919–1992	866	180	524	1316	723	970	0.3	−0.5
Pamplona	442	1880–1992	855	333	457	2334	645	934	2.2	3.0
Zaragoza	233	1858–1985	327	896	171	658	262	374	0.8	1.1
Huesca	542	1860–1992	556	158	248	1135	449	613	1.1	1.5

ance/correlation matrix, (S/R). The empirical orthogonal functions (EOFs), $e_j(x)$, $x, j = 1, \ldots, p$ are the eigenvectors with an associated variance equal to their corresponding eigenvalue.

In a strict sense, the analysis can only be performed when the database is complete (in this case, 1919–1984, since this is the common period for all the series), but there are often irregularly distributed gaps in the data. In this case it is possible to undertake PCA for a longer period, calculating each element of the covariance matrix for the common period between the two series involved u_i, u_j (von Storch and Zwiers, 1993). However, this can lead to a poor estimation of the correlation/covariance matrix, in that some of its eigenvectors are less than 0. In general, when these eigenvalues are few and small (in absolute value), the problem does not need any special consideration, although it is possible to correct for this effect (Guiot, 1983). As usual, the eigenvectors of the estimated matrix are the EOFs that represent the patterns set of the system. In this case, the principal components series a_j are obtained by minimisation of $|u_k - a_i e_i|$. The least square fit (von Storch and Zwiers, 1993) is given by

$$a_j(t) = \frac{\sum_x u_x(t) e_j(x)}{\sum_x e_j^2(x)} \tag{1}$$

where the sums are formed over those x for which $u_x(t)$ is available.

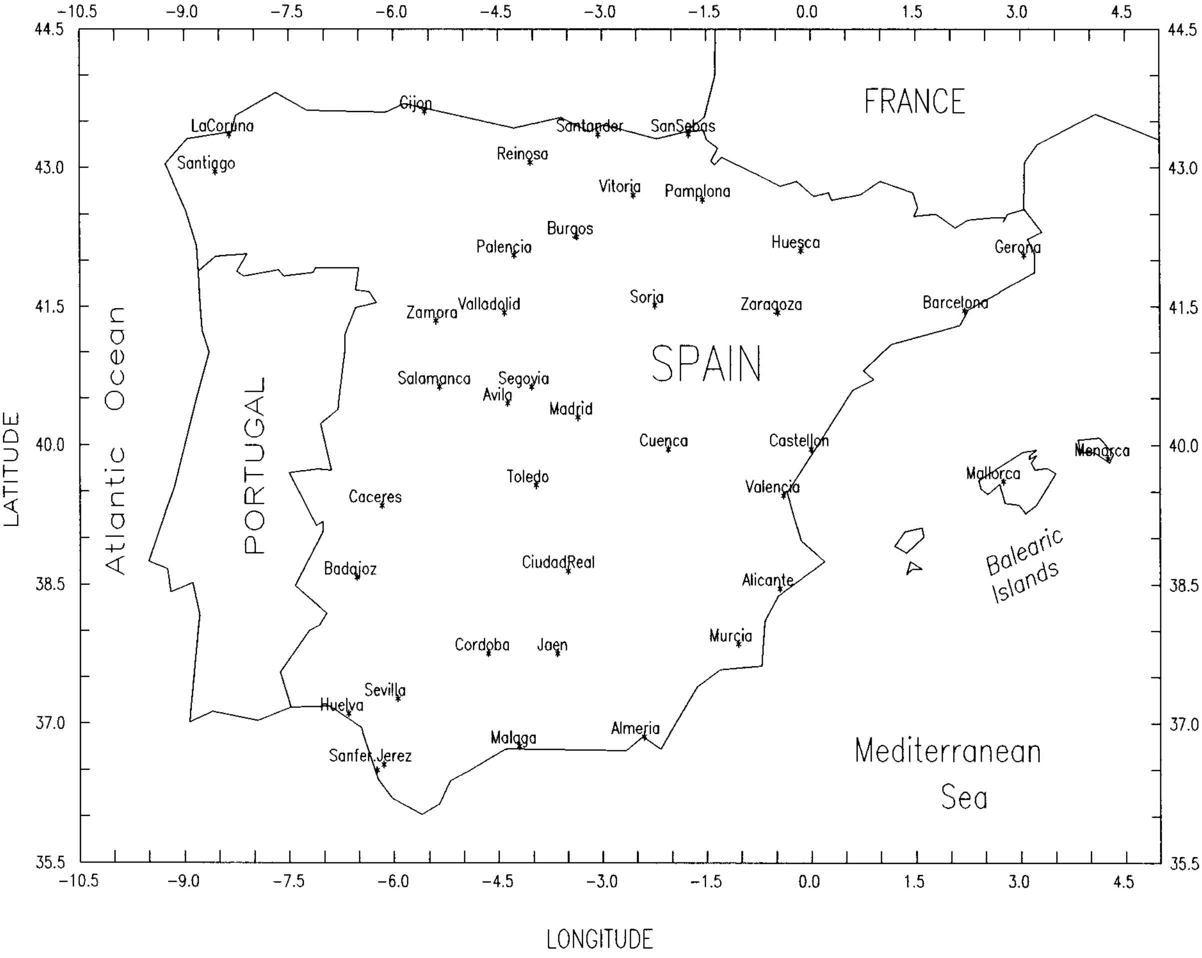


Figure 1. Location of the Spanish stations included in the data base

The N-rule (Preisendorfer, 1988) was applied in order to select the number of the significant EOFs. This is a MonteCarlo procedure to obtain the eigenvalue distribution of random covariance matrix. An alternative and possibly better interpretation of the results can be obtained rotating the significant EOFs by the Varimax procedure (Preisendorfer, 1988).

In this paper, EOFs of the Spanish precipitation anomalies for the period 1919–1984 have been analysed; this does not affect the EOFs interpretation (Esteban-Parra, 1995). On the other hand, the PCA series for the period 1880-1992 has been obtained using Equation (1). This does not affect the values of the PC series in the common period, and in this way we can extend the temporal coverage. However, the results will be less reliable for these other periods (see data temporal coverage in Section 2).

The method used for detecting trends and abrupt changes in the PC series is the sequential Mann–Kendall test. Descriptions of this non-parametric test can be found in Sneyers (1975), Goossens and Berger (1986) and Esteban-Parra *et al.* (1995). One problem in applying this test is the presence of the serial correlation in the data (Kulkarni and von Storch, 1995), so some cautions should be kept in mind when this test is applied.

The test consists of the graphical representation of two curves, computed in a similar manner. Mathematically, an abrupt change is a particular case of a trend. It is characterised by two stable sub-series with different means. We have a significant trend when the curve C_1 passes through the 5% significance level. For an abrupt change, the curve C_1 will not present a trend for the first sub-series (with a determinate mean), and will pass the 5% significance level after the point of change, when the second sub-series begins. On the other hand, the retrograde curve, C_2 (which is equivalent to C_1), will not present a trend for the second sub-series. Therefore, it will not pass the significance level. However, both curves have the same behaviour at the change point. Consequently, the two curves must intersect at this point.

4. RESULTS

4.1. EOF patterns

Figure 2 shows the significant seasonal and annual patterns of the (varimax) rotated EOFs of Spanish precipitation anomalies by drawing the isolines of the loading factor values. Table II shows the percentage of variance explained by each EOF.

The first rotated EOF pattern (Figure 2(a)) is centred principally on Andalusia and the interior part of Spain. In this region, precipitation is associated with westerly circulation, common to polar maritime (mP) and tropical maritime (mT) air masses. According to Capel Molina (1981), the most frequent flows are from the southwest, followed by west and then northwest. It can be observed that most of the mountain ranges in Spain (except for the Iberian and Penibetic ranges) have a west–east orientation. They do not impede the dominant westerly circulation regime prevailing from October to May. During the summer, this circulation is weaker, due to blocking of the Azores high, resulting in a meridional circulation anomaly (this fact is shown by the breaking of this eigenvector in two for the summer, one associated with the southern part (1st EOF, Figure 2(a)) and the other with the Central and North Plateaux (2nd EOF, Figure 2(b)). So, the summer is the only season with four significant EOFs instead of three.

The second and third EOFs (Figure 2(b, c)) are associated alternatively with the precipitation regimes in the Mediterranean and the Cantabric Coast (northern coastal stations), depending on the season. The second rotated EOF patterns for annual and spring and the third EOF for autumn and winter are associated with the Mediterranean Coast. The precipitation is produced by easterly flows, associated with meridional incursions of maritime polar air which comes from the Atlantic Ocean and flows into the Mediterranean sea after rotating in a cyclonic manner (Capel Molina, 1981), or from a tropical continental air mass (Lines, 1980). The warm humid east and southeast winds from the Mediterranean Sea lead to heavy convective precipitation over the region, especially when there is colder air at high levels.

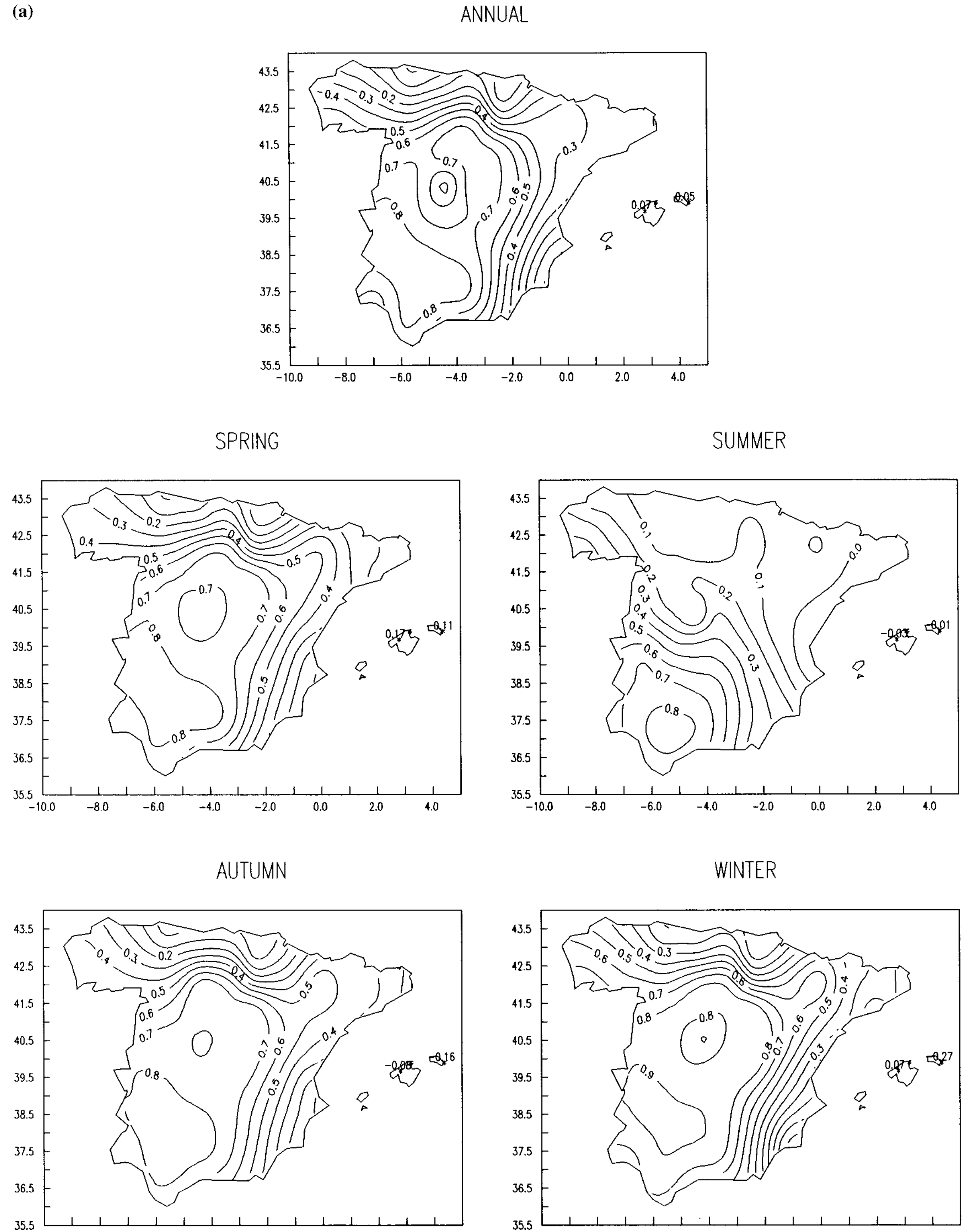


Figure 2. Seasonal and annual rotated EOF rainfall patterns for the period 1919–1984 for (a) 1st EOF; (b) 2nd EOF; (c) 3rd EOF; (d) 4th EOF

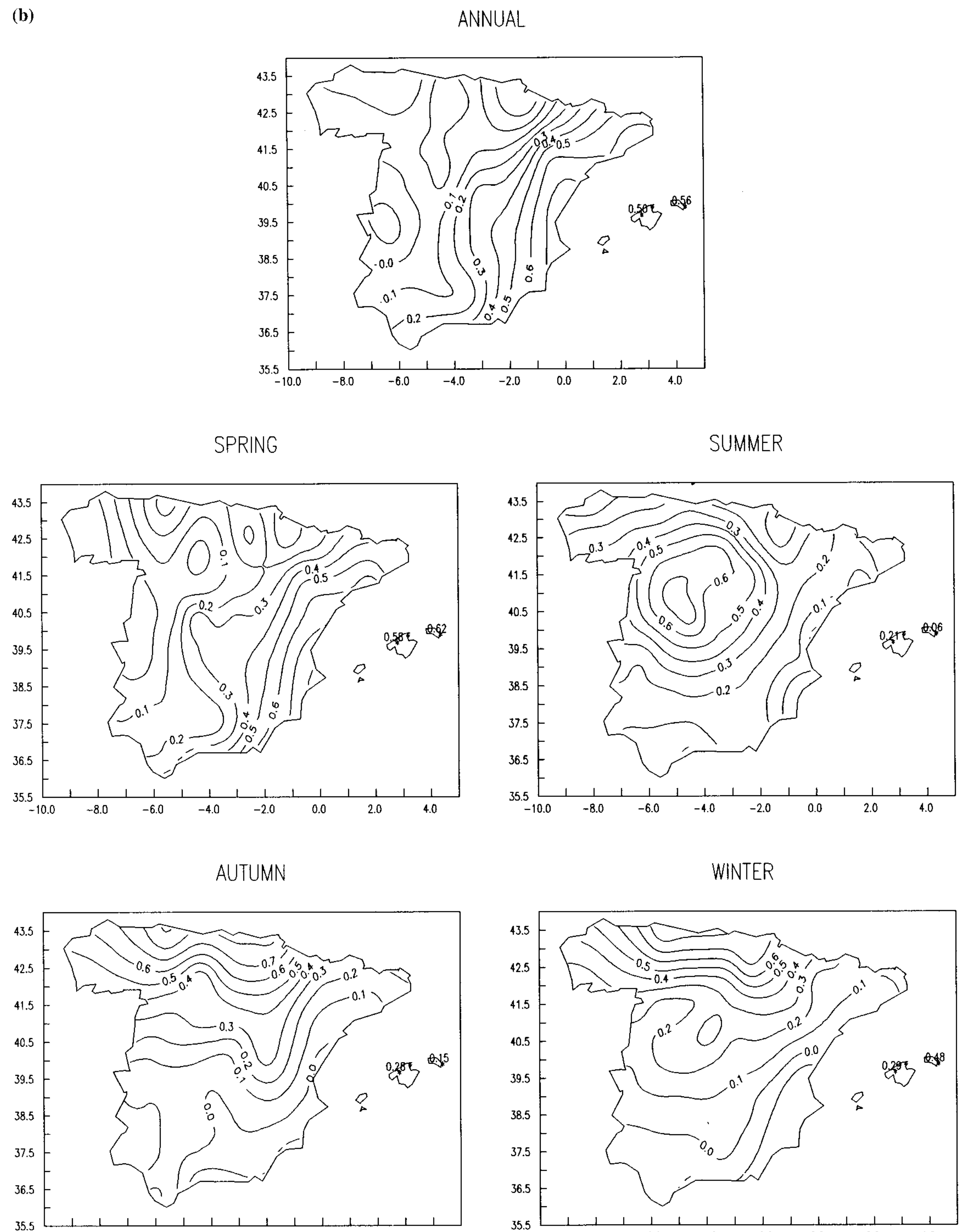


Figure 2 (*Continued*)

The second eigenvector for winter and autumn data and the third for annual, spring and summer data show the regime associated with the northern Cantabric Coast. This region is characterised by large amounts of precipitation. An important factor for precipitation in this area is the confluence of coastal

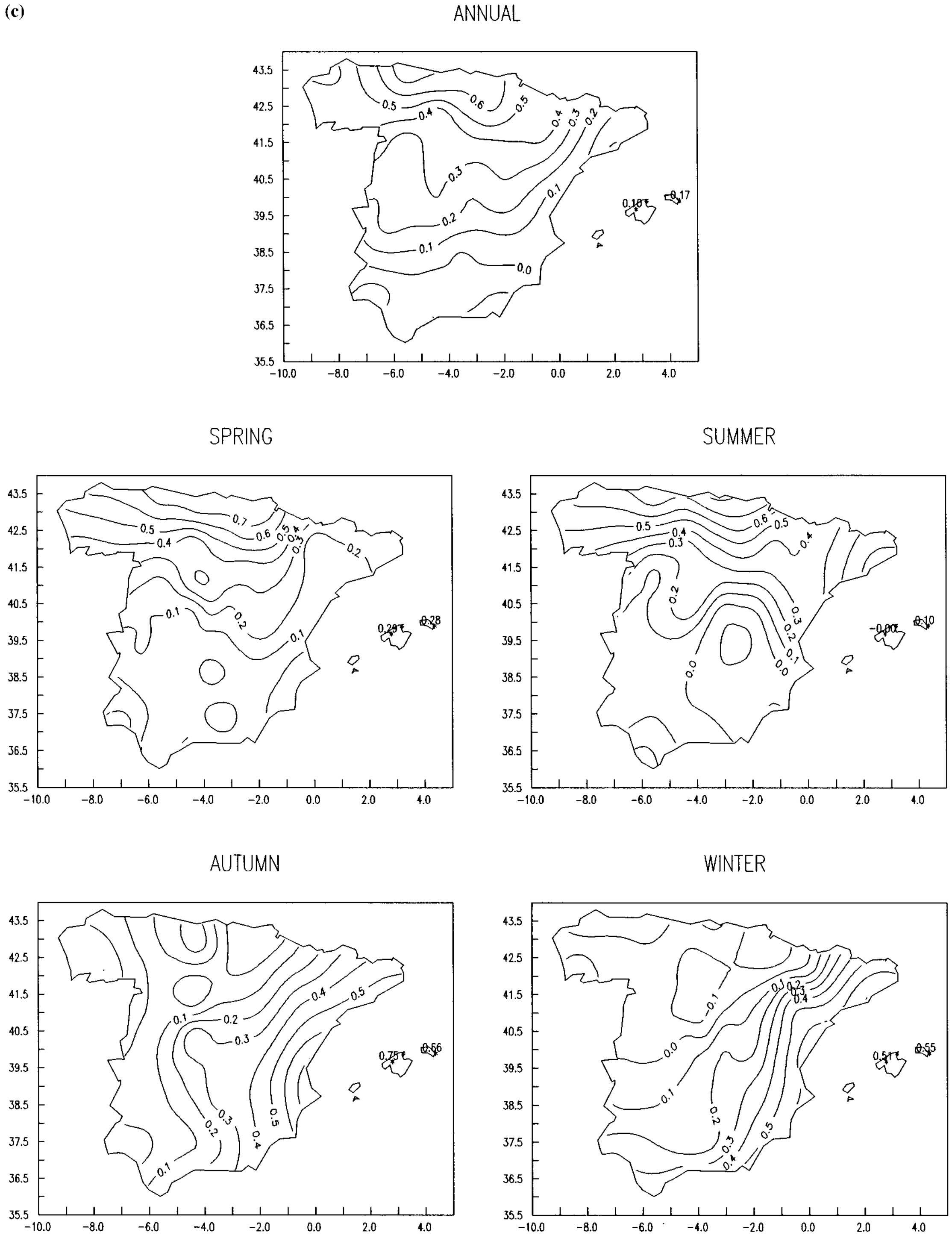
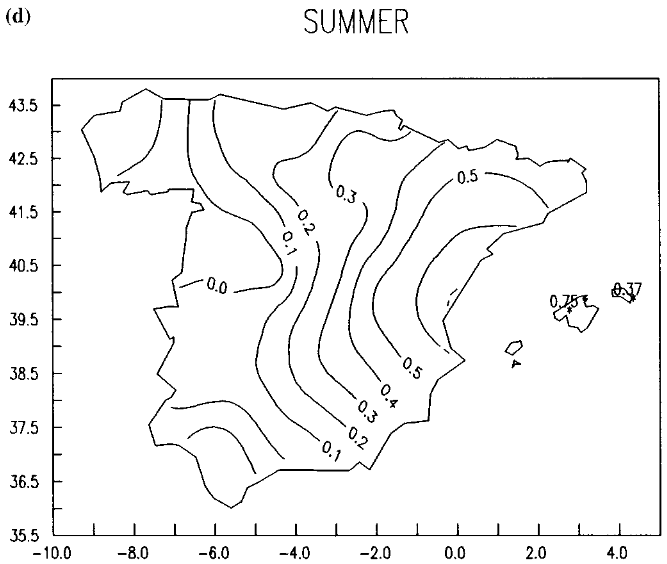


Figure 2 (*Continued*)

mountains. The precipitation originates in a meridional north or northwest circulation, associated with polar maritime and arctic maritime air masses. Cold air which arrives in the Iberian Peninsula with a high vertical instability is due to thermal subversion (Capel Molina, 1981).



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4.2. Principal component time series

As noted previously, the principal component time series for the period 1880–1992 was obtained. The interpretation of the eigenvectors for this period is the same as the period 1919–1984. The characterisation of the periods as wet or dry has been done using 10-year moving averages. The left hand side of Figure 3(a–c) shows the annual and seasonal series with the corresponding smoothed series, identifying the longer term variability.

The first annual series, associated with the Andalusia and Peninsular interior begins with rainy years, followed by a slightly dry period between 1893 and 1930. There is a relatively rainy period from then until 1945.

During the 1950s, there is a drier than normal period. The 1960s, and to a lesser extent, the 1970s, are very rainy. The 1980s are characterised as a dry period.

For the second EOF annual series (Figure 3(b)), corresponding to the Mediterranean area, the series until about 1910 is relatively wet. This is followed by moderately dry years until 1945, with some very wet years in the 1930s, and a general increase in precipitation until 1970. The last period, from 1976, is characterised by a severe drought.

The third EOF annual series (Figure 3(c)), associated with the Cantabric Coast begins with a dry period, lasting until *ca.* 1920. The following years, 1920–1940 and 1960–1985 were very rainy, while 1944–1960 was moderately dry.

Table II. Percentages of explained variance for each unrotated and rotated EOF for the annual and seasonal data

EOFs	Annual	Winter	Spring	Summer	Autumn
1st EOF unrotated	34.3	44.1	35.7	25.0	38.5
2nd EOF unrotated	12.0	13.7	11.2	13.5	11.5
3rd EOF unrotated	8.3	7.7	9.8	7.1	10.0
4th EOF unrotated				5 9	
1st EOF rotated	31.2	42.1	32.1	15.9	34.7
2nd EOF rotated	13.2	11.7	14.5	12.7	13.2
3rd EOF rotated	10.3	11.6	12.6	11.8	12.2
4th EOF rotated				11.0	

With regards to the seasonal series, the last decade represents low precipitation except for the Cantabric series during the winter (2nd EOF) and spring (3rd EOF). The autumn series corresponding to Andalusia and the interior (1st EOF) and the Mediterranean (3rd EOF) only show a rainy year (1989) in this decade, when very large amounts of precipitation occurred. This is also reflected in the annual time series.

Looking at the annual series associated with the three regions, it is possible to distinguish in a general way, a dry period from 1910 to the middle of the 1920s and a wetter period during the 1960s and the 1970s. The concordance between the series corresponding to Andalusia and the interior (1st EOF) and the Cantabric region (3rd EOF) is also shown in the humid 1930s and the drier years from 1945 to the late 1950s.

4.3. *Trends and abrupt changes*

This Section deals with identifying the presence of trends and abrupt changes in the PC time series. For these series, the serial correlation is very small (not significant at 95% level). The right hand side of Figure 3 also shows the result of the Mann–Kendall test applied to the rotated principal component series.

As can be seen, a very clear abrupt change leading to an increase is present in the Cantabric area for the annual (3rd PC series) and winter (2nd PC series) *ca.* 1920. There is also a clear abrupt change towards a decrease for the annual series of the Mediterranean region in 1908 (2nd PC series). Decreases

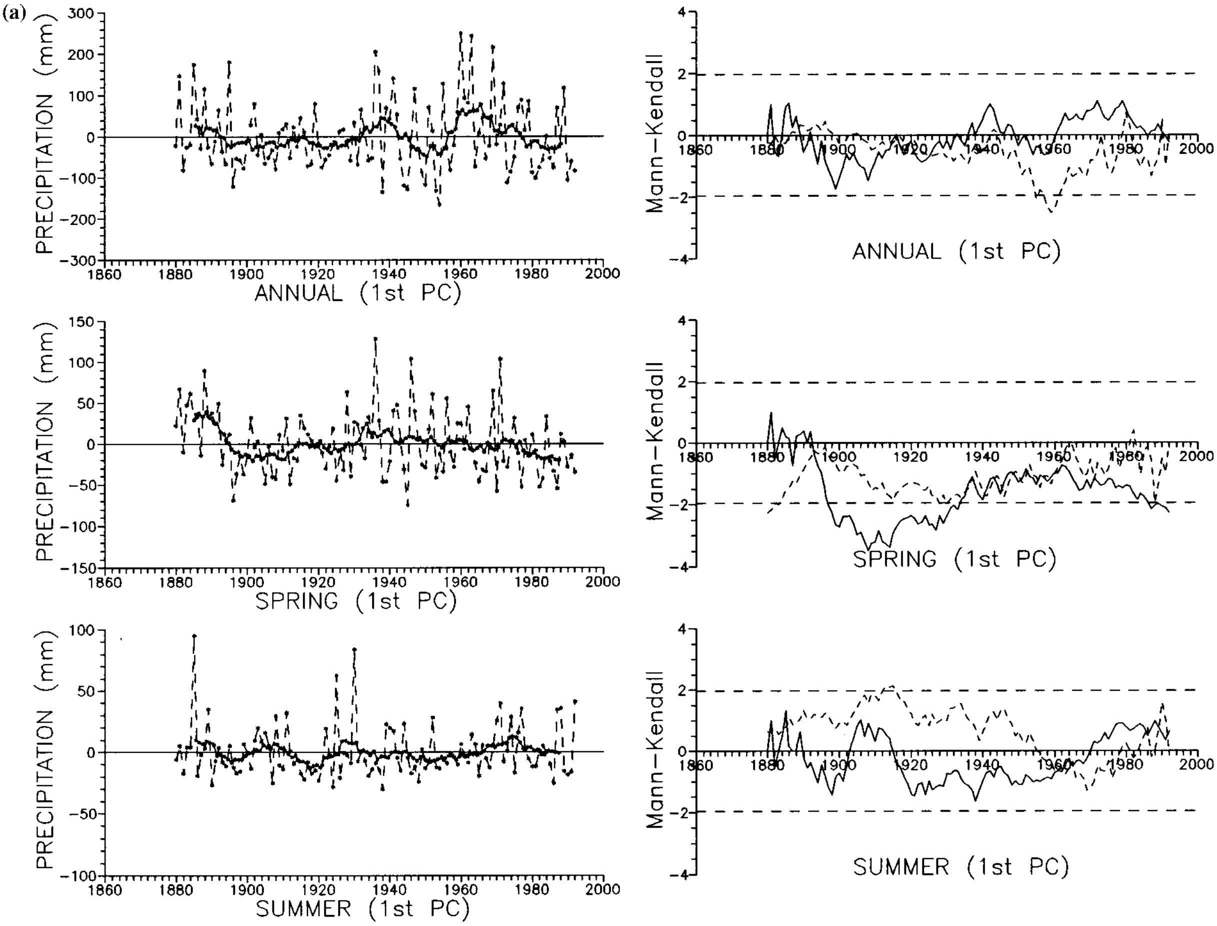


Figure 3. Rotated PC series (dashed) and the 10-year moving average (solid). On the right hand side the corresponding sequential version of Mann–Kendall test appears (C_1 solid line; C_2 dotted line):(a) Andalusia and interior series; (b) Mediterranean area series; (c) Cantabrico and Northwest area series

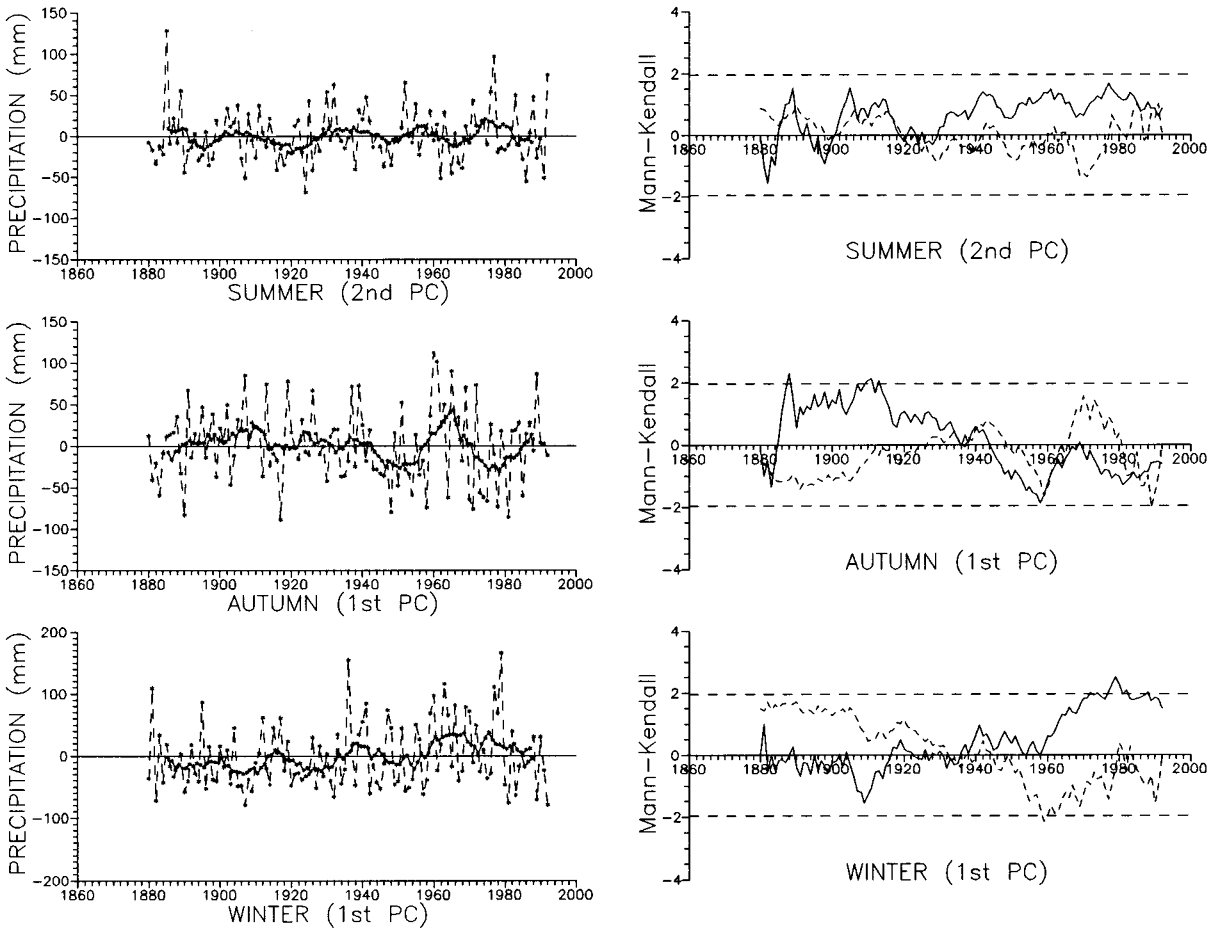


Figure 3 (*Continued*)

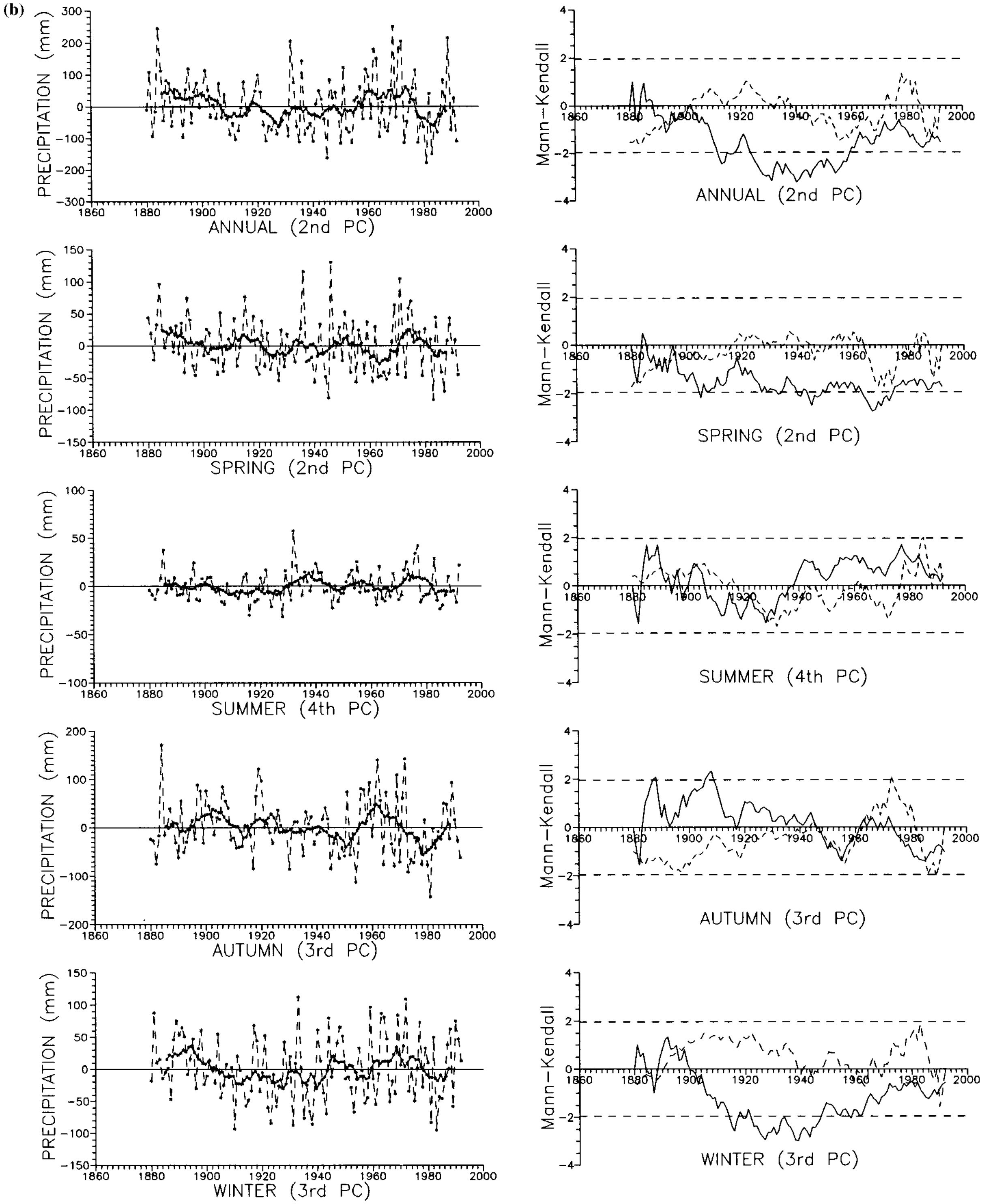
in abrupt changes (near the significance level) take place in spring in the south and interior (1st series) *ca.* 1890, and in the Mediterranean area (2nd series) in 1900. Other changes have lost their significance at the end of the series as, for instance the abrupt changes in autumn (towards an increase in 1920) in the Cantabric Coast (2nd series) and in winter (towards a decrease in 1890) in the Mediterranean (3rd series).

Table III shows the differences between the average values of the period 1980–1992 and other specified periods. The significance of these differences have been tested using the *t*-test. The test was omitted for the summer, as there were not significant changes.

The differences in precipitation between the 1930s and 1980s in the Cantabric region, indicate the high precipitation during the 1930s. Further, the values confirm an increase in precipitation after 1920. Almost all the quantities are negative or close to zero for the Mediterranean area, although only the difference between 1910 and 1920 and in the 1980s is significant during the autumn. For Andalusia and the interior area, the decreases are more significant, in particular for the annual series. Although the 1980s seems to be the drier decade, the differences between this decade and the 1920s are clearly not significant.

5. DISCUSSION

Annual precipitation is basically related to the precipitation from September to May as the correlations between the annual and seasonal PC series show (Table IV). All correlation coefficients between annual



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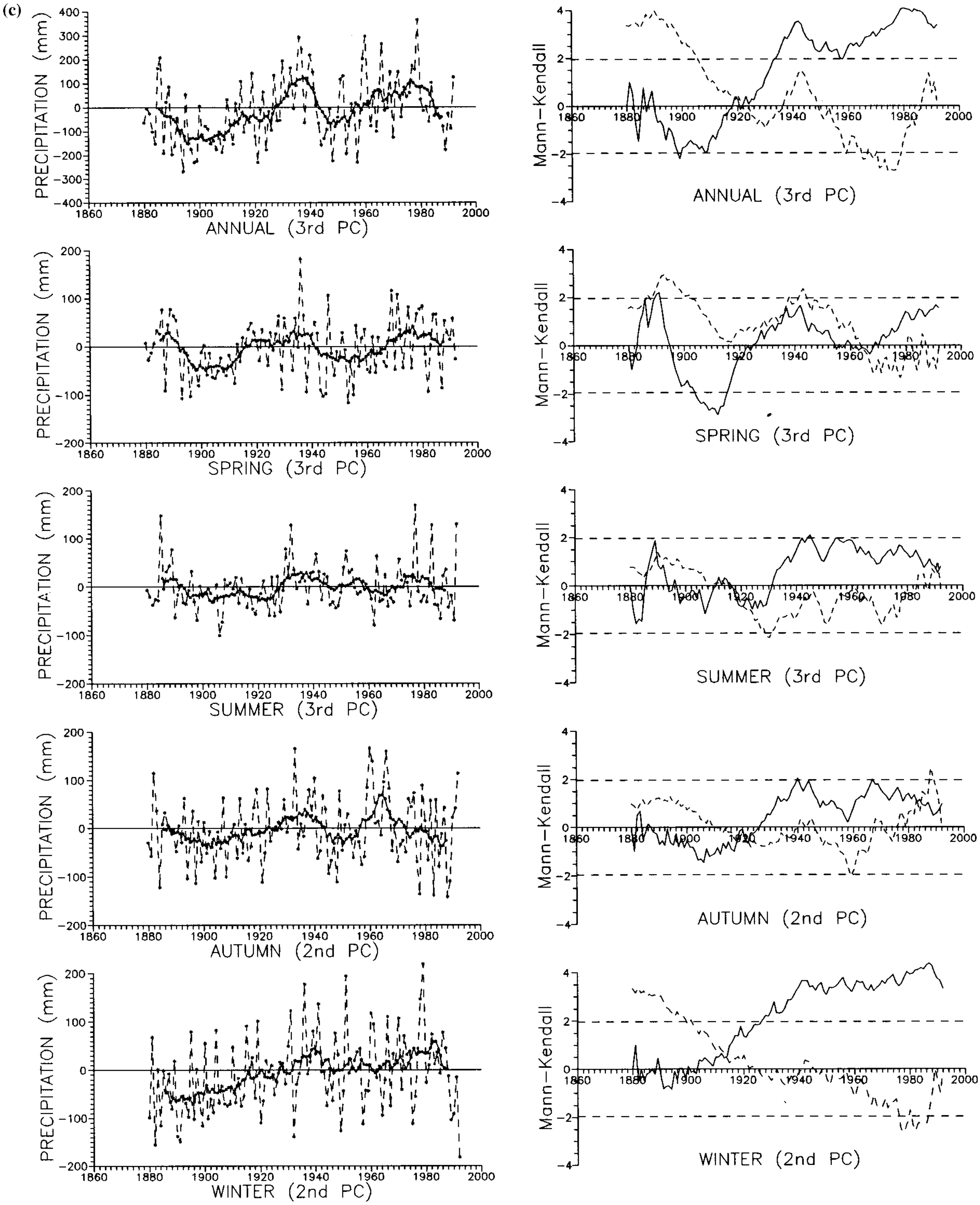

Figure 3 (*Continued*)

Table III. Differences between the mean precipitation (mm) for the period 1980–1992 and other periods

Periods	Andalusia and interior	Mediterranean	Cantabrico and Northwest
Annual			
1900–1910	−28.1	−52.0	99.1*
1920–1930	−19.0	0.5	−2.4
1930–1940	−72.9**	5.9	−140.0*
1969–1979	−69.5*	−46.0	120.0*
Winter			
1900–1910	6.3	8.0	19.5
1920–1930	2.6	0.2	9.5
1930–1940	−26.0	13.5	−45.4
1969–1979	−55.1*	−13.5	−49.0
Spring			
1900–1910	6.3	−12.8	47.6*
1920–1930	−13.8	4.7	4.8
1930–1940	−31.2**	−13.7	−6.2
1969–1979	−22.5	−23.3	31.7
Autumn			
1900–1910	−17.0	−48.1*	18.9
1920–1930	0.3	−14.3	−11.7
1930–1940	−4.0	3.8	−51.5**
1969–1979	−22.2	−2.3	12.3

* and ** denote significant differences at 95% or 90% levels, respectively.

and seasonal PC series for Andalucia and the interior stations and Cantabric region are significant, although the correlations between summer and annual series of these areas are smaller than the other seasonal correlations. For these areas, the winter is the most important season in terms of the annual totals, whereas for the Mediterranean region, the autumn is the most influential one.

The results agree partially with conclusions drawn by other researchers. There were relatively wet periods in the Mediterranean until 1914, in the 1930s, and in the 1960s and 1970s for the Mediterranean area (Maheras, 1988; Maheras and Koliva-Machera, 1990; Maheras *et al.*, 1992). The humid 1930s in the Spanish region seems to be widespread over Europe, at least for the latitudes below 50°N (Brázdil *et al.*, 1985), although it was problably less pronounced for the western and Central Mediterranean areas (Maheras, 1988; Maheras *et al.*, 1992). There is also a good concordance between dry periods. The dry period *ca.* 1920 appears also in a general way in the Mediterranean and Southern Central Europe (Brázdil *et al.* 1985; Maheras and Koliva-Machera, 1990). The 1st annual series centred on the Andalusian and interior regions of Spain is similar to the Central Europe series, particularly those located in the south (Brázdil *et al.*, 1985) from 1920 until the end of the records. The decreasing trends found for the 1st and 2nd PC series (Andalusia and interior, Mediterranean Coast) are common for southern Europe. The annual series corresponding to the Cantabric region are more similar with those series corresponding to northern Europe (Brázdil *et al.*, 1985; Vines, 1985).

Table IV. Correlation coefficients between the annual PC series and the seasonal ones

Season	Andalusia and interior	Mediterranean	Cantabrico and Northwest
Winter	0.57*	0.35*	0.54*
Spring	0.42*	0.52*	0.50*
Summer	0.23*	0.07	0.29*
Autumn	0.51*	0.67*	0.49*

* Significant at 95% level.

Table V. Correlation coefficients between the annual and seasonal m.s.l.p. at Ponta Delgada (Azores) and the annual and seasonal PC time series of precipittion in Spain

Season	Andalusia and interior	Mediterranean	Cantabrico and Northwest
Annual	−0.51*	−0.10	−0.11
Winter	−0.67*	−0.22*	−0.18*
Spring	−0.31 *	0.02	0.00
Summer	0.21, S*	−0.04	0.13
Autumn	−0.25*	−0.04	0.32*

* Significant at 95% level; S, South.

Regarding the general trends and abrupt changes, increases in precipitation have been reported by Goossens and Berger (1986) and Sneyers (1992) for stations in the Benelux countries and northern France and by Palmieri *et al.* (1991) for some stations in northern Italy (only in the cold season). These last authors found a clear decreasing trend from 1880 during April in all Italy. Maheras *et al.* (1992) also found abrupt changes in Rome and Florence *ca.* 1920. Decreasing precipitation has been found in several areas of Greece (Repapis, 1986; Amanatidis *et al.*, 1993). These results are partially in concordance with those obtained for Spain; increases of precipitation in the north and decreases (certain but less intense, during spring) in the rest of Spain.

The presence and intensity of the Azores high is a determinant factor in the Iberian precipitation regime. Effectively, the coincidence between the annual average central pressure value of the Azores high and its mean position (Sashamanogluo, 1990) and the 1st annual PC series is very clear; low precipitation is related to high values of Azores central pressure or an eastward shift of its mean position. There is also a concordance with the evolution of the other two annual series, especially during the relatively dry years between 1940 and 1960, when the Azores high shifted to the east, and during the 1980s when the intensification of the Azores high coincided with a new period of low precipitation. As proof of this relationship, Table V shows the correlation coefficients between the PC series and the seasonal and annual series of MSLP at Ponta Delgada (Azores) for which there is data from 1894 to 1981. The use of these data as representative of the Azores high is necessarily limited because this action centre has no fixed position from year-to-year and from season-to-season (Sashamanogluo, 1990). The relationship is quite good for the 1st PC time series, where the Azores high influence is particularly significant, and for the winter season, when the position of the Azores high is to the southeast of Ponta Delgada, and in optimum position for controlling the precipitation in western Iberia (Capel Molina, 1981). It is worth mentioning the positive correlation between the autumn series for the Cantabric region and the Azores high, similar to the situation for western North Europe.

There is also a good concordance between the evolution of the precipitation over the Mediterranean Coast (2nd PC series) and the mean sea level pressure over the Mediterranean (Makrogiannis and Sashamanogluo, 1990), so the negative anomalies of the pressure at 40°N from 1880 to 1900 and from 1930 to 1970 coincide with the rainy period in the beginning of the series and during the 1960s and 1970s, and positive anomalies in 1900–1930 and 1970–1980 correspond to the dry periods of the decades starting 1910 and 1920 and 1980. There is no concordance between the positive anomalies of pressure at 40°N and the precipitation during the first decade of this century, although it occurred with the negative anomalies during these years at 30°N.

One of the most useful parameters used to analyse the circulation of the North Atlantic is the zonal index. A high zonal index represents strong westerlies, and low index, a predominant meridional circulation. This study's results are compared with two different indices of the zonality over the North Atlantic. The first of these indices is computed as the difference in pressure between 35 and 65°N (or between Azores and Iceland), sometimes called the North Atlanctic Oscillation (NAO) index (Jones, 1993; Kozuschoswki, 1993). This index is usually defined for the winter season (Jones, 1993; Hurrel, 1995). Table VI shows the correlations between the annual and winter PC series and the NAO index computed by Hurrel (1995), obtained as the differences between the normalised MSLP values between Lisbon

(Portugal) and Stikkisholmur (Iceland) from November to March. In all cases, the correlations are significant, and especially so for Andalusia and the interior region (lst PC series). For this PC series, it is possible to relate the high index values during the first decades of this century to low annual, spring, summer and winter precipitation, and during the 1970s and 1980s with low autumn precipitation in the South and the interior; predominant high index values during the 1920s can also relate to little precipitation. The low index years during the 1960s are related to high precipitation. However, there is no concordance during the 1950s with low precipitation but relatively low values of the zonal index. The inverse relationship (high index–low precipitation and *vice versa*) is also found in the other PC series, which is less clear due mainly to the influence of easterly patterns for the Mediterranean Coast and the influence of the mountains for the Cantabric area. Another way to compute the zonal index is to take the difference in pressure between 35 and 55°N (Makrogiannis *et al.*, 1982; Makrogiannis, 1983). The inverse relationship is clearer with this index for the 1st annual PC series, except during the 1930s (relatively high index–high precipitation) and the 1950s (relatively low index–low precipitation). The westerlies are commonly associated with rain for the major part of Europe, but it is not true for the Iberian Peninsula. In fact, these westerlies need an intensification of the high pressure in western Iberia, producing blocking situations over the study area, which explains the negative character of the coefficients obtained. As an example the years 1923, 1928 and 1954 can be mentioned. Described by Jones and Kelly (1982) as rainy years for the UK, they were for the most part dry for Spain. This is a general feature for Southern Europe for the cold season (Kozuschowski and Marciniak, 1988; Maheras, 1988). The 1980s have a very high index, particularly during winter (Bardossy and Caspary, 1990) which can be related to the lower precipitation experienced by much of Spain.

Lastly, the Spanish PC series of precipitation is compared with global averaged series and zonally averaged series of the Northern Hemisphere (Bradley *et al.*, 1987), in order to establish general relations with the output obtained by GCMs. There is a relatively good agreement for some periods between the Spanish PC series and the series obtained by Bradley *et al.* for Europe, obviously taking account of the previous discussion. There are only some differences in the length of some dry or rainy periods, but they are quite different from the 35–70°N series; only the series associated with the Cantabric Coast represent an increase from the 1950s. Although GCMs simulations with doubled CO_2 are consistent with the Northern Hemispheric series, they inadequately reflect the precipitation changes for southern Europe. However, the results of several experiments of high resolutions GCM models match with the tendencies over the area during the last year (IPCC, 1996). In any case, the meteorological/geographical transition position of Spain makes it harder to obtain a good prediction of this important variable.

6. CONCLUSIONS

The annual and seasonal precipitation values at 40 Spanish localities for the period 1880–1992 have been analysed by applying principal component analysis. The conclusions of this paper are as follows.

The results of the PCA allow us to consider three coherent regions in the area under study, namely South and interior Spain, the eastern Mediterranean Coast, and the northern Cantabric Coast (for summer only, it appears another region exists as a result of the split of the first EOF in two, associated with the southern and northern interior region, respectively. This is a consequence of the strengthening and presence of the Azores high during this season).

Table VI. Correlation coefficients between the NAO index and the annual and winter PC series of precipitation in Spain

Season	Andalusia and interior	Mediterranean	Cantabrico and Northwest
Annual	−0.55*	−0.22*	−0.33*
Winter	−0.67*	−0.31*	−0.42*

* Significant at 95% level.

It is possible to establish the existence of some wet/dry periods. The three regional series of annual PCs makes it possible to distinguish, in a general way, a dry period from 1910 to the mid-1920s and a wetter period during the 1960s and 1970s. The concordance between the series corresponding to Andalusia and the interior (1st EOF) and the Cantabric region (3rd EOF) is also shown in the wet 1930s and the drier years from 1945 to the late 1950s. It is also possible to establish a general increase in precipitation for the Cantabric stations, whereas the other two regions show a decrease in precipitation in the latter part of the records, with significant negative differences between the amounts registered during the 1980s and other decades. These results are in general agreement with the conclusions obtained for other parts of Europe.

It is possible to relate the changes in the precipitation series found with variations in the large scale circulation features of western Europe and Atlantic Ocean. The intensification of the Azores high and a shift to the east of its normal position is linked with low values of precipitation in many parts of Spain. Inverse relations between the pressure in the Mediterranean and the zonal index (western circulation) and Spanish precipitation can be established as in other Mediterranean countries. However, not all fluctuations and changes can be explained solely in terms of circulation variations. This point addresses the need for a further study of this relationship as a possible way to distinguish between 'natural' or 'unnatural' responses of precipitation, and the influence of other factors, such as relations with SST and ENSO phenomena, etc.

The simulations obtained by some GCMs are consistent with the situation reported during the last 10 years (not with the more extended opinion for Europe; increase of precipitation during winter and light decrease during summer). It is clear that Spain is in a critical area for GCM-based estimations. It would be unwise to attribute these changes to the enhancement of greenhouse gases, even supposing that this increase would affect the incidence of weather patterns over the area. Nevertheless, important fluctuations in precipitation have occurred over large regions and precipitation trends may provide an additional indicator (including temperature) of the evolution of greenhouse gas induced climate change. Moreover, taking note of the previous comments, further studies and the monitoring of the precipitation in Spain can be useful in order to evaluate the validation of regional GCMs estimations, and to understand the processes of such important variables for the Mediterranean area.

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