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CIRCULATION WEATHER TYPES AND THEIR INFLUENCE ON THE PRECIPITATION REGIME IN PORTUGAL

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ABSTRACT

An objective classification scheme of the atmospheric circulation affecting Portugal, between 1946 and 1990, is presented, where daily circulation is characterized through the use of a set of indices associated with the direction and vorticity of the geostrophic flow. The synoptic characteristics and the frequency of ten basic circulation weather types (CWTs) are discussed, as well as the amount of precipitation associated with each type between 1957 and 1986. It is shown that the anticyclonic (A) type, although being the most frequent class in winter (37%), gives a rather small (less then 16%) contribution to the winter precipitation amount, observed on a daily basis. On the other hand, the three *wettest* CWTs, namely the cyclonic (C), southwesterly (SW) and westerly (W) types, together representing only 32% of all winter days, account for more than 62% of the observed daily precipitation. Results obtained highlight the existence of strong links between the interannual variability of monthly precipitation and interannual variability of CWTs. Multiple regression models, developed for 18 stations, show the ability of modelling monthly winter precipitation through the exclusive use, as predictors, of the *wet* CWTs (i.e. C, SW and W). The observed decreasing trend of March precipitation is also analysed and shown to be especially associated with the decrease of the three *wet* weather types. The anomalous low (high) frequency of *wet* CWTs during the hydrological year is shown to be strongly related with the occurrence of extreme dry (wet) years in Portugal, which had important impacts on Portuguese agriculture. Overall, the results suggest that the precipitation regime over Portugal, including interannual variability, trends and extremes, may be adequately explained in terms of variability of a fairly small number of circulation weather patterns. On the other hand, observed contrasts in the spatial distribution of correlations between frequency of *wet* CWTs and rainfall amounts suggest that precipitation regimes are of a different nature in northern and southern regions of Portugal; the former possessing an orographic origin and the latter being associated to cyclogenetic activity. Copyright © 2000 Royal Meteorological Society.

KEY WORDS: atmospheric circulation variability; droughts; Portugal; precipitation; weather typing

1. INTRODUCTION

The precipitation regime in Portugal possesses a highly irregular behaviour in both the spatial and temporal dimensions, namely in the amount and distribution of rainfall (Daveau, 1977). The study of precipitation variability is therefore of primary importance, particularly because of its impact on social and economic activities, such as agricultural production, land use and water resources management.

The intra-annual variability of precipitation in Portugal may be understood in terms of the broad characteristics of the general circulation of the atmosphere, taking into account Portugal's geographic location, in the south-westerly extreme of the Iberian Peninsula (between 37° and 42°N and 6.5° and 9.5°W).

However, if the spatial distribution of rainfall, as well as its seasonal variability, may be explained in terms of the broad characteristics of the global circulation and regional climate factors (e.g. latitude, orography, oceanic and continental influences), this is not true in respect of the interannual variability,

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which is of a different nature. In fact several authors have identified the North Atlantic Oscillation (NAO) as the main large-scale phenomenon controlling winter precipitation over the western Iberian Peninsula and Morocco (Hurrell and van Loon, 1997; Osborn *et al.*, 1999). Despite a strong association between the monthly NAO index and monthly precipitation in Lisbon (Hurrell, 1995), it would be, however, unreasonable to expect the daily precipitation regime in Portugal to be totally controlled by just one mode of atmospheric circulation variability. Other features at the synoptic and smaller scales must play an important role. Different techniques have been used to relate Iberian monthly precipitation and atmospheric circulation indices, namely canonical correlation analysis (Zorita *et al.*, 1992; von Storch *et al.*, 1993), and principal component analysis coupled with spectral analysis (Rodriguez-Puebla *et al.*, 1998). Recently, Goodess and Palutikof (1998) have applied a weather typing approach for the southern part of Spain, suggesting that this type of technique may also be worth applying over the Mediterranean region.

As pointed out by Daveau (1977), 'Only an exhaustive study, focusing on a large number of years and at the same time supported by an individual study of 'atmospheric situations' from the point of view of their evolution and spatial differences both at the surface and aloft, will allow to make progress in the understanding of the mechanisms that govern the succession of rainy weather types in Portugal'.

The main aim of this paper is to present an objective classification of circulation weather types (CWTs) for Portugal and, based on such a scheme, outline a framework that allows identification of the main characteristics of the precipitation regime in Portugal, namely its intra and interannual variability, as well as any long-term trends and extremes. The use of so-called objective methods to classify CWTs, such as those based on indices derived from atmospheric pressure fields, represent an advantage over more subjective studies of CWTs, such as the Lamb weather type (LWT) classification (Lamb, 1972) and the *Grösswetterlagen* catalogues (Hess and Brezovsky, 1977). Objective classification schemes, based on circulation indices, were initially developed for the British Isles (Jenkinson and Collison, 1977; Jones *et al.*, 1993) in order to automatically reproduce the subjective LWT classification. Automated classification procedures have also been used in the prediction of daily rainfall in England (Conway *et al.*, 1996), validation of GCM outputs (Hulme *et al.*, 1993) or downscaling from GCM outputs with the aim of producing future rainfall scenarios for southeastern Spain (Goodess and Palutikof, 1998).

Automated classifications of atmospheric circulation affecting Portugal both on monthly (Corte-Real *et al.*, 1995) and daily (Zhang *et al.*, 1997; Corte-Real *et al.*, 1998) time scales have also been developed, based on the use of principal component analysis (PCA) followed by a k-means cluster analysis. Despite the mathematical advantages of such a methodology, it is not always possible to attribute unambiguous physical meaning on a synoptic basis to the obtained circulation patterns. In particular, PCA results may vary significantly both with dataset length and with size of the window used, whereas k-means cluster analysis requires a predefinition of the number of clusters to be retained, giving a wide range of results for the same area of study. Such dependency might explain the diversity of results obtained for Portugal, ranging from only four major circulation types (Corte-Real *et al.*, 1998) to as much as 13 circulation patterns (Zhang *et al.*, 1997).

In Section 2 we devise the main aspects of the spatial and temporal precipitation variability in Portugal, then in Section 3 we present the procedure used to derive the CWTs for Portugal and their synoptic characteristics. The influence of each CWT on the precipitation regime in Portugal at both daily and monthly time scales is presented in Section 4. The results of this analysis are then applied, in Section 5, to two distinct case studies: (i) a decreasing trend in March precipitation, (ii) extreme situations related with drought spells and wet years. Finally, some conclusions are presented in Section 6.

2. THE PRECIPITATION REGIME IN PORTUGAL

In order to characterize the precipitation regime in Portugal, we used monthly precipitation data from 18 stations distributed evenly over Portugal (Figure 1), and covering the 45 year period January 1946–December 1990 inclusive. The main characteristics of these stations were summarized in Table I.

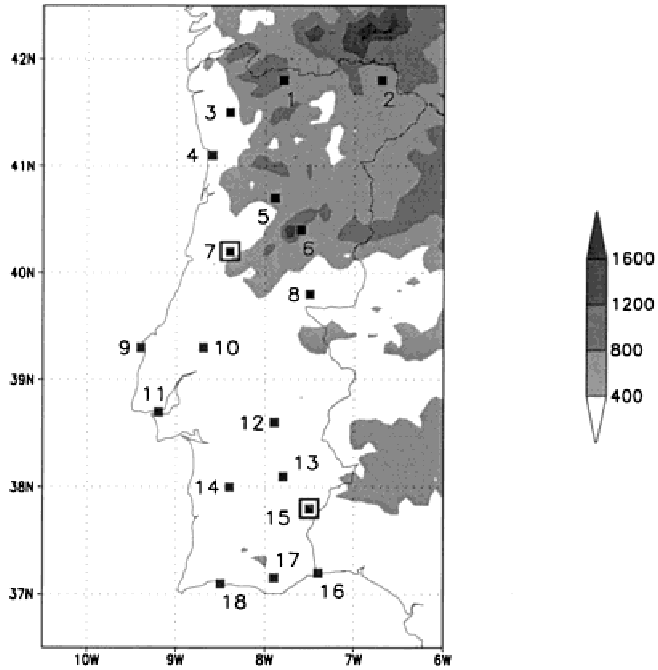

Figure 1. Portuguese continental territory showing the location of climatological stations used in the analysis; monthly data from all 18 stations (dots) and daily data from two stations (dots with open squares). Elevation above 400 m is highlighted

Table I. The main characteristics of the 18 stations used in this work

	Station	Latitude (°N)	Longitude (°W)	Altitude (m)	Mean annual precipitation (mm)	Standard deviation (mm)
1	Montalegre	41.82	7.78	1005	1418	425
2	Bragança	41.80	6.73	690	737	175
3	Braga	41.55	8.42	190	1455	325
4	Porto	41.13	8.60	93	1228	298
5	Viseu	40.67	7.90	443	1226	329
6	Penhas Douradas	40.41	7.55	1380	1726	430
7	Coimbra	40.20	8.42	141	991	243
8	Castelo Branco	39.81	7.48	380	782	214
9	Cabo Carvoeiro	39.35	9.40	32	588	135
10	Santarem	39.25	8.70	54	708	168
11	Lisbon	38.72	9.15	77	742	191
12	Evora	38.57	7.90	51	651	163
13	Beja	38.02	7.87	246	584	142
14	Alvalade	37.95	8.40	61	560	134
15	Mertola	37.75	7.55	190	545	189
16	Vila Real de S^{to} Antonio	37.18	7.42	7	500	181
17	São Bras de Alportel	37.17	7.90	325	887	282
18	Praia da Rocha	37.10	8.50	21	465	122

The mean and standard deviation of the annual precipitation were computed for the period 1946–1990.

The spatial distribution of mean annual rainfall in Portugal reveals a sharp contrast between north and south as well as between coastal and inland areas (Figure 2). This contrast is of particular significance if one takes into account the size of the country (ca. 550 and 150 km respectively in the north–south and east–west directions). It should also be noted, that the amounts recorded can be significantly higher on

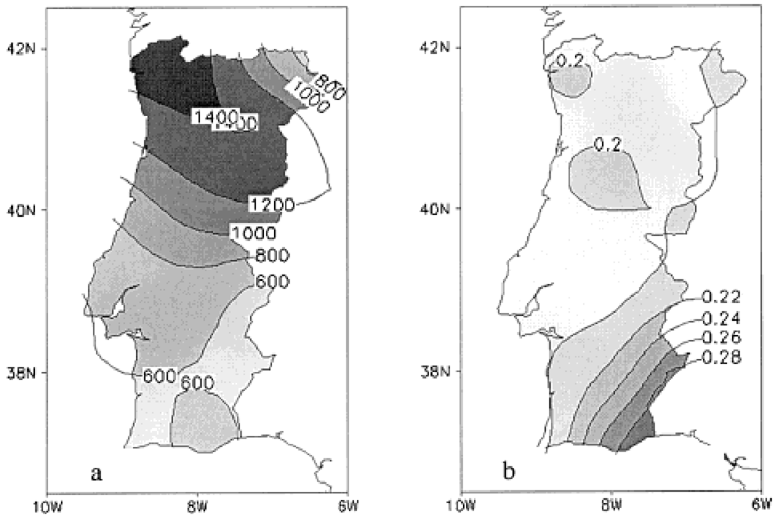

Figure 2. (a) Spatial distribution of total annual (mm) precipitation over Portugal for the 1946–1990 period; (b) percentage of variation coefficient for the period 1946–1990

some hillsides and mountains, especially in the northwest, where mean annual totals may be greater than 2500 mm, ranking amongst the highest in Europe. In fact, the spatial variability of precipitation mainly reflects the uneven distribution of orography (Figure 1), with 95% of the area with an elevation above 400 m being concentrated in the northern half of Portugal (Soeiro de Brito, 1994).

On the other hand, the distribution of precipitation exhibits a marked seasonal character (Figure 3), with a strong contrast occurring between a 'dry season', with almost no rainfall during the months of July and August, and a wetter period throughout the rest of the year. April/May and September/October correspond to the transition months into and out of the 'rainy season'.

During summer the large-scale atmospheric circulation is steered by the Azores anticyclone, which is displaced towards its northwesterly position, producing northerly or northeasterly winds that bring warm and dry air into Portugal, which is either of continental or maritime origins (the latter modified by continental influence). This circulation is usually reinforced at the regional scale by the development of a thermal low, centred over the Iberian Peninsula (Amorim Ferreira, 1954a).

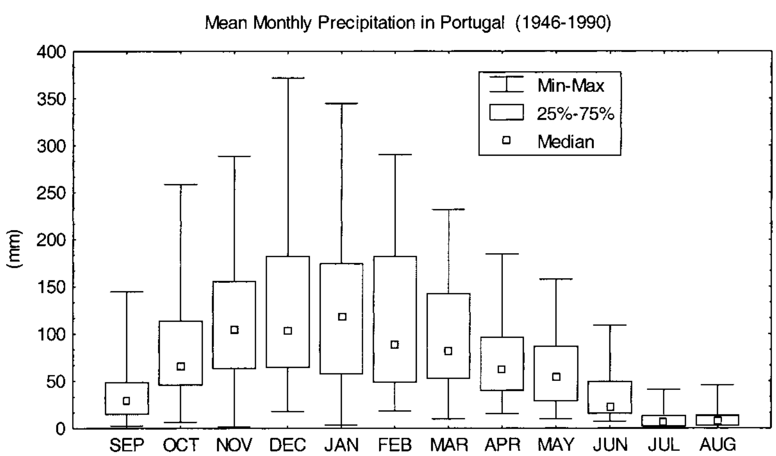

Figure 3. Box plots showing the annual cycle of the variability of average monthly precipitation. The small squares □ represent the median value for each month, the lower (upper) box limits represent the first (third) quartile and the lower (upper) whisker represents the minimum (maximum) monthly precipitation

During winter the large-scale circulation is mainly driven by the position and intensity of the Icelandic low, and Portugal is affected by westerly winds that carry moist air and produce rainfall events mainly in northern Portugal. This precipitation is intensified by the passage of cold fronts associated with families of transient depressions. The described mechanism of precipitation is particularly efficient when the Icelandic low is very deep and positioned at a more southerly latitude. However, during winter Portugal may also be affected by northward extensions of the Azores anticyclone. This steers warm and dry airflow into Portugal of tropical maritime origin, but modified to become polar continental (Amorim Ferreira, 1954b). Figure 3 also displays a high degree of interannual variability, which translates into positively skewed monthly distributions of rainfall, encompassing wide ranges of values. This feature plays an important climatic role, namely in what respects to the frequent occurrence of very dry or very wet years, as will be shown in Section 5.

3. CIRCULATION WEATHER TYPE CLASSIFICATION FOR PORTUGAL

3.1. Methodology

Based on Jenkinson and Collison (1977) and Jones *et al.* (1993) procedures developed to define objectively LWTs for the British Isles, daily circulation affecting western Iberia is characterized through the use of a set of indices associated to the direction and vorticity of geostrophic flow. The indices used were the following: southerly flow (SF), westerly flow (WF), total flow (F), southerly shear vorticity (ZS), westerly shear vorticity (ZW) and total shear vorticity (Z). These indices were computed using sea level pressure (SLP) values obtained for the 16 grid points (p_1–p_{16}) shown in Figure 4 using the following expressions:

$$\mathrm{SF} = 1.305[0.25(p_5 + 2 \times p_9 + p_{13}) - 0.25(p_4 + 2 \times p_8 + p_{12})] \quad (1)$$

$$\mathrm{WF} = [0.5(p_{12} + p_{13}) - 0.5(p_4 + p_5)] \quad (2)$$

$$\mathrm{ZS} = 0.85 \times [0.25(p_6 + 2 \times p_{10} + p_{14}) - 0.25(p_5 + 2 \times p_9 + p_{13}) - 0.25 \times (p_4 + 2 \times p_8 + p_{12}) + 0.25(p_3 + 2 \times p_7 + p_{11})] \quad (3)$$

$$\mathrm{ZW} = 1.12 \times [0.5 \times (p_{15} + p_{16}) - 0.5 \times (p_8 + p_9)] - 0.91 \times [0.5 \times (p_8 + p_9) - 0.5 \times (p_1 + p_2)] \quad (4)$$

$$\mathrm{F} = (\mathrm{SF}^2 + \mathrm{WF}^2)^{1/2} \quad (5)$$

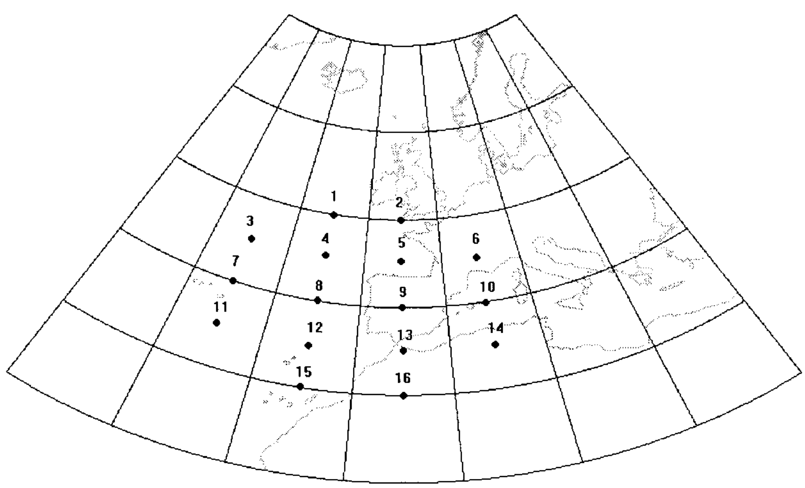

Figure 4. Grid points used to compute the vorticity (ZS, ZW) and flow (SF, WF) indices

$$Z = ZS + ZW \quad (6)$$

Daily gridded fields (5° × 5° longitude–latitude) of SLP provided by NCAR (National Center for Atmospheric Research) were used over an area defined from 40°W to 25°E and from 20° to 70°N, covering the period January 1946–December 1990. We established the following set of rules to define different types of circulation:

1. Direction of flow is given by $\tan^{-1}(WF/SF)$, 180° being added if WF is positive. The appropriate direction is computed using an eight-point compass, allowing 45° per sector.
2. If $|Z| < F$, flow is essentially straight and considered to be of a pure directional type (eight different cases according to the compass directions).
3. If $|Z| > 2F$, the pattern is considered to be of a pure cyclonic type if $Z > 0$, or of a pure anticyclonic type if $Z < 0$.
4. If $F < |Z| < 2F$, flow is considered to be of a hybrid type and is therefore characterized by both direction and circulation (8 × 2 different types).

This method allows 26 different CWTs to be defined (Table II). Unlike some other authors (Jenkinson and Collison, 1977; Jones *et al.*, 1993), we did not use an unclassified class, opting to disseminate the fairly few cases (< 2%) with possibly unclassified situations among the retained classes. In order to devise a practical, though reliable, statistical analysis scheme, the 26 circulation types were re-grouped into ten basic ones. For this purpose we adopted a similar approach to Jones *et al.* (1993); each of the 16 hybrid types was included with a weight of 0.5 into the corresponding pure directional and cyclonic/anticyclonic types (e.g. one case of ANE was included as 0.5 in A and 0.5 in NE). The ten CWTs types retained in this study are shown in Table III.

Table II. The 26 original classes of CWTs with eight directional types, 16 hybrid types and two types controlled by geostrophic vorticity (A and C)

Directional types	Anticyclonic types	Cyclonic types
NE	ANE	CNE
E	AE	CE
SE	ASE	CSE
S	AS	CS
SW	ASW	CSW
W	AW	CW
NW	ANW	CNW
N	AN	CN
	A	C

Table III. The ten classes of CWTs retained, with eight types controlled by directional geostrophic flow and two types controlled by geostrophic vorticity

CWTs	Symbol
Anticyclonic type	A
Cyclonic type	C
Northeasterly type	NE
Easterly type	E
Southeasterly type	SE
Southerly type	S
Southwesterly type	SW
Westerly type	W
Northwesterly type	NW
Northerly type	N

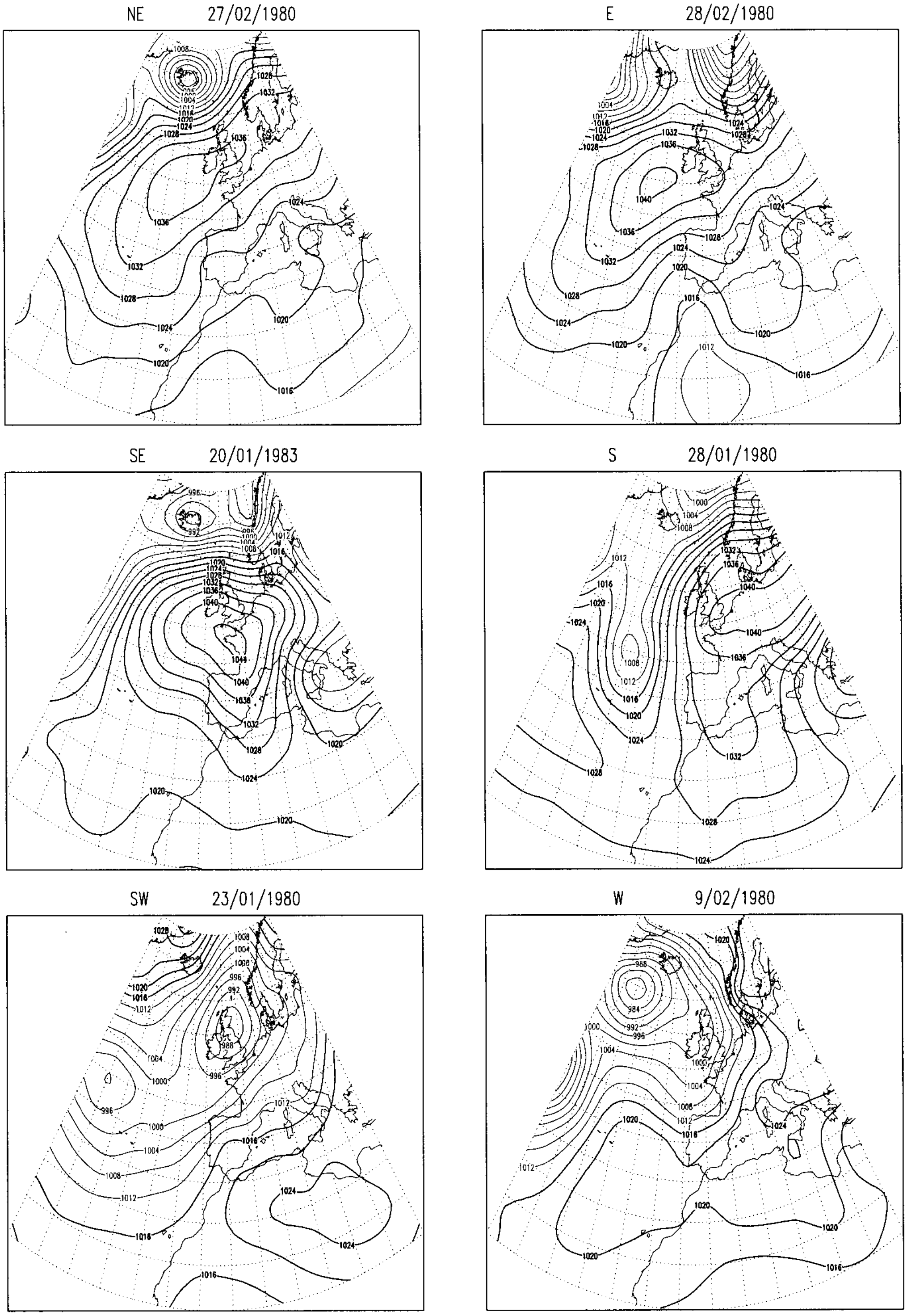

Figure 5. SLP fields characteristic of the ten basic CWTs. The contour interval is 4 hPa (*continued overleaf*)

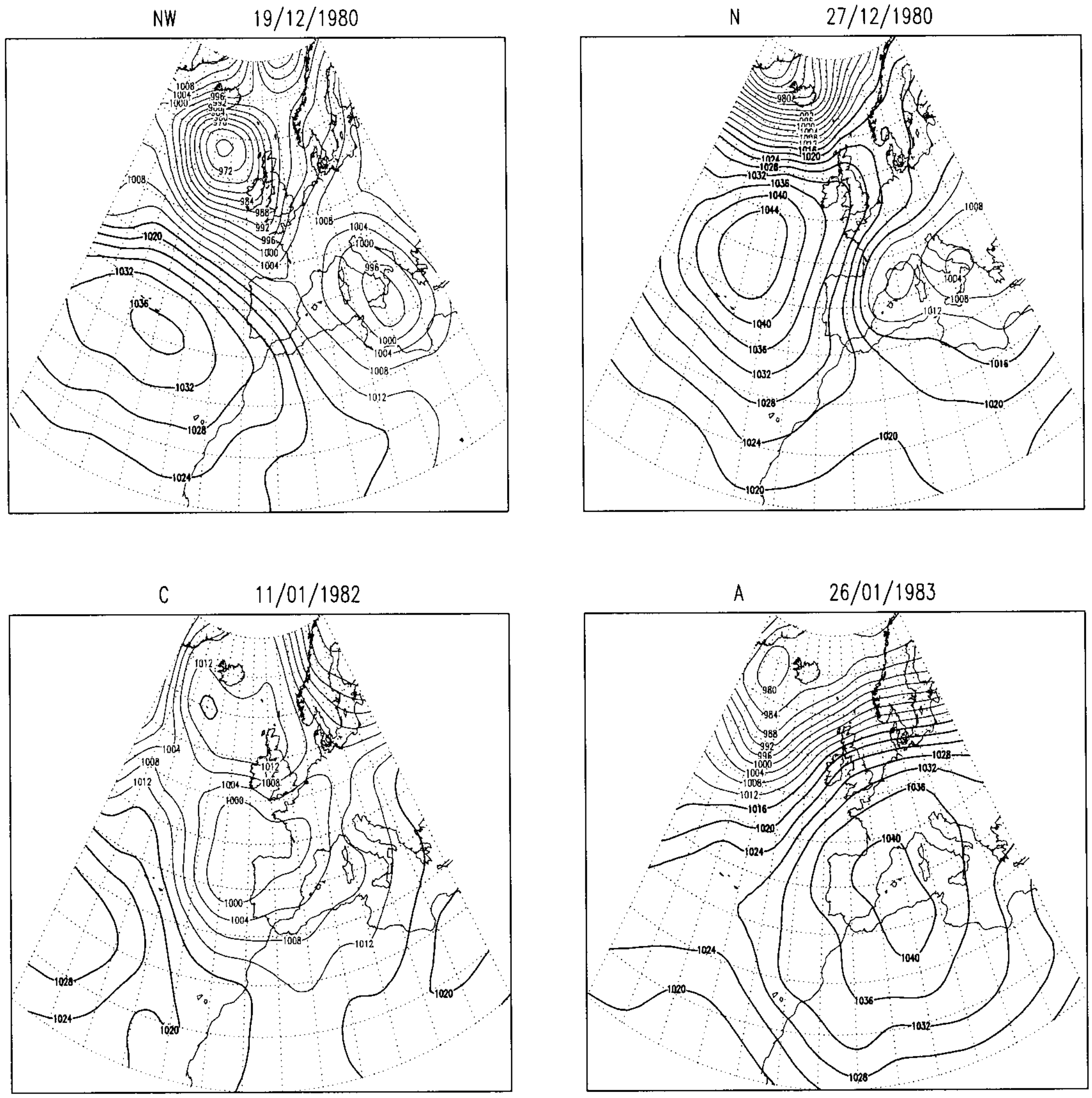

Figure 5 (*Continued*)

Composite maps of each CWT were computed for the period 1946–1990 for every month and season. In Figure 5 we present an example of each CWT obtained for winter months (Dec, Jan and Feb). Composite maps of the SLP anomaly fields for all CWTs (Figure A1) and their respective synoptic characteristics (Table AI) are described in Appendix A.

3.2. Intra-annual variability

The relative frequency of each CWT for every month of the year is shown in Figure 6. The anticyclonic type (A) is the most frequent weather pattern throughout the year, except during the summer months, which are dominated by the northeasterly type (NE) and northerly type (N). Both the NE and N situations correspond to an extended Azores high pressure, which generally affects most parts of western Europe during the summer months and the Iberian Peninsula in particular, and produces consistently northerly winds near the Portuguese coast (Appendix A).

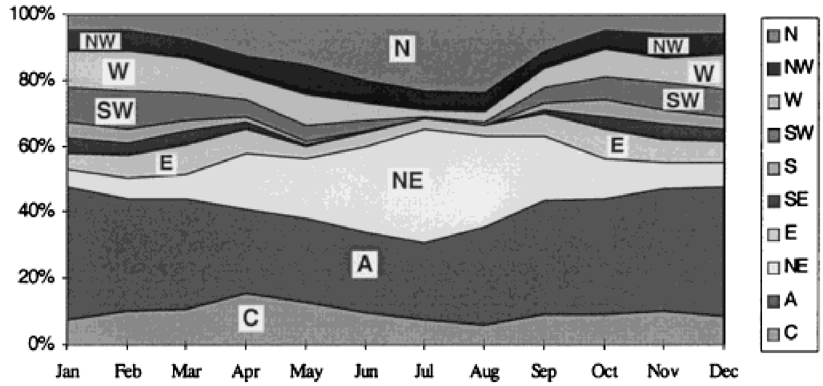

Figure 6. Mean monthly percentage frequency of CWTs for each month of the year

It is worth noting that the relative frequency of cyclonic situations (C) is almost constant throughout the year, attaining a maximum value during spring in accordance with the maximum frequency of Atlantic blocking episodes for that time of the year (Treidl *et al*., 1981). The three CWTs, with a westerly component and originating in the Atlantic, namely southwesterly (SW), westerly (W) and northwesterly (NW) types, present very constant relative frequencies through most of the year, although the SW type barely occurs during the summer months. Finally, the remaining types, i.e. easterly (E), southeasterly (SE) and southerly (S), are the least frequent of all weather types throughout most of the year; in fact the relative frequencies of S and SE are virtually zero between May and August.

4. RELATIONSHIPS BETWEEN PRECIPITATION AND CWTs

In order to validate the developed CWT classification, long-term comparisons were made of the daily circulation types and the corresponding daily values of precipitation. The aim of the analysis was to determine whether the results would agree with those obtained from synoptic experience. For this purpose we used two contrasting stations, one (Mertola) located in Alentejo region of southern Portugal, a region characterized by frequent drought episodes (Mendes, 1993), and the other (Coimbra) located in the northern half of Portugal, characterized by a much wetter precipitation regime than Mertola (Figure 1).

Table IV. Contribution from different circulation classes to winter precipitation over Coimbra and Mertola, during the period 1957–1986

		Coimbra		Mertola	
CWTs	% days	mm/day	% Tot. prec.	mm/day	% Tot. prec.
NE	6.0	1.0	1.3	1.0	2.8
E	5.9	0.2	0.3	0.9	2.6
SE	4.1	0.5	0.4	0.5	0.9
S	4.5	1.7	1.7	1.3	2.8
SW	11.5	6.3	15.5	2.3	12.6
W	11.9	12.6	32.1	4.1	23.1
NW	6.1	10.8	14.1	3.5	10.1
N	4.8	4.6	4.8	2.0	4.5
C	8.4	8.0	14.4	8.0	32.0
A	36.8	1.9	15.3	0.5	8.6

% days, frequency of each class; mm/day, mean daily precipitation for all days in each class; % Tot. prec., contribution of each class to the overall winter precipitation observed at that station.

Table IV presents values of the relative frequency of number of days with each CWT in winter during the period 1957–1986 (% days). Table IV also shows, for both stations, the average daily precipitation for all days within each CWT class (mm/day), as well as the corresponding values of the relative contribution of those days to total observed amount of rainfall (% total precipitation).

The last line of Table IV shows that although the relative frequency of anticyclonic type (A) is the highest for winter it accounts for only 15.3% (8.6%) of the observed precipitation in Coimbra (Mertola). This result is in accordance with the very low values of mean daily precipitation for this CWT. The next most frequent CWTs are the westerly type (W) (11.9%), the southwesterly (SW) (11.5%) and the cyclonic type (C) (8.4%).

It is worth noting that only 32% of all days corresponding to the above mentioned three types, namely westerly (W), cyclonic (C) and southwesterly (SW), account for 62% (67%) of the observed precipitation in winter for Coimbra (Mertola). In terms of average precipitation *per* class, the highest values occur in Coimbra with W (12.6 mm/day), followed by NW (10.8 mm/day), then C (8.0 mm/day) and SW (6.3 mm/day). On the other hand, for Mertola the highest mean values *per* class correspond to the cyclonic (C) class with the same amount (8.0 mm/day) as Coimbra, but with much lower values for the other wet classes, namely W (4.1 mm/day), NW (3.5 mm/day) and SW (2.3 mm/day).

These results suggest that the cyclonic (C) class is associated with a fairly homogeneous distribution of precipitation over most of the country. On the other hand, the 'rainy' classes with an Atlantic origin (W, SW and NW) are to be associated to the observed strong decrease in precipitation from North to South.

Similar results are obtained for spring and autumn, the two other main contributive seasons in terms of total annual precipitation, and are shown in Figure 7(a) and (b). For Coimbra it is worth noting, during spring and autumn, a decrease in relative importance of the precipitation associated with SW and W types, and an increase of the relative importance of the precipitation associated with NW and C types. For Mertola a decline of the precipitation associated with SW and W classes may also be observed as well as small increments in N, SE and E types. It may be noted that the observed increase (decrease) from winter to summer in the relative importance of CWTs with a northward (southward) component is consistent with the poleward displacement of both centres of action and storm tracks during the two intermediate seasons. Summer (Jun, Jul and Aug) precipitation, which shows very low values over the whole country and is almost close to zero values in southern Portugal, is sometimes associated with local convective activity, making a CWT approach much more difficult to use in this case. These storms can occur with a large degree of independence from the circulation weather type, which characterizes the Iberian circulation for that specific day. In fact, the large increase of precipitation associated with the NE (and N) CWTs in the summer is mainly related with the increase of NE and N frequencies from winter to summer. In any case, in terms of absolute values, the amount of precipitation associated with these two CWTs in summer is residual.

Although it would be desirable to perform the same type of analysis for the 16 remaining stations (Figure 1), we were limited by the unavailability of corresponding daily data. However, we are confident that the previous daily analysis for two representative stations was an important first step to assess the relative importance of each CWT over the northern and southern parts of Portugal.

In order to investigate further the relationship between local precipitation and CWTs on a monthly basis, we compare on the one hand, the long-term variabilities of precipitation at four different stations, respectively located in the North (Montalegre), Central (Coimbra) and Southern (Lisbon and Evora) regions of Portugal and on the other hand, of the combined frequency of CWTs that were shown to be related to precipitation activity over Portugal, namely C, W and SW types. The results obtained for winter are shown in Figure 8 and reveal a high degree of association between these two time series through the whole territory, with correlation coefficients between 0.77 and 0.88, all statistically significant at the 99% confidence level.

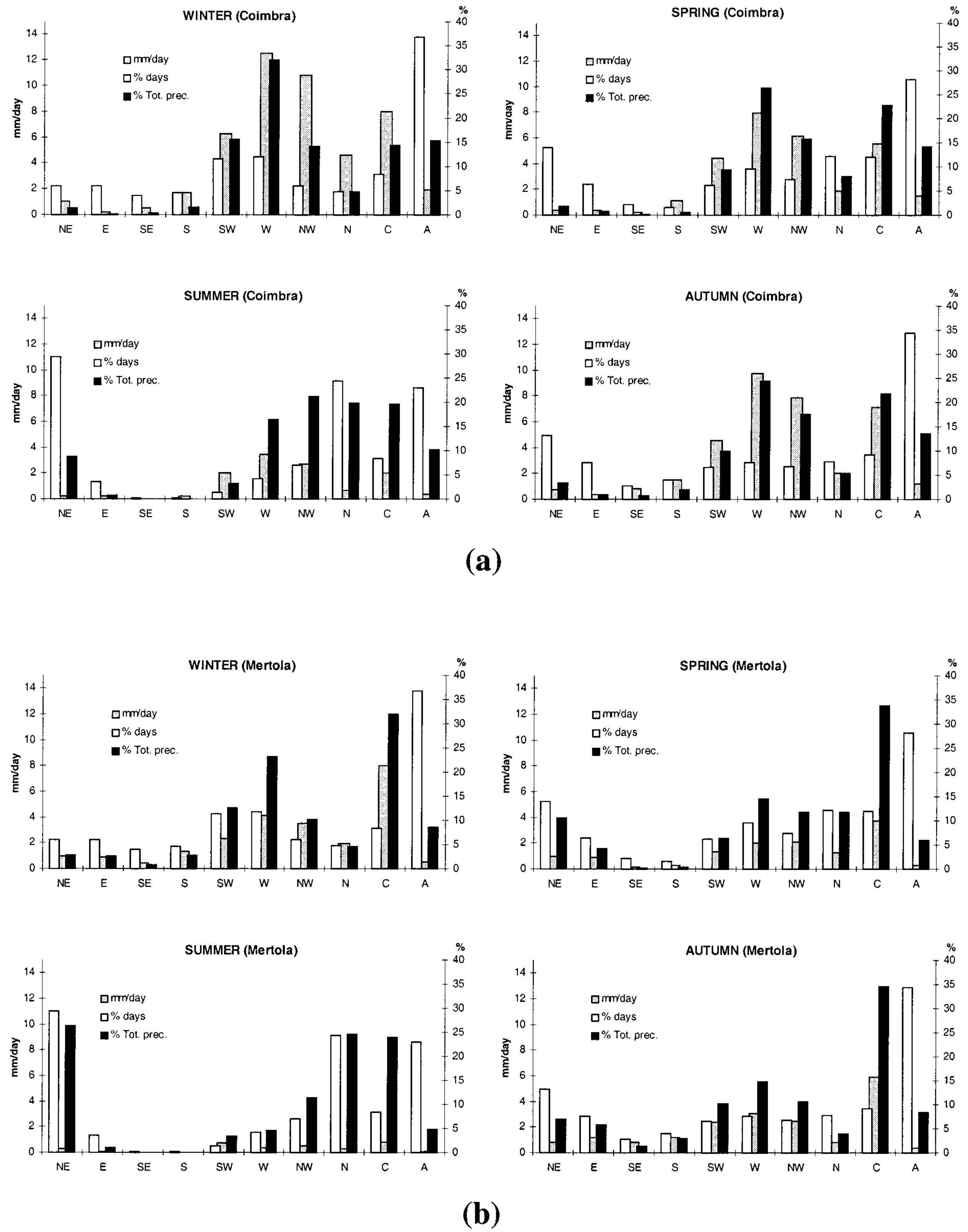

Figure 7. Contribution from different circulation classes to precipitation over (a) Coimbra and (b) Mertola, for all seasons during the period 1957–1986. % days, frequency of each class; mm/day, mean daily precipitation for all days in each class; % Tot. prec., contribution of each class to the overall precipitation observed at that station

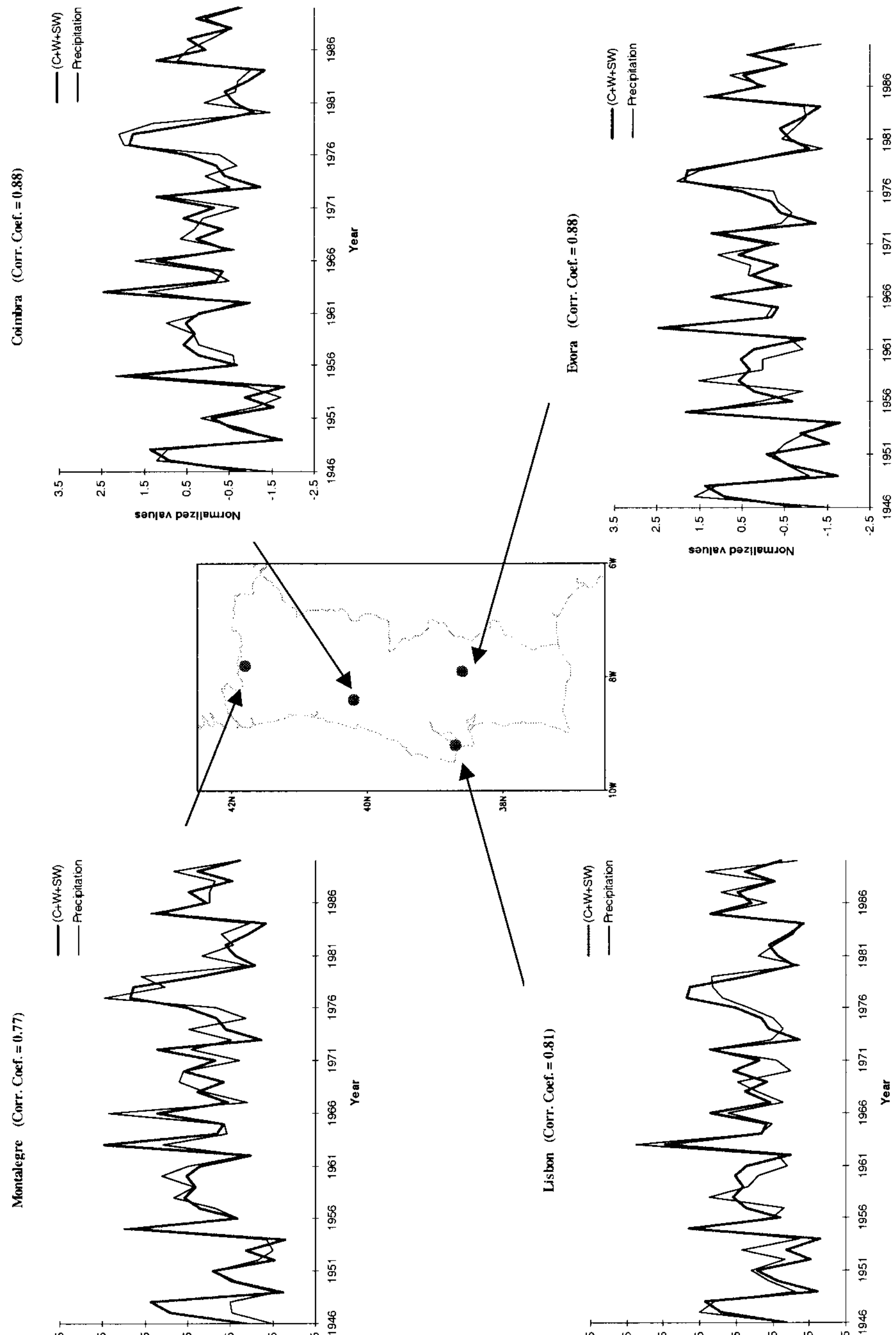

Figure 8. Normalized values of winter precipitation (thin line) and total number of days from classes C, W or SW (thick line) during the 1946–1990 period for Montalegre, Coimbra, Lisbon and Evora. The corresponding correlation coefficient is also presented

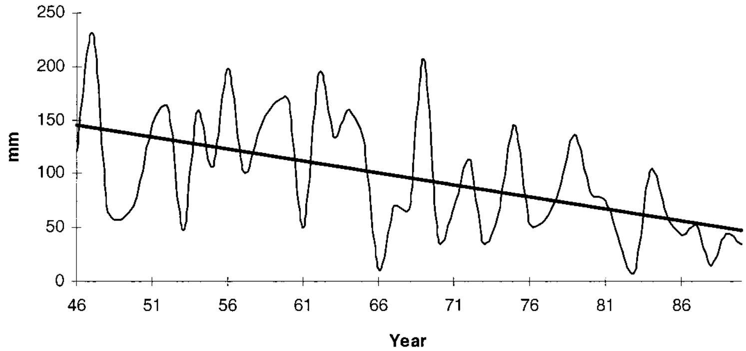

Figure 9. Long-term variability of observed March precipitation averaged over all 18 stations, and the respective linear trend

5. TRENDS AND EXTREMES

5.1. Models applied to a case study: March

As mentioned in the first section, most precipitation in Portugal falls between autumn and spring and may generally be described until the 1960s as bimodal, with two distinct periods of high values: one during December and January and the other during March. As shown by several authors, this behaviour has been changing in the last few decades. Mendes (1993) has noticed a significant decrease in spring precipitation averaged over southern Portugal, from 194 mm (1932–1961) to 150 mm (1962–1991). Also for the southern region of Portugal, but on a monthly basis, Zhang *et al.* (1997) found that the decrease of precipitation in March was accompanied by an increase in February precipitation. On a regional scale, Schönwiese *et al.* (1993) clearly showed that there has been a significant decrease in the observed March precipitation over the whole of the Iberian Peninsula, between 1961 and 1990, especially in the southern zones of Portugal and Spain.

The long-term variability of March precipitation and corresponding linear trend may be seen in Figure 9. Application of a simplified version of the non-parametric Kendall test (Vautard *et al.*, 1992) confirmed that the decreasing trend is statistically significant at the 95% confidence level.

We would like to assess the capacity for modelling the decrease of precipitation observed in March solely based on the developed objective classification of CWTs. Accordingly, monthly frequencies of C, W and SW types for the period 1946–90 were used to predict monthly mean values of precipitation at 18 stations over Portugal. Multiple regression models were then developed for each station using the three most important CWTs as predictors. Each model was calibrated using winter months and then validated against March observations.

Despite the large variation in the amount of observed precipitation for each station, all models are able to reproduce satisfactorily the temporal variability of March precipitation, including the conspicuous decline that has been observed since the 1960s. Three examples of these models, corresponding to the north, central and southern regions of Portugal, are shown in Figure 10.

Figure 11 displays the correlation coefficient between observed and modelled precipitation for all station models, showing a similar magnitude for the calibration winter period (Figure 11(a)) and the March validation period (Figure 11(b)). It is worth noting that results are slightly better in the northern half of Portugal than in the southern region.

The relative importance of each CWT to the regression equation varies considerably from station to station. To make comparisons easier, correlation coefficient values were normalized (i.e. adding 100%) for each station (Figure 12). A strong decrease (increase) in importance may be observed for C (W) type from south to north (Figure 12(a) and (c)). It is important to emphasize the similarity between the spatial distribution of the relative importance of W type (Figure 12(c)) and the spatial distribution of winter precipitation (Figure 12(d)), revealing on a monthly scale the homogenous influence of W type in

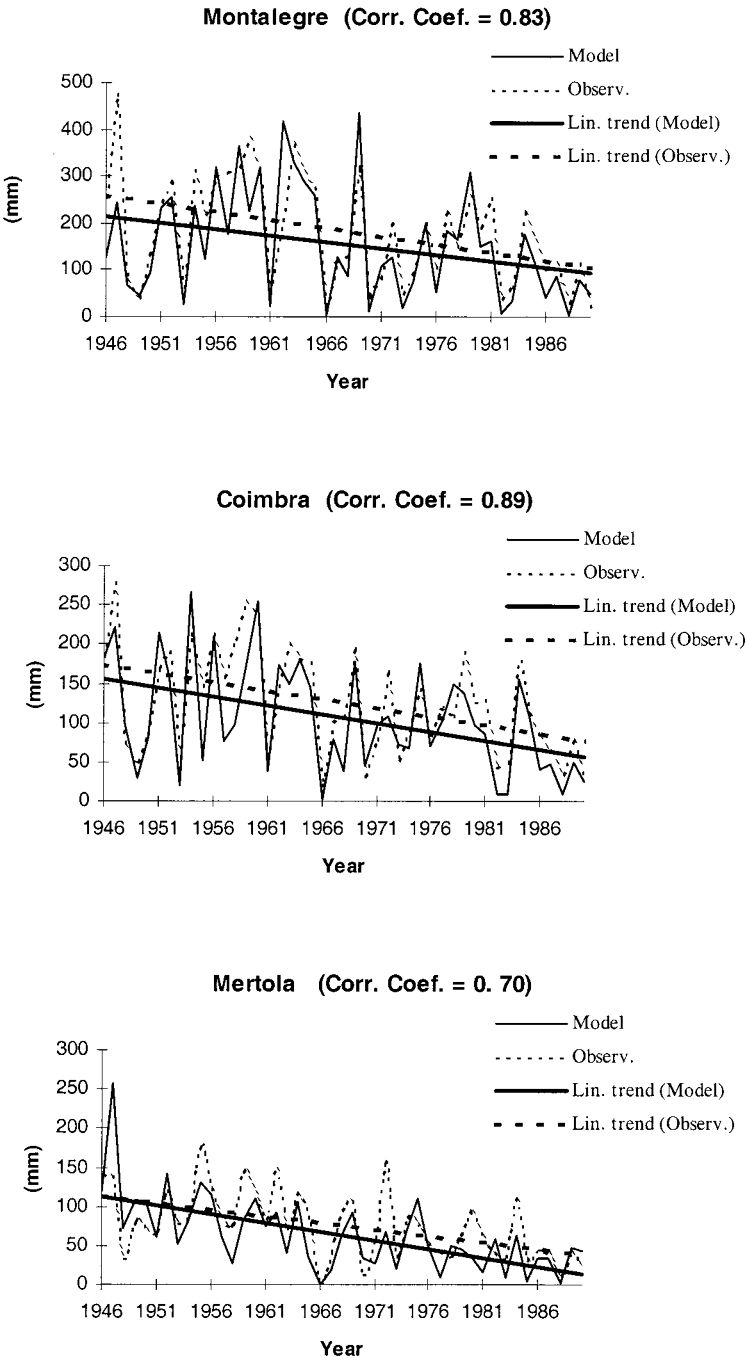

Figure 10. Observed and modelled March precipitation and their corresponding linear trend for Montalegre, Coimbra and Mertola

Portuguese precipitation. Finally, the third CWT used to model precipitation (SW) assumes a similar importance throughout Portugal, with slightly higher values in the north (Figure 12(b)).

We acknowledge that our predictors do not fulfil all the necessary conditions of a conventional linear regression model. In fact, the monthly percentage of occurrence of different CWTs is not a continuous variable but a discrete one. However, we are confident that a reasonable approximation is achieved by using a large dataset (45 years of daily CWTs classification), thus largely reducing this undesirable caveat.

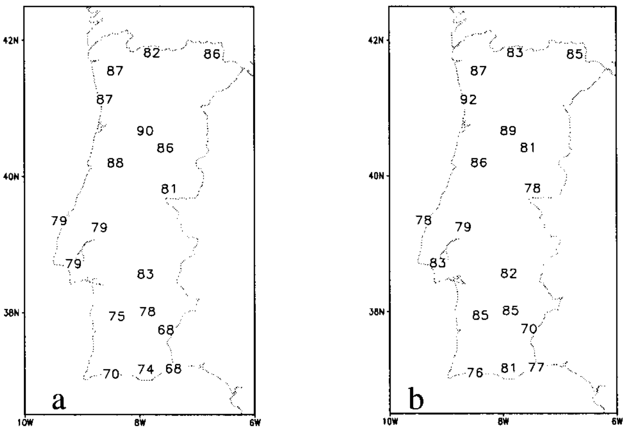

Figure 11. Correlation coefficient between observed and modelled precipitation for each station model. Spatial distribution for (a) the calibration period (winter) and (b) the validation period (March).

Furthermore, the previous results obtained with monthly multi-linear regression models are in good agreement with those presented on a daily scale (Section 4) for the two available stations.

These results highlight the relative importance of different mechanisms associated with the precipitation regimes in Portugal. Frontal systems, associated with SW and W types, are responsible for precipitation throughout the whole territory, with higher relative importance in northern parts of the country in agreement with the distribution of the orography (Figure 1). On the other hand, precipitation regimes associated with vertical motions induced by cyclogenic activity, i.e. related with the frequency of C type, seem to be predominant in the southern parts of the country.

5.2. Extreme episodes

An important climatological consequence of the character of interannual variability of precipitation (Figure 3) is the frequent occurrence of drought spells over Portugal. These episodes may be especially harmful in the southern plains of Portugal (Alentejo), where most of the country's cereals are produced. As shown in Figure 2, this region is characterized by an annual average rainfall that ranges between 500 and 600 mm and, owing to its agricultural relevance, special attention has been devoted to the impact of drought spells over the Alentejo region (Ferreira and Ferreira, 1983).

The study of droughts in the Iberian region using the civil year (January–December) definition may result in misleading conclusions, since the winter precipitation amount may be wrongly split into two different years. A previous study by Feio and Henriques (1986) pointed to the need to adopt a hydrological year starting in September of the previous year and ending in August of the year being considered, which differs from the official Portuguese hydrological year, which begins in October and ends in September. The September–August definition of the hydrological year, already adopted in Figure 3, will be used hereafter. Therefore, only 44 complete hydrological years (1947–1990) were considered in the study.

Feio and Henriques (1986) defined an extreme drought year as being one with a rainfall amount below 60% of the annual average. During the period under study (1947–1990), we retained only two extreme episodes, 1948–1949 and 1980–1981, hereafter referred to as the 1949 and 1981 droughts. The ten driest episodes for the whole territory are listed in Table V, where mean precipitation (second column) and percentage from the average hydrological year precipitation (third column) are, respectively, presented for each year.

In order to analyse the seasonal evolution of extreme drought episodes, the mean value of precipitation for every month of the hydrological year and the corresponding values for the two driest episodes—1949 and 1981—are compared in Figure 13. These two extreme cases present distinct characteristics: the 1949

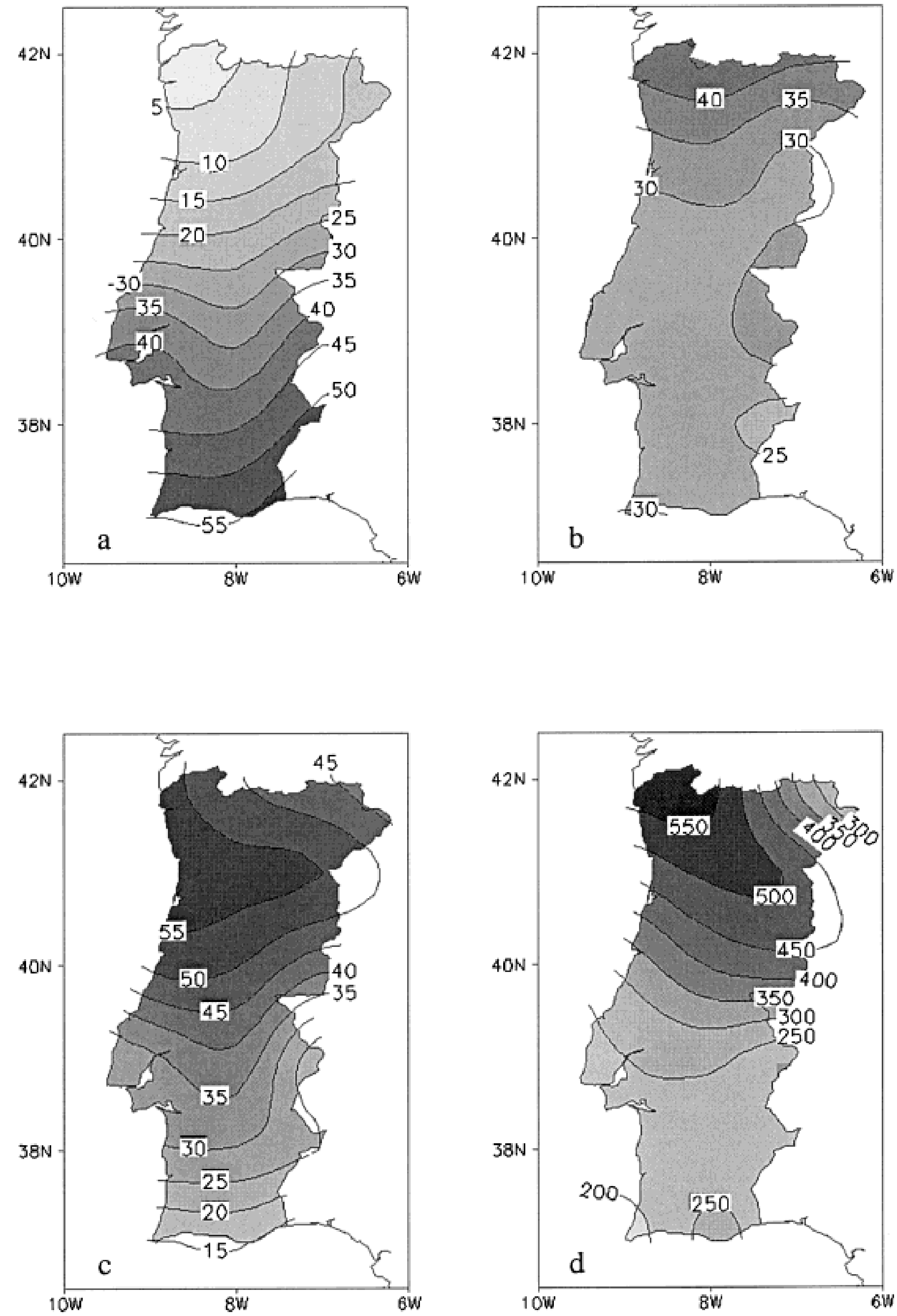

Figure 12. Contour lines showing the spatial variability of the normalized coefficients of the regression equation models for respectively: (a) cyclonic C, (b) southwesterly SW and (c) westerly W. Spatial distribution (d) of winter mean precipitation (mm)

episode (Figure 13(a)) being characterized by precipitation amounts well below the respective climatological values for most of the year (with the exception of December); and the 1981 episode (Figure 13(c)) presenting a very pronounced dry winter period with close to normal values during autumn and spring. An analysis on corresponding values of frequency of C, W and SW CWTs may be observed in Figure 13(b) and (d). Agreement between corresponding pairs of figures is worth noting for both episodes, clearly

Table V. Ranking of the ten most severe droughts in Portugal, using the whole hydrological year (Sep–Aug)

Year	Average precipitation (mm)	% Mean precipitation
1981	501	0.57
1949	516	0.59
1965	561	0.64
1976	564	0.64
1953	582	0.66
1975	626	0.71
1989	660	0.75
1957	675	0.77
1972	688	0.78
1983	705	0.80

The table shows the year of occurrence, the average precipitation for that year (mm) and the corresponding percentage from the average hydrological year.

showing, in the case of extreme events, the decisive role played by identified links between anomalous precipitation amount and anomalous frequency of *wet* CWTs.

A similar analysis performed on the wettest years reveals a similar pattern of association. Examples for the wettest year (1966) and for 1977 are shown in Figure 14, where it may be observed that months with

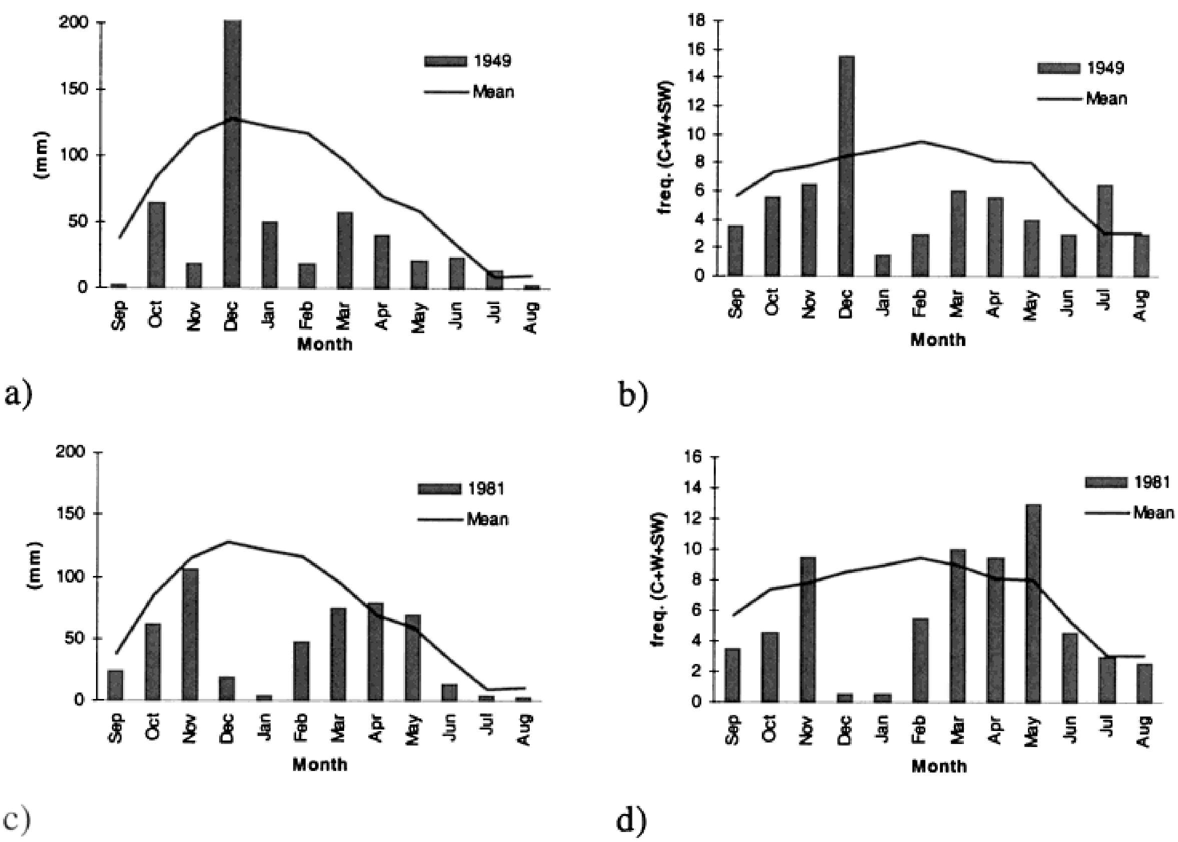

Figure 13. Intra-annual variability of the monthly precipitation during the (a) 1949 and (c) 1981 drought episodes (columns), and the corresponding frequency of C + W + SW CWTs for (b) 1949 and (d) 1981. Mean values (1947–1990) are represented by the thick line

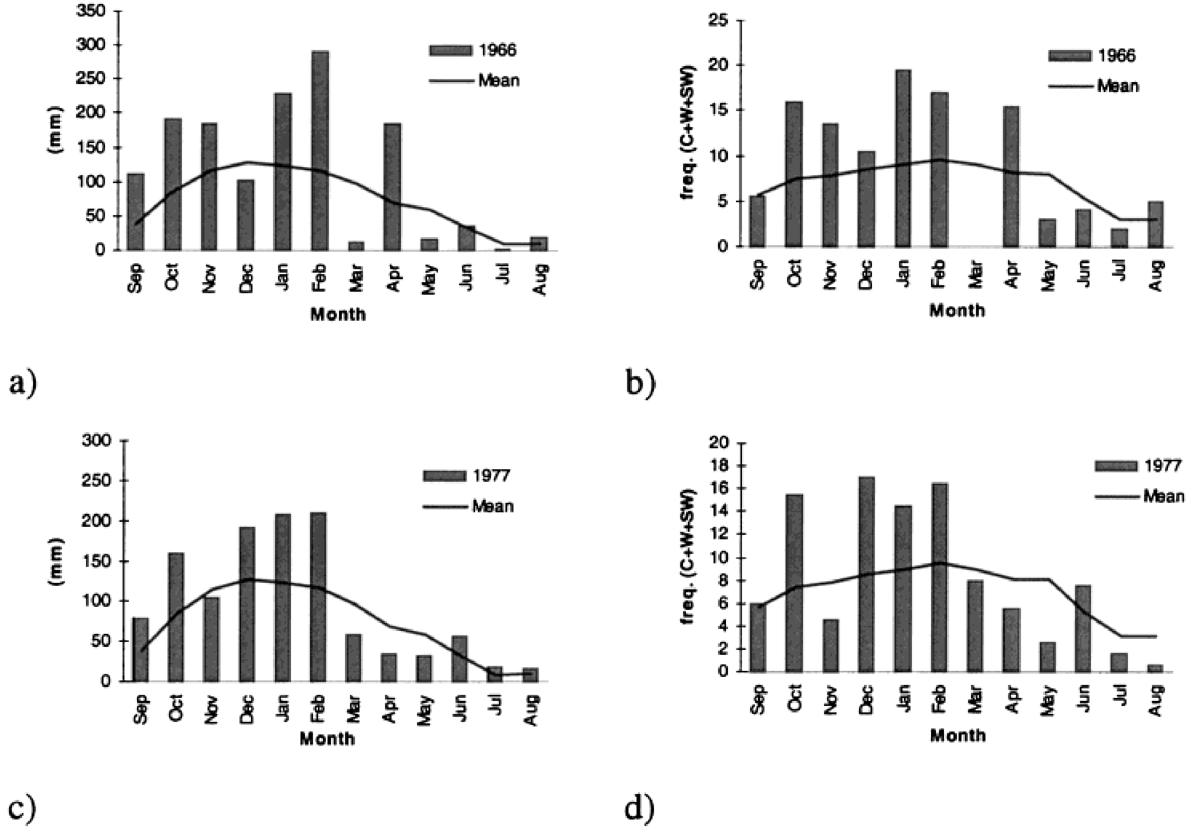

Figure 14. As in Figure 13, but for the 'wet' years of (a) and (c) 1966 and (b) and (d) 1977

above (below) normal values of monthly frequency of *wet* CWTs correspond to months with greater (smaller) than average precipitation.

Previous studies have showed a predominance of a large Azores anticyclone during dry years, which restricts the number of depressions and frontal systems affecting Portugal. Such studies, however, have employed a manual synoptic classification, and were restricted to small datasets, typically of less than 10 years (Ferreira and Ferreira, 1983; Ramos, 1987).

In order to assess interannual variabilities of precipitation and corresponding frequency of wet weather types during the mean hydrological year, a more restrictive period should be used than the hydrological year based on a September–August definition. In fact, during the summer period, the vast majority of days are dry, independently of dynamical characteristics of atmospheric circulation, i.e. independently of CWT classification. Accordingly, we will use the period from October to April, as more than 80% of the observed precipitation falls within this period. Table VI shows the ten driest episodes but respecting to the 'short' hydrological year defined from October to April. A simple comparison between Tables V and VI reveals that not only the driest year is 1981 but that nine out of ten dry years are common to both tables, although not necessarily in the same order.

The interannual variability of both the standardized annual (October–April) precipitation and the standardized combined frequency of the three weather types (C, W and SW) may be observed in Figure 15. The interannual evolution of both two curves is remarkably similar (correlation coefficient of 0.88) and it is possible to verify that most of the driest years are characterized by very low values of the combined frequency of the *wet* CWTs mentioned above. The same conclusion may be drawn with respect to the wettest years, which also present the highest values of the combined frequency of those three CWTs.

Table VI. As in Table V but using the 'short' hydrological year definition (Oct–Apr)

Year	Average precipitation (mm)	% Mean precipitation
1981	389	0.53
1976	435	0.59
1949	456	0.62
1965	483	0.66
1957	490	0.67
1983	592	0.67
1953	501	0.69
1975	536	0.73
1989	550	0.75
1967	571	0.78

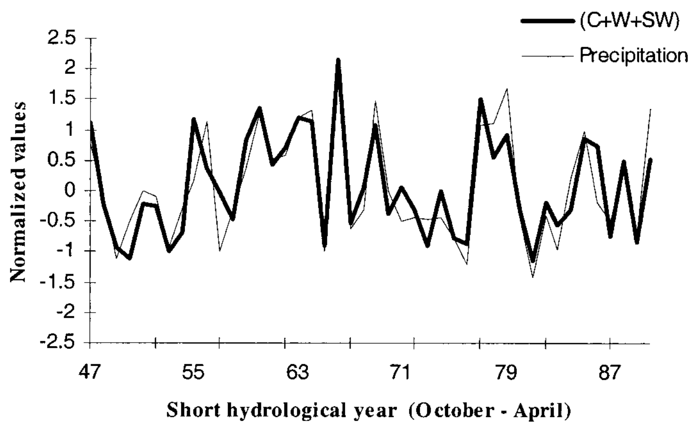

Figure 15. Normalized values of precipitation and total number of days from classes C, W or SW during the 1947–1990 period using the short hydrological year

6. CONCLUSIONS

Daily atmospheric circulation affecting Portugal was characterized through the use of a set of indices associated with direction and vorticity of geostrophic flow over an area covering the Iberian Peninsula. A semi-empirical set of rules was established, allowing us to define a set of 26 CWTs, which were later regrouped into ten basic ones in order to keep a physically based but statistically reliable scheme of analysis.

The impact of each CWT on the winter precipitation regime was studied for Coimbra and Mertola on a daily basis between 1957 and 1986. During this period, the most frequent CWT (37%) was the anticyclonic (A) type, which was associated with quite dry conditions (1.9 mm/day). On the contrary, three of the *wettest* CWTs, namely cyclonic (C), westerly (W) and southwesterly (SW) types, that together contributed to less than one third of all observed days, accounted for almost two thirds of the observed precipitation. Similar results for these two stations were obtained with respect to spring and autumn seasons.

Special attention was devoted to the observed decreasing trend of March precipitation over Portugal from 1946 to 1990. A strong decrease, statistically significant at the 95% level, was found for the averaged precipitation over Portugal as well as for the combined monthly frequency of days of C, W and SW types.

Multiple regression linear models were developed for all 18 stations, using as predictors the frequency of the three *wet* CWTs. These models revealed a reasonable capacity of reproducing the interannual variability of the winter precipitation (calibration period) and both the observed variability and decreasing trend of March precipitation (validation period).

The two most intense drought episodes—1949 and 1981—were analysed, and it was found that the driest months were always characterized by much lower than average frequency values of C, W and SW types.

Similar results were also obtained for two of the wettest years (1966 and 1977), stressing the existence of strong links between anomalous frequency of *wet* CWTs and anomalous values of monthly precipitation with a deep impact on wet and dry extreme years.

It is worth mentioning that some of these results have already been found, at least in a qualitative way. However, we should stress that the vast majority of previous works developed for Portugal have employed subjective classification schemes and relatively small datasets, typically less than 10 years (a direct consequence of the enormous task required when analysing daily synoptic charts manually). These two factors have major consequences, namely that such classifications are very difficult to reproduce by another researcher and, owing to their small length, do not allow for a proper evaluation of the circulation–precipitation relationships on an interannual scale.

These results suggest that the adopted weather typing approach may constitute a very useful tool to help understanding of certain dynamical aspects related with the precipitation regime in Portugal, namely the observed wide range values of interannual variability, the decreasing trend of March rainfall and the occurrence of severe drought episodes that frequently affect Portugal. On the other hand, obtained results suggest that different mechanisms of precipitation are associated with northern and southern precipitation regimes, which are respectively controlled by orographic and cyclogenic processes.

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APPENDIX A

The composite maps of the SLP anomaly fields for all ten CWT obtained for winter are shown in Figure A1 and the corresponding synoptic characteristics for CWTs that were retained in this study are described in Table AI.

Table AI. Synoptic characteristics of the ten CWTs defined

NE (northeasterly)	Days characterized by an extended Azores high pressure to the northeast and by low pressure over the Mediterranean region
E (easterly)	Synoptic situations characterized by an anticyclone between the British Isles and the Iberian Peninsula
SE (southeasterly)	Days characterized by low-pressure regions extending from Madeira to the Azores Islands and high pressure over Northern Europe
S (southerly)	Situations characterized by low pressure north of Azores, and by high pressure over central Europe
SW (southwesterly)	Days characterized by a weakening of the Azores high pressure and strong low pressure located between Iceland and the Azores
W (westerly)	Weather circulation characterized by the setting of the Azores high pressure at 30°N and by low-pressure centres west of the British Isles
NW (northwesterly)	Days characterized by the localization of Azores high pressure between the Azores and Madeira Islands and low-pressure centres over northern France
N (northerly)	Days characterized by the presence of the Azores high pressure north of the Azores Islands and low pressure over southern Europe and the Mediterranean basin
C (cyclonic)	Synoptic situations characterized by a low-pressure centre over the western Portuguese coast, sometimes accompanied by a blocking anticyclone located between Iceland and the British Isles
A (anticyclonic)	Days characterized by a high-pressure centre over the Iberian Peninsula, and between Iberia, Madeira and the Azores Islands

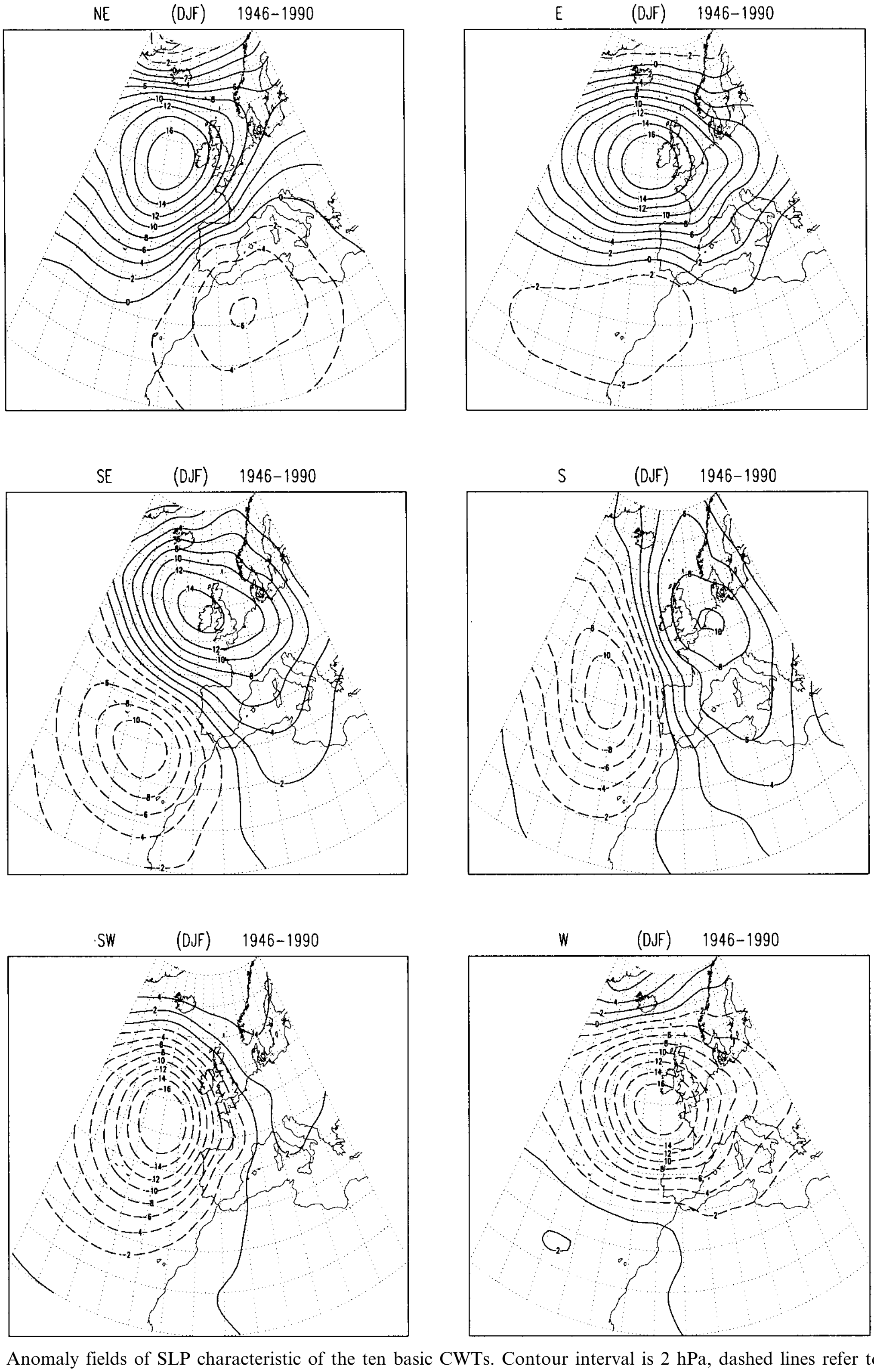

Figure A1. Anomaly fields of SLP characteristic of the ten basic CWTs. Contour interval is 2 hPa, dashed lines refer to negative values whereas continuous contours refer to positive anomalies (*continued overleaf*)

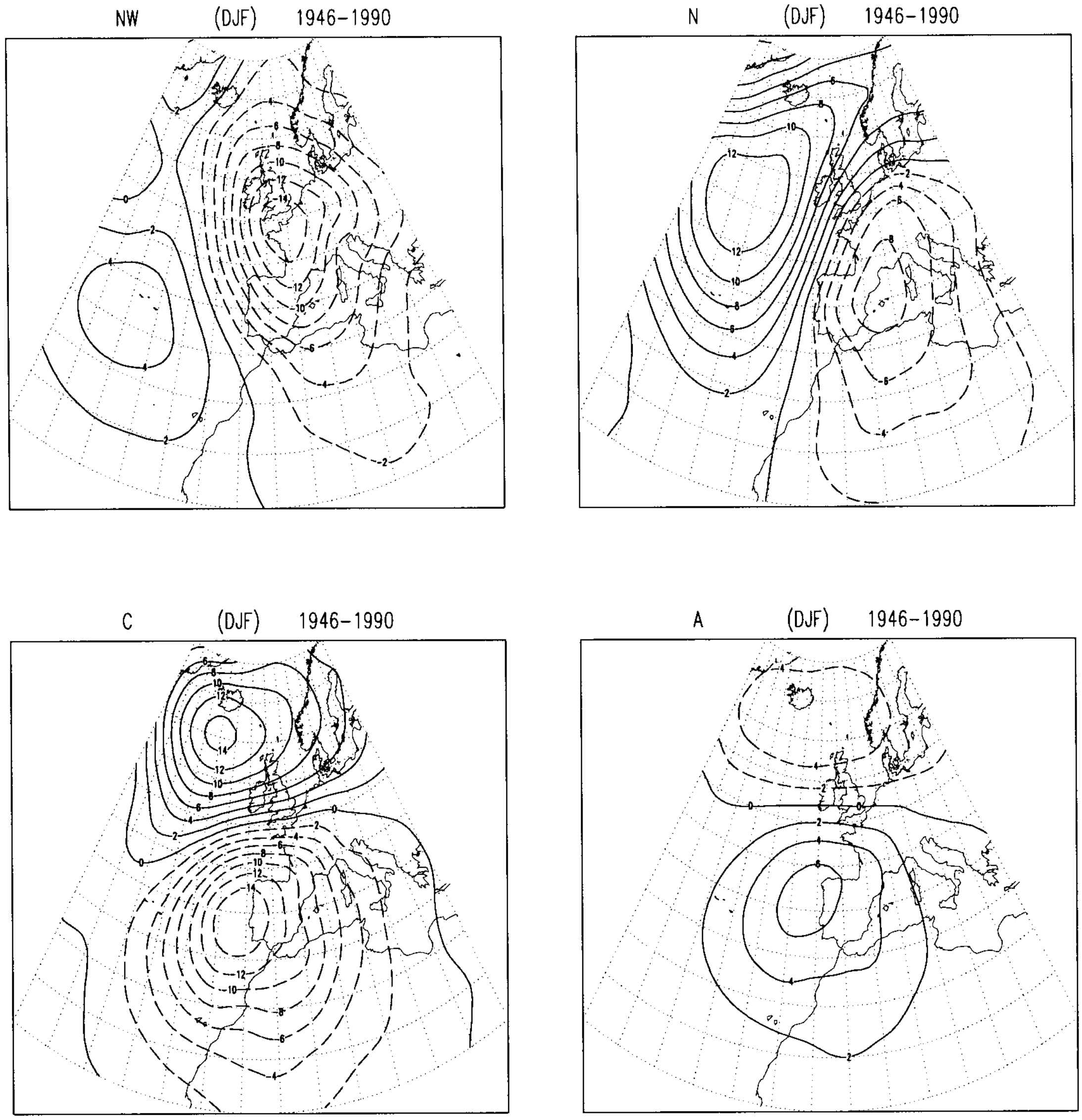

Figure A1 (*Continued*)

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