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DAILY RAINFALL PATTERNS IN THE SPANISH MEDITERRANEAN AREA: AN OBJECTIVE CLASSIFICATION

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ABSTRACT

Using a 30-year data base of daily precipitation at 410 sites of Mediterranean Spain, the main spatial patterns controlling significant and 'torrential' daily rainfalls in the area are derived. This is done by applying cluster analysis on the most relevant principal directions extracted from a principal components analysis of the between-day correlation matrix. Seasonal and decadal frequency distributions of the emergent rainfall patterns as well as their principal interlinks are presented and discussed.

Despite the large proportion of convective rainfalls in the area, the clusters obtained are quite definite and clearly display the dominant role exerted by the complex topography and its connection with the main rain bearing flows. Patterns for significant rainfalls and those for the subgroup of torrential days display very similar spatial characteristics, meaning that rainfalls are similarly highly structured regardless of their type, and strongly linked to the topography. Nevertheless, a certain tendency of enhancing the importance of coastal zones for torrential events is observed.

Plots of interseasonal variability reveal a different incidence of significant and torrential rainfall patterns through the year. The western patterns, largely stimulated by Atlantic flows, show peak frequencies in winter for total rainfalls, but similar incidence in winter and autumn for torrential events. On the contrary, the eastern patterns, which are strongly influenced by the Mediterranean dynamics, exhibit a diversity of behaviors for the general case depending on the zone, but they all dominate in the fall season for the torrential case. Copyright © 1999 Royal Meteorological Society.

KEY WORDS: Western Mediterranean Spain; rainfall patterns; cluster analysis; mesoclimatology; topography; rainfall, daily; rainfall, heavy

1. INTRODUCTION

The western Mediterranean region, depicted in Figure 1, constitutes an ideal scenario for mesoclimatological studies on spatial and temporal variability of rainfall. This is, primarily, because the area possesses quite a complex topography which configures the western Mediterranean Sea as a closed basin, largely isolated from other regions (see Figure 1). This important orography leads to accentuated rainfall contrasts between uplands and lowlands, and between areas with different exposure to the Atlantic or Mediterranean humid winds. Indirectly, the topography interacts with the atmospheric disturbances coming from the Atlantic, frequently generating new cyclones in favorable areas such as the lee of the Atlas, Pyrenees and Alps (Reiter, 1975). In addition, the closed characteristics of the western Mediterranean Sea and the high insolation received during the summer leads to high sea surface temperatures and therefore to important latent heat fluxes during the fall season. As a consequence, the Mediterranean air mass often exhibits convective instability (Meteorological Office, 1962; Ramis, 1995), which is eventually

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released as organized and effective convection over the coastal areas (Font, 1983; Riosalido, 1990). Thus, Mediterranean rainfalls very often have a torrential character. In the second place, the western Mediterranean region is a transition zone between the mid-latitude low pressures and the subtropical highs as a result of its latitude (36–44°N). This fact leads to significant pluviometric differences between north and south of the basin, and more importantly, imposes strong seasonal contrasts. In particular, the summer is critically dry in some areas, such as southern Spain (Font, 1983).

All the above aspects were highlighted in a previous and complementary study (Romero *et al.*, 1998b) for the Mediterranean regions of Spain: Catalonia, Valencia, Murcia, Andalucía and Balearic Islands (Figure 1). Figure 2 shows a detailed map of this area, with an indication of the main relief units. Specifically, in Romero *et al.* (1998b), an homogenized data base of daily rainfall at 410 sites (Figure 2) for 30 years (1964–1993), was used to produce yearly and seasonal maps characterizing, in an average sense, the cumulative amounts, frequencies, intensities, and persistence or absence of the rainfalls in the region. Such analysis was applied separately for the three consecutive decades 1964–1973, 1974–1983 and 1984–1993. A successive drying was found in the most sensitive areas to the winter Atlantic depressions (western Catalonia, and Central and West Andalucía), and a quite dry second decade in Mediterranean-governed zones as a result of abnormally dry autumns (see the sequence of Figure 3 in Romero *et al.*, 1998b). The autumn season, indeed, is the wettest period in the latter zones and the most torrential in general, particularly in the coastal areas (see Figure 7(e) in Romero *et al.*, 1998b).

This work attempts to advance a further step towards the pluviometric characterization of Mediterranean Spain, and therefore towards a better knowledge of its regional climate. The first aim of the paper is to find the principal spatial patterns under which significant daily rainfalls tend to occur. A second objective is to derive a more concrete classification for what we call torrential days, which are of our

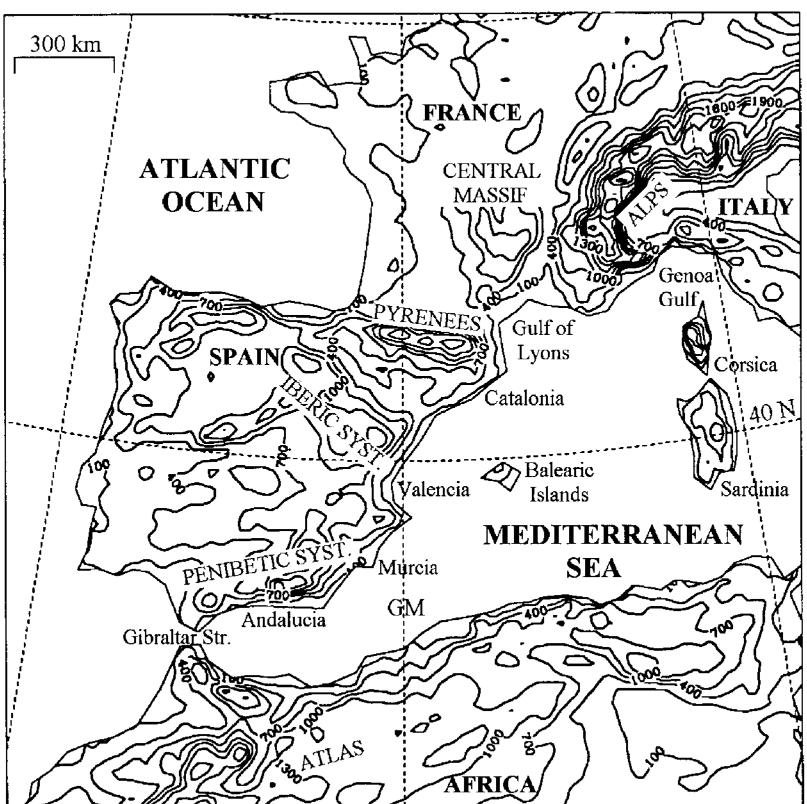

Figure 1. The western Mediterranean region and its orography (contour interval is 300 m starting at 100 m). The sites mentioned in the text are indicated

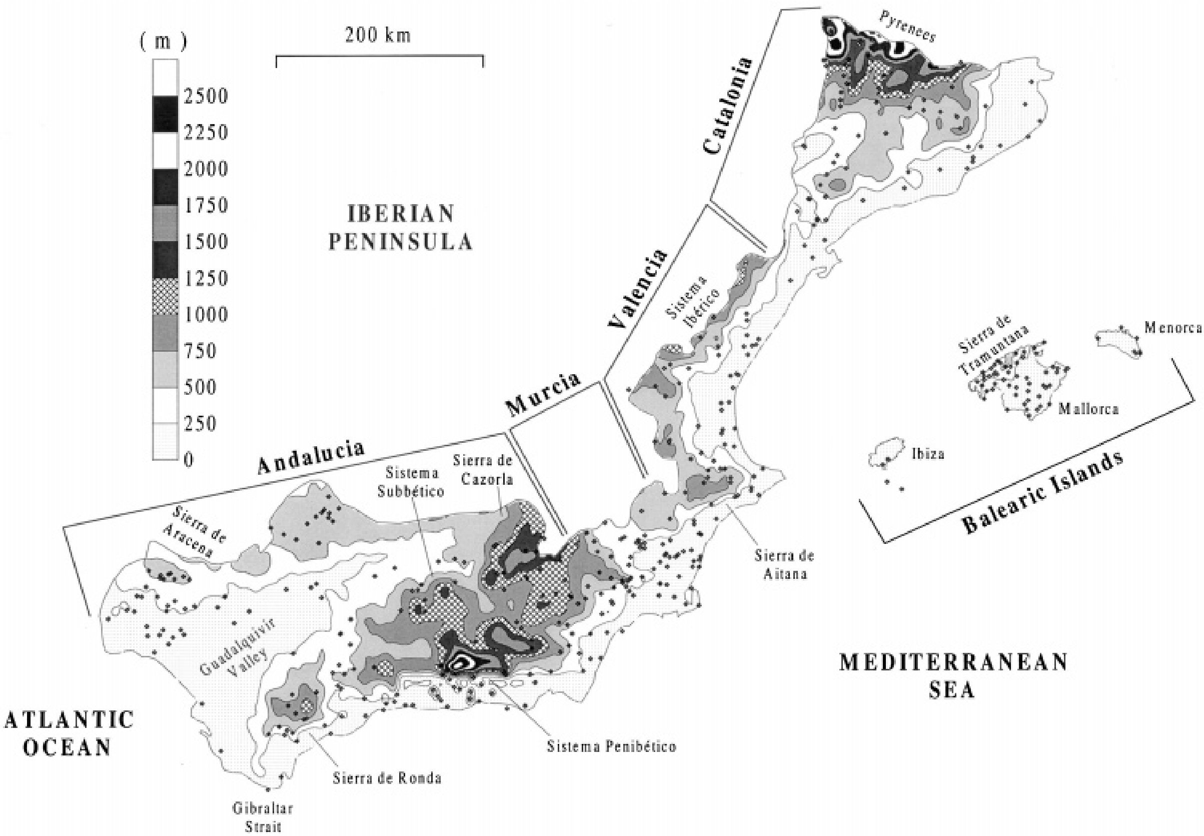

Figure 2. The Spanish Mediterranean area under study comprises Catalonia, Valencia, Murcia, Andalucía, and Balearic Islands. It includes a smoothed version of its orography, the position of the data base stations (410 in total), and some geographical references mentioned in the text. The two stations adjacent to Ibiza belong to the small island of Formentera, which is not represented

particular interest. From our regional experience, and from the previous results of Romero *et al.* (1998b), it can be anticipated that the resulting rainfall patterns will be strongly linked to the topography of the region, and that distinctive seasonal distributions will characterize them.

Although this type of classification, objectively based, has been applied to different regions of the world—Po valley in Italy (Cacciamani *et al.*, 1994); New Zealand (Kidson, 1994), Wales (Sumner, 1996) etc., similar studies do not exist for the considered area. Using a parallel methodology to that followed here, but for a smaller spatial context, Sumner *et al.* (1995) offer a detailed delimitation of the significant daily rainfall patterns and responsible surface circulations over the island of Mallorca (see Figure 2 for location).

Although the spatial patterns being sought constitute, of course, a simplification of the complex reality, they can be useful as additional objective elements for regional forecasters. That practicality may be increased in a future work in which the search of the synoptic circulation patterns associated with the typical rainfall distributions will be attempted.

The structure of the paper starts with a description of the data base used and the details of the methodology employed (Section 2). In Section 3, the emergent rainfall patterns are presented and discussed. Finally, Section 4 is dedicated to the conclusions and perspectives for future research.

2. DATA BASE AND METHODOLOGY

The data base is formed by daily rainfall series at 410 stations (347 in peninsular Spain and 63 in the Balearic Islands (Figure 2), for the period 1964–1993 (30 years). The coverage is globally satisfactory (exceptional in Mallorca), although some gaps exist in the Guadalquivir valley, in mountainous areas of Andalucía, north of Valencia, and some areas of Catalonia.

Initially, the available data consisted of 3366 records during some period between 1951–1995, provided by the Spanish Instituto Nacional de Meteorología (INM). The final data base was the result of a first selection, in which a minimum of 1000 daily data (almost 3 years) were required (2842 stations), and a second selection in which we searched the longest subperiod having the highest number of stations with tolerable completion. We decided to keep all stations with 90% of data during 1964–1993 (410). The following task was to apply a method of data completion and homogenization. We followed an iterative method in which data of all initial 2842 stations for the whole period 1951–1995 were used. The details of the algorithm can be found in Romero *et al.* (1998b).

A large proportion of the 10958 days contained in the 30 years of data are absolutely dry in most of the stations, and therefore a restrictive criterion must be imposed to keep only those days characterized by significant rainfall over the area. It was decided to keep those days in which at least 5% of the stations registered more than 5 mm, yielding a total of 3941 days. Of course, such thresholds are arbitrary. Other values were tested (15%, 5 mm; 30%, 5 mm, etc.) and quite similar rainfall patterns were obtained. However, since 3941 days represent a considerable population, we judged the 5%, 5 mm limit opportune for statistical reasons. In addition, the 5% threshold implies 20 stations, which are sufficient to represent the main topographic units and adjacent lands that we aim to resolve (see Figure 2). Of the 3941 selected days, 30.0% occurred in winter (December, January, February), 29.6% in spring (March, April, May), 26.8% in autumn (September, October, November), and only 13.6% in summer (June, July, August).

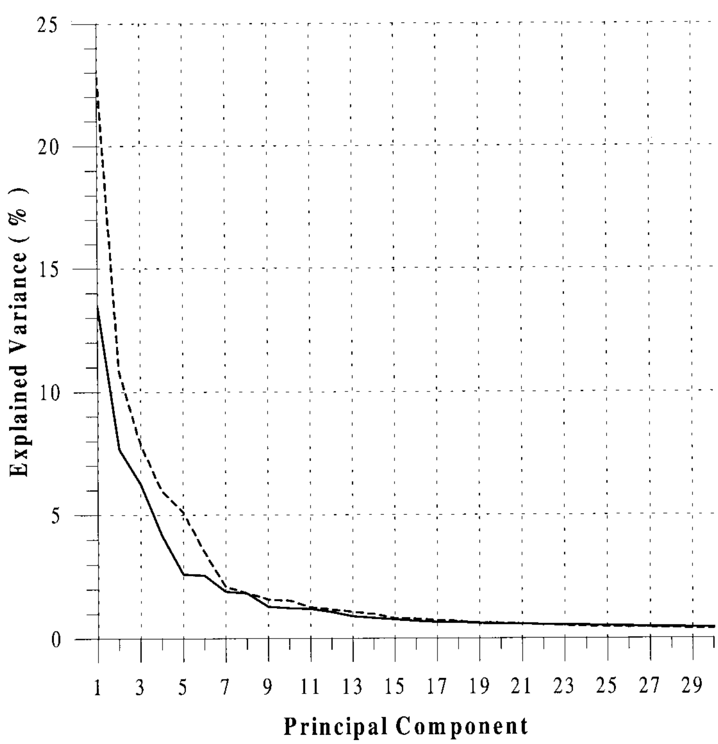

Figure 3. Principal components scree plot for significant days (full line), and torrential days (dashed line). Only the first 30 PCs of the resulting 409 PCs are shown

As torrential days, we decided to filter days with rainfalls exceeding 50 mm in at least 2% of stations (8 stations). This criterion yielded 449 days (15 per year on average, normally grouped in a few episodes), and was considered the most appropiate compromise for three reasons: eight stations is an adequate number to represent the main torrential centers (Sierra de Aracena, Sierra de Ronda, Sierra de Aitana, Sierra de Tramuntana, coastal domains), and ensures that very localized events are not included; other more restrictive criteria reduce strongly the number of filtered days (for example, 2%, 60 mm gives only 226 days, and 5%, 50 mm, 124); finally, it could be verified that well-known case studies appeared in the literature (e.g. Ramis *et al*., 1994; Fernandez *et al*., 1995; Romero *et al*., 1997, 1998a) were effectively captured by the selected criterion. It is interesting to note that all the 449 torrential days were also significant days. In this case, 44.8% belong to the autumn season, 35.2% to winter, 14.9% to spring, and 5.1% to summer. Clearly, there is a preeminence of the autumn season, as was expected.

As in Sumner *et al*. (1995), the approach followed to derive the typical precipitation patterns consists in subjecting the *T*-mode (day-by-day) correlation matrix to principal components analysis (PCA), and carrying out cluster analysis (CA) on the most important extracted components. That is, days participating with similar loadings on the extracted components will be clustered together. This approach is aimed to join days with similar precipitation distributions, irrespectively of the precipitation amounts. The method is the analogue to that applied in regionalization studies, where the *S*-mode (site by site) correlation matrix is used instead (White *et al*., 1991; Bonell and Sumner, 1992; Sumner *et al*., 1993; Gong and Richman, 1995).

The PCA is designed not merely as a data reduction technique, but as a method to achieve the requirement that only the fundamental modes of variation of the data are considered for the clustering process. Several criteria have been suggested for deciding how many PCs to retain in order to separate 'signal' from 'noise' (Jolliffe, 1986; Barring, 1987; Preisendorfer, 1988), but a clear-cut number of PCs is certainly rare. The simple scree test of Cattell (1966) was adopted. Figure 3 shows the scree plot obtained from the analysis of significant and torrential data sets. Several breaks of the slope are present in both cases. We obtained 17 PCs for significant days, which account for 49% of the total variance; and 15 PCs for torrential days, which account for 68.5% of the total variance.

Some authors promulgate the use of rotated PCs and have demonstrated its benefit in spatial contexts, in which the *S*-mode decomposition is used (e.g. Richmann, 1986; White *et al*., 1991). Some experimentation was done with obliquely rotated PCs, which produced moderate simple structures (see Richmann, 1986). The precipitation patterns obtained were similar to those based on unrotated PCs. However, we found the latter classification superior after noting that some randomly selected maps had been allocated in better agreement with our subjective criteria. Therefore, the solution based on unrotated PCs was finally selected.

For the cluster analysis, the nonhierarchical *k*-means method (Anderberg, 1973), as implemented in the Statistica Utility (1994), was used. The Euclidean distance was taken as the similarity index. Gong and Richman (1995) showed that nonhierarchical methods, such as the one used, outperformed hierarchical techniques. Nevertheless, hierarchical tree plots generated by Ward's method (Ward, 1963) were also considered as reference for deciding how many clusters to create. The final decision on the proper number of clusters is still an unresolved problem (Gong and Richman, 1995), prone to subjectivity and most of the time dictated by the researcher's experience. It was judged that the solution of 11 typical patterns was satisfactory for significant rainfalls, and eight patterns for torrential rainfalls. These patterns are presented and discussed in next section (consider Figure 2 for locations mentioned therein).

3. EMERGENT PATTERNS AND DISCUSSION

3.1. Significant days

Figure 4 shows rainfall composites for the 11 clusters (referred to as pattern groups, PGs), which are summarized in Table I. The area considered is large enough as to yield a clear separation of the PGs, in

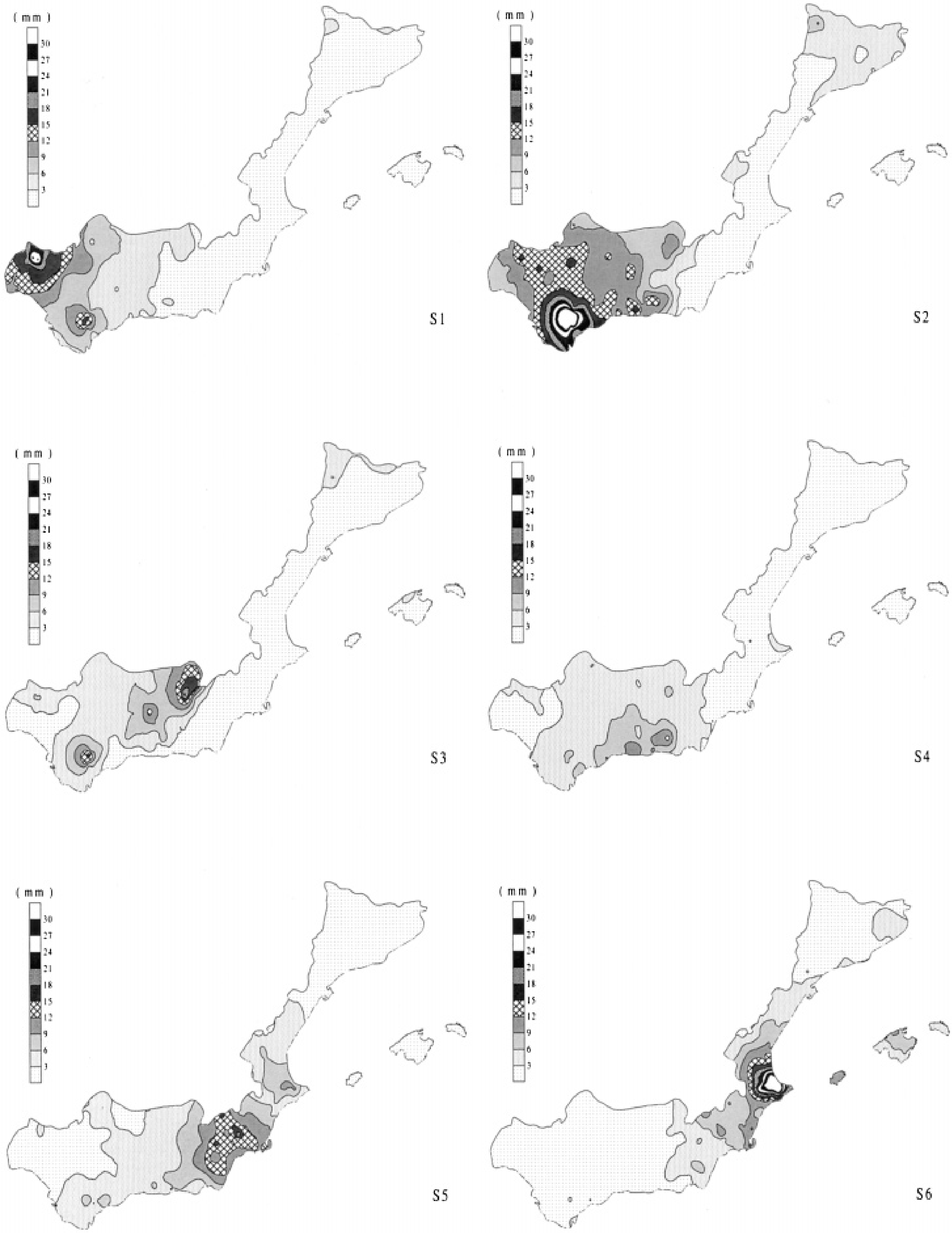

Figure 4. Daily rainfall composites for the 11 pattern groups (PGs) obtained in the classification of significant events

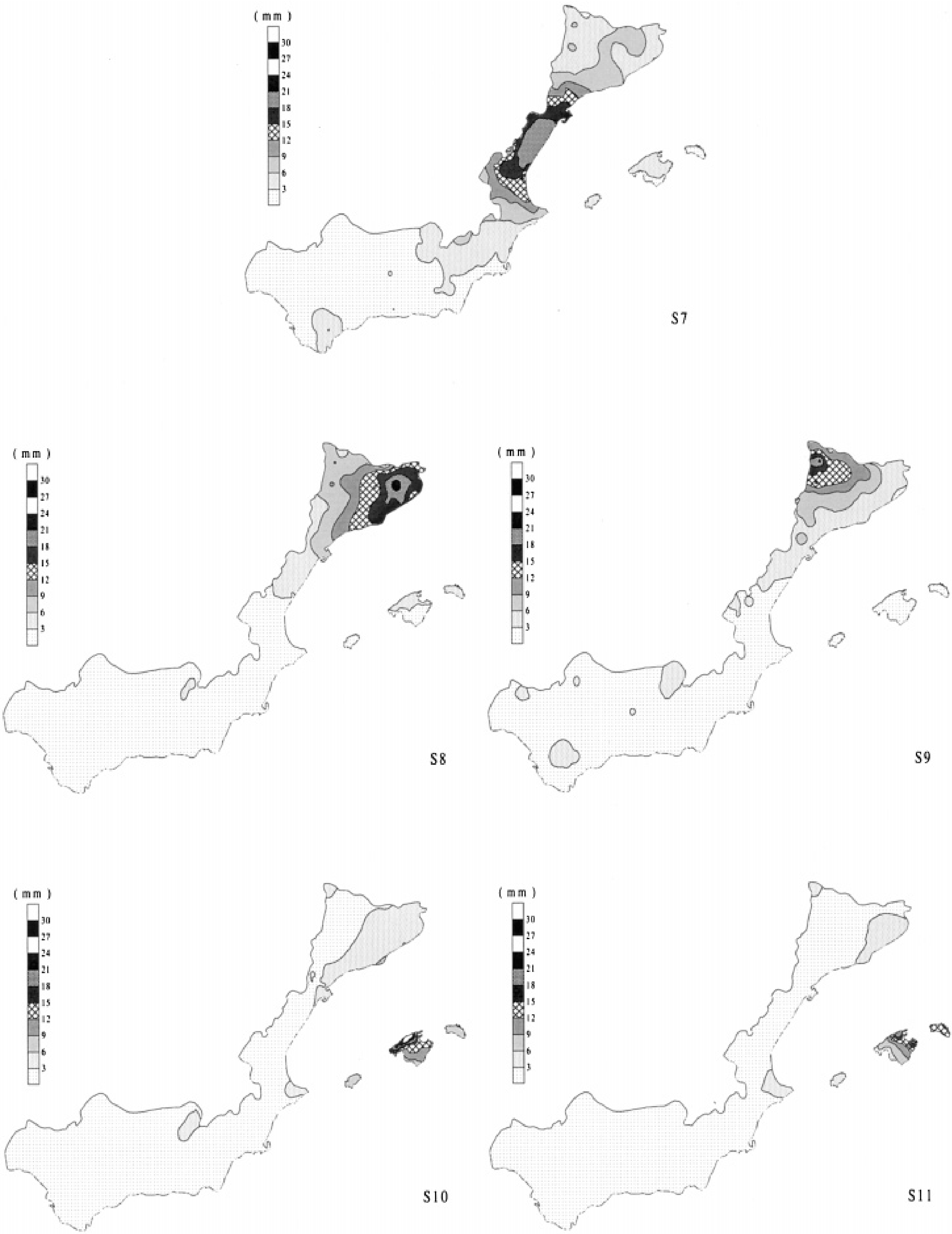

Figure 4 (*Continued*)

the sense that each of the patterns tends to highlight distinct localities and their areas of influence do not overlap exceedingly. All the PGs appear clearly associated with the topographic entities of the region (Figure 2). The relative position of these entities and the main rain-bearing atmospheric systems will determine the occurrence of these idealized patterns. Although the attribution of meteorological causes to the rainfall patterns is not the objective of this work, we made a visual inspection of a sample of meteorological maps for each cluster (as given by ECMWF gridded analyses), in order to better interpret each PG.

S1 represents rainfalls almost exclusive of western Andalucía, especially in its westernmost part. The maximums are found, therefore, in the mountains of Sierra de Aracena. A secondary maximum is found about Sierra de Ronda, which also participates actively in other PGs. As emphasized in Romero *et al.* (1998b), Sierra de Ronda is a peculiar zone, favourably exposed to a wide range of flows, and as a consequence presenting the maximum yearly rainfalls of the whole region. Pattern S1 is principally associated with Atlantic depressions west of the Iberian peninsula inducing southerly to westerly humid winds over western Andalucía.

S2 characterizes quite substantial rainfalls about the Gibraltar Strait area (maximum in Sierra de Ronda), but affecting in general the bulk of Andalucía except its eastern part. This is a very extensive pattern that may be also reflected in Catalonia region, especially in the Pyrenees mountains. As S1, this pattern is a logical result of upper level troughs close to the Atlantic coasts with the associated low-pressure systems at low levels providing southwesterly-westerly flows over Andalucía. The teleconnection between this area and Pyrenees mountains is explained by large depressions lying about western Spain, which provide the aforementioned flows and also warm and moistened southerly flows over the Pyrenees mountains. Atlantic depressions are hardly effective for the remainder areas, which become strongly sheltered (especially the southeast). As a result, this PG is characterized by little rain in these areas.

S3 is characterized by rainfalls in the mountainous interior of central and western Andalucía, away from the coast except in the Gibraltar Strait area. In this case, the main centre is Sierra de Cazorla, and secondary maximums are found in Sistema Subbético, Sierra de Ronda and Sierra de Aracena. The Pyrenees mountains, and even Sierra de Tramuntana mountains of Mallorca, can sporadically participate in this PG. S3 pattern is principally related to the passage of cold fronts over the Iberian Peninsula, which are associated with mid-latitude disturbances.

S4 is a particular PG of Andalucía, especially of its central part, and is maximized over the south/southeast facing slopes close to the coast. Probably the signal over the Sistema Penibético mountains is too weak due to the poor coverage of stations in these mountains (see Figure 2). This PG

Table I. Summary of the 11 pattern groups obtained for significant daily rainfalls (see Figure 2 for locations)

Pattern group	Days included	General area (maxima)
S1	551	Western Andalucía (Sierra de Aracena, Sierra de Ronda)
S2	492	Central–western Andalucía and Pyrenees mountains (Gibraltar Strait area)
S3	388	Interior Andalucía, Gibraltar Strait area and Pyrenees mountains (Sierra de Cazorla, Sistema Subbético, Sierra de Ronda)
S4	211	Central Andalucía (Sistema Penibético and South Coast)
S5	259	Southeast area (east-facing slopes and coastal areas)
S6	294	Southern Valencia, East Murcia, Ibiza and northern Mallorca (Sierra de Aitana area)
S7	296	Northern Valencia and South Catalonia (Gulf of Valencia)
S8	385	East of Catalonia (coastal zones)
S9	368	Pyrenees mountains and interior Catalonia (western Pyrenees)
S10	401	Mallorca (Sierra de Tramuntana mountains)
S11	296	Mallorca and Menorca (north-eastern mountains of Mallorca)
	3941	

is associated with troughs about southern Spain, frequently presenting cut-off low characteristics. There is not a clear preference for specific surface flows in this case, but Mediterranean warm flows tend to be present in most of the cases.

S5 represents the rainfalls in the southeast, which is the most arid zone of Spain (see Romero *et al.*, 1998b). Logically, this PG relies principally on easterly-southeasterly flows over the area, most of the time associated with well marked troughs or lows at upper levels along western Spain. For easterly flow regimes, other adjacent areas are also favourably exposed. As a consequence this PG is rather extensive, and exhibits two secondary maximums about Sierra de Ronda and Sierra de Aitana. We also observed that S5 sometimes occurs with very weak flows at low levels, but with cold air aloft over eastern Spain.

Pattern S6 represents the rainfalls that affect southern Valencia and Murcia, exhibiting a strong maximum in the Sierra de Aitana area. In Romero *et al.* (1998b), it was shown that the Sierra de Aitana area, and also Sierra de Ronda, are characterized by the most abundant rainfalls of the whole region. It is reasonable to conclude that this PG is mainly the result of depressions located in the southern part of the western Mediterranean region, but in this case providing rather easterly-northeasterly winds over the Sierra de Aitana area. Indeed, this is what was generally observed from the ECMWF fields. A notable aspect of this PG is that the nearby island of Ibiza and the mountainous north of Mallorca may participate appreciably of these situations.

S7 is characterized by rainfalls in the general area of Valencia and south of Catalonia, but in this case the main center is not Sierra de Aitana area but shifts to the north adopting an elongated shape along the Gulf of Valencia, parallel to the coastal mountains. In this case, easterly-southeasterly flows over the Gulf of Valencia benefit this pattern. This PG is quite extensive, since any sector of the eastern regions may be favoured by these airflows.

Pattern S8 is very local and characterizes those rainfalls of Catalonia concentrated close to the coast. This PG exhibits a marked suppressing gradient from the coast toward the interior of Catalonia (one of the driest zones of the area studied; Figure 3 of Romero *et al.*, 1998b). The maximum is found in the northeastern sector, over the prelitoral foothills of the Pyrenees mountains. Southerly-southeasterly onshore flows, cold fronts from the north, and also easterly to northerly flows induced by frequent depressions in the north of the Mediterranean basin (also reflected in northern Mallorca and Menorca), assist in explaining this pattern. Warm season convection forced in the slopes of the Pyrenees mountains may also contribute to this PG.

S9 is the complementary pattern of S8 over Catalonia. It represents rainfalls on its western side with maximum values found along the Pyrenees range. Apart from the typical mid-afternoon convection of the warm season, the main contributors to this pattern are the Atlantic fronts during its circulation over northern Spain.

S10 and S11 form two particular patterns of the Balearic Islands. Such degree of detail for a comparatively small territory could have been motivated by the large number of stations available over Mallorca (see Figure 2). Both PGs were already isolated as the most important precipitation structures in the work by Sumner *et al.* (1995). S10 closely resembles the mean annual rainfall of Mallorca. It clearly reflects the rainfall enhancement produced by the uplands of this island (notably, Sierra de Tramuntana mountains) for a wide variety of flows (Sumner *et al.*, 1995). S11 represents a wetting gradient toward north-eastern Mallorca and Menorca, this PG principally being linked to northerly airflows associated with a low to the east of the islands, and with cold fronts linked to higher latitude disturbances (Sumner *et al.*, 1995).

Of the 11 PGs (see Table I), the most frequent are S1 and S2. This is what can be expected, since these patterns are essentially linked to the Atlantic dynamics which quasiperiodically influence the Spanish latitudes during the cold season. Consequently, S3 also exhibits an important frequency. PGs S8, S9 and S10 (and its variant S11) could be included in a second group. This group is also contributed to by Atlantic disturbances circulating at higher latitudes, and is also influenced by secondary cyclones generated frequently over the northern part of the Mediterranean basin (e.g. the well studied Genoa Gulf cyclone, Reiter, 1975). Those PGs which more frequently rely on the Mediterranean dynamics (S4, S5, S6 and S7) present the lowest frequencies.

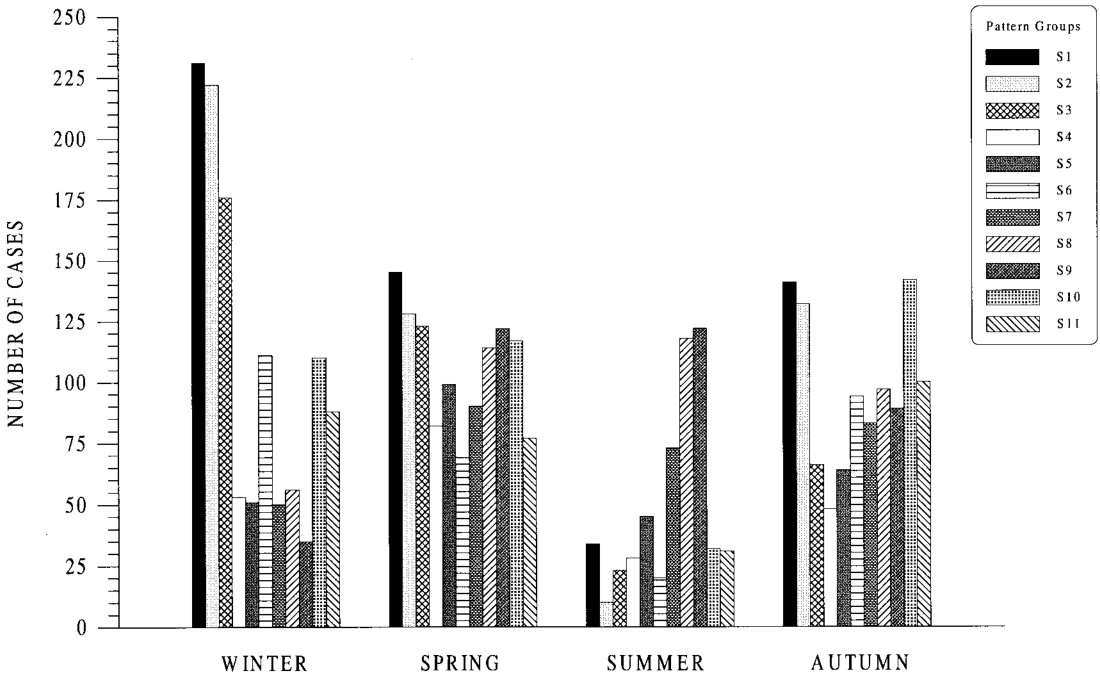

Figure 5. Seasonal distribution for the 11 PGs of significant daily rainfall

The seasonal distribution (Figure 5) also shows distinct behaviours among the PGs. Some PGs maximize their occurrences during winter (S1, S2, S3, and less strongly S6); others reveal peak values in spring (S4, S5 and S7); S10 and S11 during autumn, although with similar frequencies in winter and spring; the Catalan patterns S8 and S9 exhibit their maximum occurrences in summer, closely followed by spring.

In comparative terms, Figure 5 shows that the Andalusian patterns S1, S2 and S3 clearly dominate during the winter months, since Atlantic depressions tend to affect directly the western part of Andalucía during that period. S6 and the Balearic patterns S10 and S11 are also comparatively frequent during that season. During spring, there are not such large differences among the patterns occurrence. Nevertheless, S1, S2 and S3 exhibit again the highest frequencies (sensibly smaller than in winter, however), followed very closely by S8, S9 and S10. For all PGs except for S7–S9, the lowest frequencies occur during summer. The important summer contribution to PGs S7–S9 (representative of the northern peninsular sector) reflects the relevant weight of the typical mid-afternoon convection in the interior north of Valencia and north of Catalonia during summer. That convectional activity is triggered over Sistema Ibérico and Pyrenees mountains with the support of the Iberian thermal low (Alonso *et al*., 1994). During autumn, the most frequent PG is S10. As in winter and spring, S1 and S2 are very frequent, but not S3 in this case.

In conjunction with the results of Romero *et al.* (1998b), where the three decades 1964–1973, 1974–1983 and 1984–1993 where analyzed separately, it was considered interesting to examine the interdecadal variability of the PGs (Figure 6). In Romero *et al.* (1998b), it was shown that Central Andalucía, western Catalonia, and to a lesser extent, western Andalucía, had experienced a significant drying through the three decades (see Figure 3 in that work). That fact has its correspondence in the distribution of Figure 6. It can be seen that the incidence of pattern S9 (characteristic of western Catalonia, Figure 4) suffers a strong decrease through the 3 decades. The same happens for S4, and from second to third decade for S3 (both PGs are representative of central Andalucía, Figure 4). Frequency of PG S1 is also characterized by a slight decrease, which is more accentuated from second to third decade. The occurrence of S2, however, suffers an appreciable reduction the from first to second decade, but the opposite tendency from the second to third decade.

Another important result of Romero *et al.* (1998b) (see its Figure 3) was the observation of an important drying in the Southeast and southern Valencia in the second decade, but a rather wet third decade in the same zones. This is nicely reflected in Figure 6, where an important decrease of S5 and S6 frequencies is followed by a still larger increment. A similar tendency is observed for S11, but the other Balearic pattern S10 experienced the opposite tendency. As a result, the Balearic Islands kept aside from the remarkable variations registered in the neighbouring Valencia region. PG S7 exhibits quite similar frequencies in the three decades; and PG S8 increases its incidence, especially from second to third decade (this was also highlighted in Figure 3 of Romero *et al.* (1998b) as an increase of mean precipitation in north-eastern Catalonia).

The degree of persistence of the PGs is investigated, and to quantify their linkages, we have calculated the probabilities of all PGs conditioned to the occurrence of these PGs on the previous day. For completeness, an additional type comprising the remaining days without rain or with insignificant rain (owing to the 5%, 5 mm criterion), has also been included. This probability index may provide some notion on the most important rainfall sequences that, on the daily time scale, occur in the region. These sequences are logically caused by the typical storm tracks, storm characteristics (shape, size, etc...), and most common cyclogenetic episodes, but the study of such elements is beyond the scope of this work.

Results are displayed in Table II. It is interesting to note that wet periods tend to be highly concentrated in time, since an insignificant day is followed by another insignificant day in as much as 83.4% of the occasions, in spite of having 3941 significant days (more than 1/3 of the total). As expected, most of the transitions from a dry day to a wet day (last line in Table II), are done through PGs S1 (the southern westernmost) and S9 (the northern westernmost), or through those other PGs normally connected to high latitude disturbances (S8, S10, S11). Another logical result is that the easternmost PGs S10 and S11, and the northernmost ones, S8 and S9, are followed by dry days in a large proportion of occurrences (last column in Table II). High values are also found for S3 and S4, whereas the lowest values are found for S1, S2, S5 and S7.

Persistences over 20% (as read in the diagonal of Table II) are given by the western Andalucía PGs S1, S2 and S3, but interestingly, the most persistent PG, reaching 28%, is the less frequent eastern pattern S6.

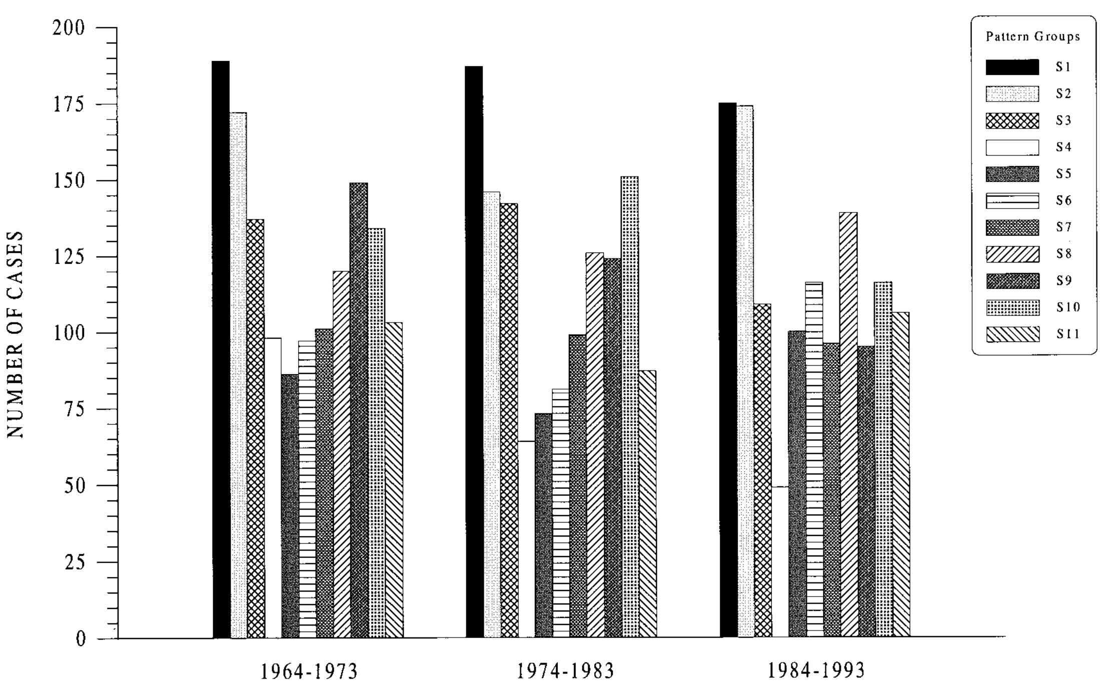

Figure 6. Interdecadal variability for the 11 PGs of significant daily rainfall

Table II. Probabilities (%) of getting the 11 significant rainfall PGs or an insignificant day (columns), conditioned to having the 11 PGs or an insignificant day (rows) on the previous day

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	INSIG
S1	21.6	26.5	8.0	3.6	3.8	1.8	3.6	3.1	9.3	2.4	1.3	15.1
S2	10.6	26.2	12.6	10.0	4.7	3.7	3.3	5.7	6.5	3.7	3.7	9.6
S3	7.0	6.2	24.7	3.4	2.8	1.0	2.3	3.6	4.1	5.9	5.2	33.8
S4	8.1	8.1	6.2	10.9	12.8	4.7	1.9	2.8	2.4	4.3	2.8	35.1
S5	3.9	4.6	1.9	11.6	18.5	11.6	9.7	3.1	2.7	3.5	2.7	26.3
S6	2.0	2.4	1.7	3.4	8.2	28.2	7.8	3.7	0.7	6.1	5.1	30.6
S7	3.7	4.1	4.4	2.7	4.4	8.8	19.9	13.9	5.4	6.4	4.1	22.3
S8	5.7	3.9	2.3	1.8	3.1	3.9	4.9	16.6	3.6	10.4	6.5	37.1
S9	5.7	3.8	6.3	2.7	0.8	1.6	7.3	11.4	15.2	4.9	1.9	38.3
S10	3.2	2.5	5.2	1.5	0.2	3.0	3.0	4.5	1.7	19.2	10.2	45.6
S11	3.0	4.1	3.4	1.4	2.4	4.4	3.4	3.4	0.3	12.8	14.5	47.0
INSIG	3.5	1.3	1.2	0.4	1.0	1.0	1.0	1.8	2.3	1.7	1.4	83.4

Pattern S4 is typically sporadic, since it combines its low frequency (Table I) with a very low persistence (Table II).

As seen in Table II, PG S1 is very often followed by S2 (26.5%), even exceeding its own persistence (21.6%). It is also very linked to PG S9 (9.3%), since both PGs rely on approaching Atlantic disturbances. S2 is normally followed by the Andalusian PGs, and secondarily by PG S9 as the previous one. PG S3 does not exhibit large differences among the other PGs. It is interesting in its connection with the Balearic patterns S10 and Sll (5.9 and 5.2% respectively). PG S4 is preferentially followed by the southeastern pattern S5 (12.5%), exceeding its own persistence (10.9%); and S5 is mainly coupled to its neighbors S4 and S6 (11.6%), and to S7 (9.7%). PG S6 shows sligthly higher links in the south–north axis with S5 and S7, than in the west–east direction with S10 and S11. In contrast with PGs S5 and S6, which are similarly linked to their northern and southern neighboors, S7 shows a stronger link with S8 than with S6. PG S8 exhibits important linkages with the Balearic patterns S10 and S11, but only 3.6% of S8 occurrences are followed by occurrences of the western Catalonia pattern S9. On the contrary, as the natural west–east storm paths suggest, S9 is followed many times by S8 (11.4%), and in second place by S7, S1 and S3. As expected, PGs S10 and S11 are strongly interconnected but show weak linkages with the remainder PGs, especially with S9, S4 and S5.

3.2. Torrential days

Figure 7 shows the 8 PGs obtained in this case. A summary of their main characteristics is provided in Table III. Although much more intense, they resemble the patterns obtained in last section (Figure 4). This fact evidences the leading action of the topography for the spatial organization of rainfall, and states that both weak/moderate and torrential events are produced by the same basic synoptic patterns, with the particularity that these patterns become very effective for the latter case. Nevertheless, there are some structural differences between both solutions that we have proven to be independent on the number of clusters considered, since they were also present for 9, 10 and 11 cluster solutions: a single PG appears for torrential rainfalls in the Balearic Islands (T8); the Pyrenees cluster S9 does not appear as an independent cluster in the torrential case, rather these mountains play their role as part of clusters T3 and T7; S4 does not have its counterpart in Figure 7, but in contrast, the southern coasts of Andalucía play a more major role in T3 than in S3.

Figure 7 clearly depicts the preference of heavy precipitations for coastal areas and interior mountainous zones. PG T1 represents substantial rainfalls in western Andalucía with maximums in Sierra de Aracena and Sierra de Ronda. PG T2 is representative of heavy precipitations in the Gibraltar Strait area which can extend inland or along the southern coasts of Andalucía. PG T3 represents a broad band connecting central Andalucía with the Pyrenees mountains, with maximum values in the peaks and slopes

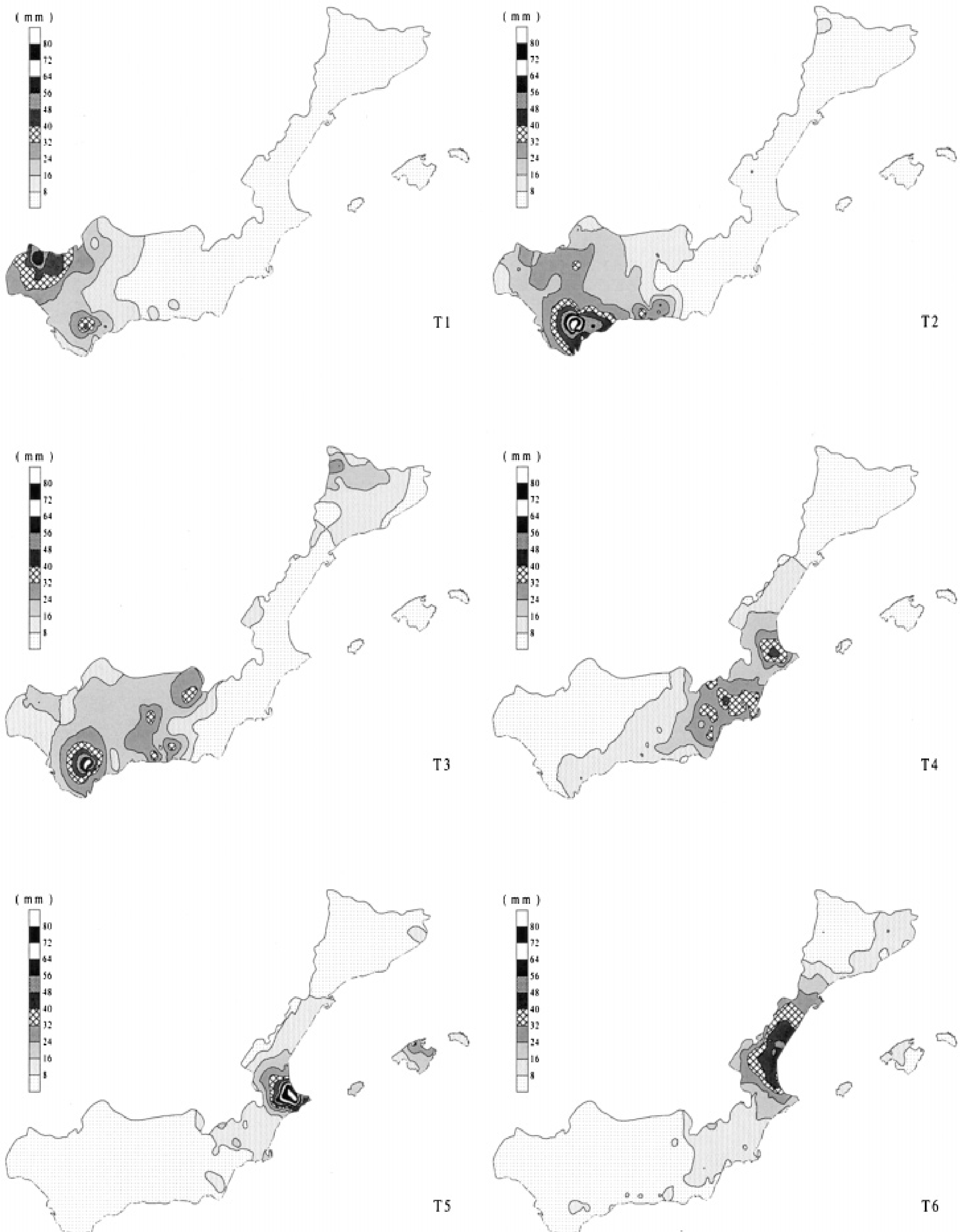

Figure 7. Daily rainfall composites for the eight PGs obtained in the classification of torrential events

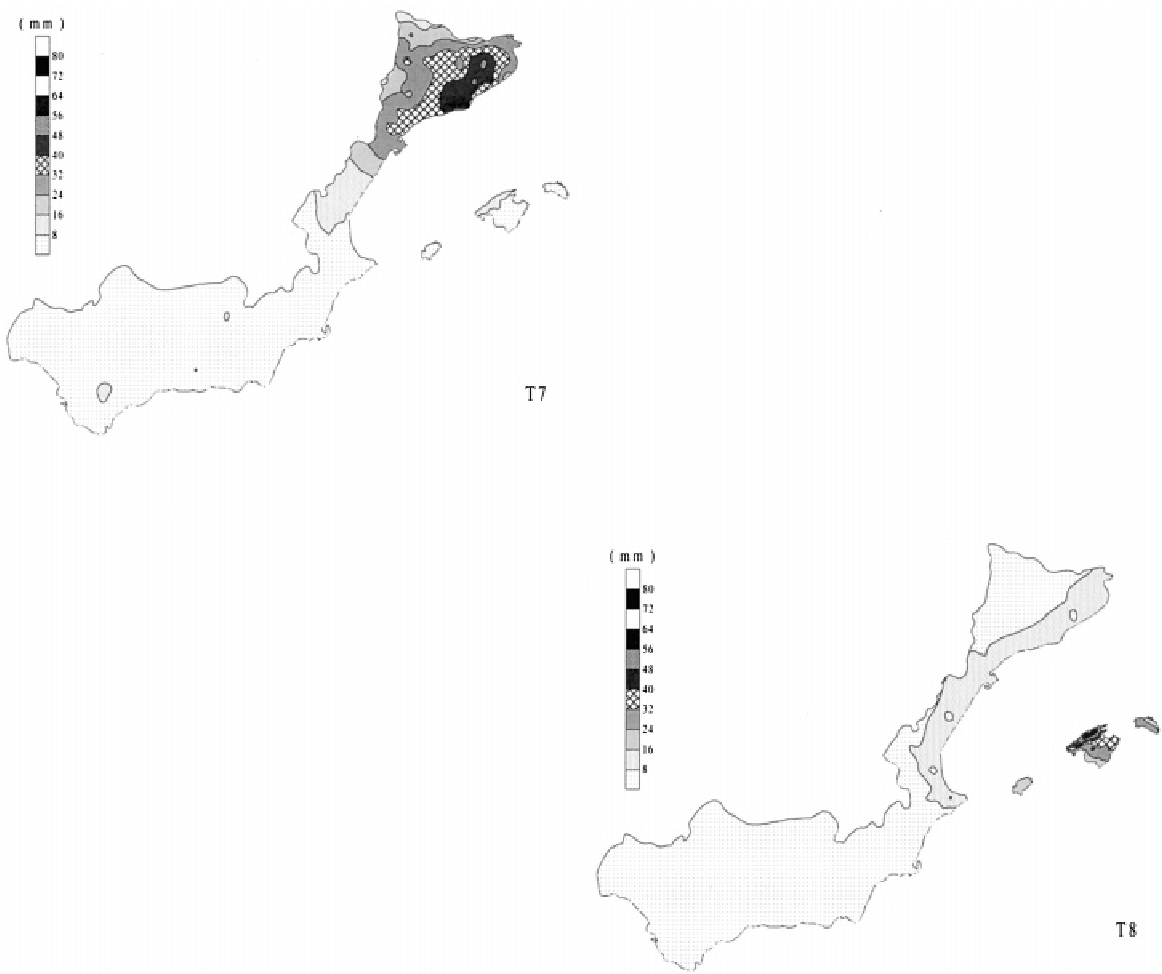

Figure 7 (*Continued*)

of Sierra de Ronda, Sistema Subbético, Sistema Penibético, Sierra de Cazorla and Pyrenees. PG T4 represents heavy precipitations in the southeast, and T5 is a more local PG representative of heavy rainfalls forced by Sierra de Aitana mountains. PG T6 is characteristic of rainfalls along the coastal band

Table III. Summary of the eight pattern groups obtained for torrential daily rainfalls (see Figure 2 for locations)

Pattern group	Days included	General area (maxima)
T1	54	Western Andalucía (Sierra de Aracena, Sierra de Ronda)
T2	77	Central–western Andalucía (Gibraltar Strait area)
T3	43	Central Andalucía and Pyrenees (Sierra de Ronda, Sistema Subbético, Sierra de Cazorla, South Coast and western Pyrenees)
T4	57	Southeast region (east-facing slopes, Sierra de Aitana and coastal zones)
T5	47	Sierra de Aitana zone, Ibiza and northern Mallorca (Sierra de Aitana area)
T6	59	Northern Valencia (coastal areas)
T7	49	Catalonia (coastal areas)
T8	63	Mallorca and Menorca (Sierra de Tramuntana mountains)
	449	

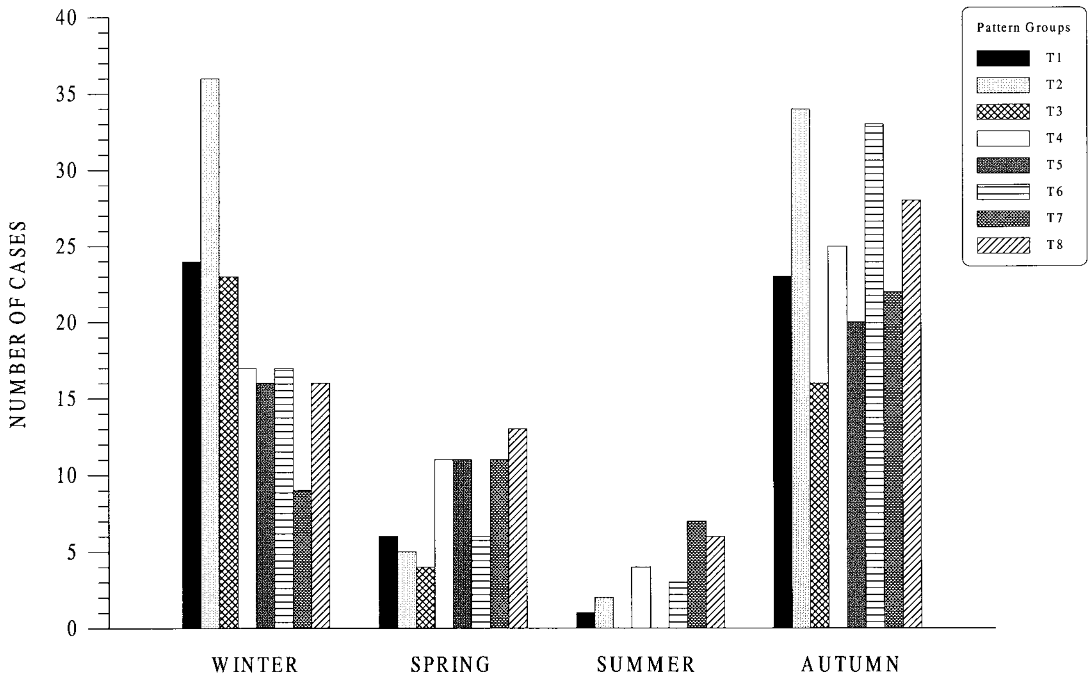

Figure 8. Seasonal distribution for the eight PGs of torrential daily rainfall

of eastern Spain, most pronounced along the Gulf of Valencia. The Catalan pattern T7 focuses its main action on litoral and prelitoral areas; and T8 is characteristic of important rainfalls in the Balearics, with the maximums usually found in Sierra de Tramuntana mountains.

As seen in Table III, T2 pattern is significantly more frequent than the remainder PGs, and is followed by the Mallorca pattern T8. The least numerous group is T3, that relies importantly on interior zones. Note that the lowest probability obtained in the last section for significant rainfalls in eastern Andalucía, Murcia and Valencia (S4 to S7; Table I), is not observed for torrential rainfalls (Table III).

The seasonal distribution of the PGs (Figure 8) confirms a different scenario for the occurrence of heavy precipitations than for general rainfalls (Figure 5). An accentuated maximum is observed in this case during the autumn season. In this period, synoptic disturbances become very effective through the strong interaction between large amounts of water vapour released from the warm Mediterranean and coastal terrain features (Romero *et al.*, 1997, 1998a; Doswell *et al.*, 1998). This is the most substantial season for all PGs except for the Andalusian patterns T1, T2 and T3, which tend to manifest higher frequencies in winter (but not so clearly as in the general case, Figure 5). The spring season loses its relative importance in this case, and torrential events are rarely observed during June, July and August (none of T3 and T5 events have occurred in 30 years).

As for significant rainfalls, the decadal distribution in this case (Figure 9) shows distinct behaviours in the different subdomains. It is worth noting the accentuated reduction during the second decade of T4, T5 and T6 rainfalls, which are characteristic of the eastern peninsular regions (see Figure 7). These patterns approximately double their frequencies in the third decade, widely exceeding the levels of occurrence of the first decade. Such a tendency was also observed for significant rainfalls in the same areas, but only for the first two PGs (S5 and S6 in Figure 6). Concerning the Andalusian PGs, it is remarkable for the decrease of T3 events during the third decade (also experienced by the similar S3), and the important increase of T2 events in the same period. The Catalan pattern T7 reduces its incidence during the last decade, and the Balearic PG T8 shows a remarkable maximum in the second decade.

4. CONCLUSIONS

As part of the general objective of characterizing the pluviometry of Mediterranean Spain, in this work the authors' attentions have been focused on the spatial distribution of rainfalls in that area. Considering daily rainfalls of enough significance on one hand (3941; 1964–1993), and only heavy rainfalls on the other hand (449; for the same period), our particular objective has been to derive a simplified collection of spatial patterns governing those events. This task has been accomplished by means of cluster analysis, forcing all individual days to become classified in non-overlapping clusters, or pattern groups (PGs). As a result, 11 and 8 PGs have been produced for significant and torrential rainfalls, respectively (Figures 4 and 7).

A visual inspection of those PGs confirms that the extent of region and the exposure/sheltering systems induced by the complex topography are sufficiently important as to produce a clear regionalization of the rainfalls. In a broad sense, three main scenarios can be easily conceived: (i) characteristic of rainfalls in the bulk of Andalucía except its eastern part, and occasionally including the Pyrenees mountains; (ii) representing wet events along the east-facing lands of eastern Andalucía, Murcia and Valencia, and sometimes the Balearics and coastal Catalonia; (iii) comprising rainfalls in definite zones of the northern part of the Spanish Mediterranean (Pyrenees mountains, eastern Catalonia–northern Valencia, or the Balearic Islands). However, the resulting PGs complete that oversimplified model with additional details, and have permitted a quantitative analysis of the pattern frequencies, interseasonal and interdecadal variability, and also their persistences and links across wet episodes.

It is interesting to note that the spatial patterns obtained for both types of rainfalls are basically equivalent. The patterns reflect in both cases the dominant role exerted by the topography for the spatial distribution of rainfalls. Distinct seasonal distributions have been observed though. For rainfalls in general, the western Andalucía patterns show a clear preference for the winter months, followed almost indistinctly by spring and autumn, and are infrequent in summer, whereas for the torrential limit, winter and autumn are similarly important and the spring season becomes unimportant. With regard to the eastern patterns, for the general case they tend to be similarly frequent in spring and autumn, showing

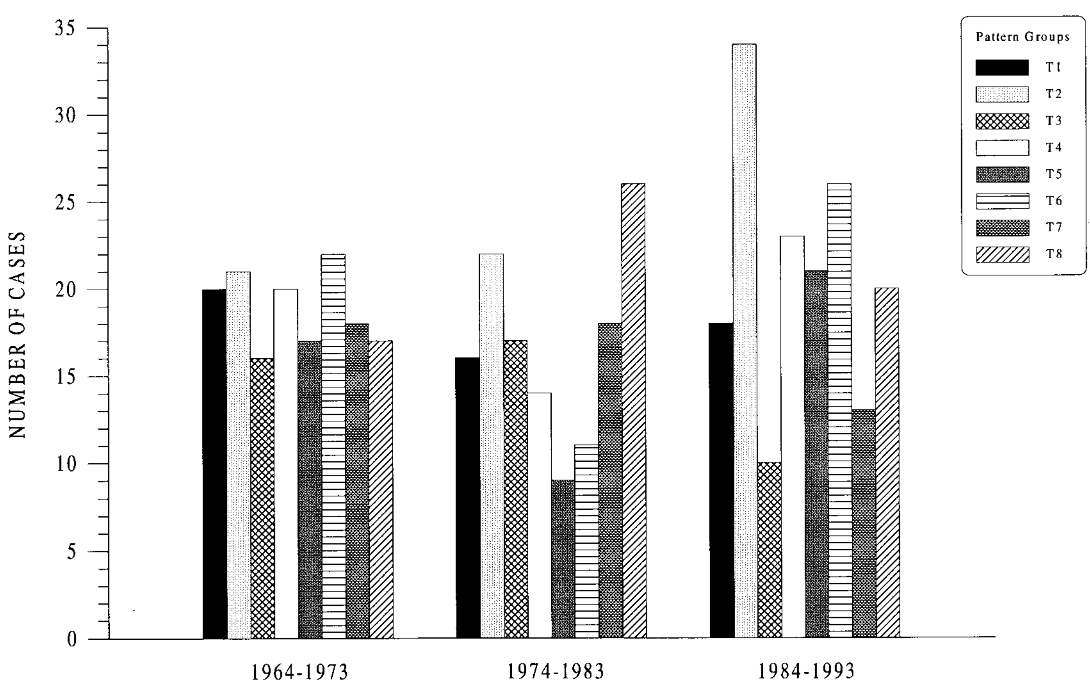

Figure 9. Interdecadal variability for the eight PGs of torrential daily rainfall

additional peak values in winter the Balearic and southern Valencia PGs and in summer the northern Valencia and Catalan patterns, whereas for torrential events, all of them have a clear predilection for the autumn season.

On the other hand, whilst precipitation forecasts from mesoscale models are certainly promising, it is thought the results here could be taken into consideration for weather forecasting tasks. Precipitation is a very complex variable, being the final result of a wide range of atmospheric scales and their interactions. For that reason, accurate rainfall forecasts can not be given directly by operational large-scale numerical weather prediction models. Rather, the forecaster has to use the model outputs in combination with regional conceptual models on rainfall distribution, which in the case of the western Mediterranean are intimately related with the topography. Undoubtedly, once the fundamental synoptic (or sub-synoptic) circulation patterns leading to each of the PGs is determined (this work is reserved for a following paper), new predictive elements will be available for the regional forecaster. The distinction made between total and torrential rainfalls may have particular sense when searching the governing atmospheric structures, since discriminant factors of the latter type of rainfalls could be obtained. Finally, the synoptic climatology started in this paper may contribute to assess the impact of future tendencies of the general circulation on the rainfall regimes of Mediterranean Spain.

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