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A CLASSIFICATION OF THE ATMOSPHERIC CIRCULATION PATTERNS PRODUCING SIGNIFICANT DAILY RAINFALL IN THE SPANISH MEDITERRANEAN AREA

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ABSTRACT

This study investigates the synoptic atmospheric circulations associated with 11 typical spatial patterns for significant rainfall days for Mediterranean Spain, which have been identified in an earlier paper. Using cluster analysis on the most relevant T-mode principal components, a classification into 19 fundamental circulations emerged, based only on geopotential fields at 925 and 500 hPa, using ECMWF gridded data for the period 1984–1993.

The derived atmospheric patterns comprise a wide variety of flows over the Iberian Peninsula, with a clear distinction between Atlantic and western Mediterranean disturbances. Distinct seasonal distributions are also observed. Despite the comparatively higher resolution of the rainfall patterns, and the uncertainty derived from working with a daily time scale, a clear association emerged between each of the circulation types and a small number of the characteristic rainfall patterns. These associations can be physically interpreted in terms of the position of the 500 hPa trough, disturbances at the 925 hPa level, and the interaction of the surface rain bearing flows with the complex topography of the region.

The final part of the analysis concentrated on establishing links between identified circulation patterns and notable (torrential) precipitation events recorded during the 1984–1993 decade. Some of the identified circulations that are important for the occurrence of significant rainfalls, produce few or no torrential rainfall episodes. Most torrential rainfall events in Mediterranean Spain are associated with disturbances located near or over the south of the Iberian Peninsula. Copyright © 1999 Royal Meteorological Society.

KEY WORDS: Mediterranean Spain; cluster analysis; rainfall patterns; circulation types

1. INTRODUCTION

The Spanish Mediterranean area, depicted in Figure 1, possesses a quite complex topography. It is influenced by both Atlantic low pressure systems (notably in the west and north of the area) and by Mediterranean disturbances (in the eastern part), and it is subject to extreme seasonal contrasts as a result of its latitude (36–44°N). All these factors yield daily rainfalls of considerable spatial and temporal variability (Romero *et al.*, 1998).

In order to study the rainfall of the region at a sufficiently high resolution, a homogeneous and complete data base comprising daily rainfall series at 410 stations during the period 1964–1993 was recently created (Romero *et al.*, 1998). Using this data base, Romero *et al.* (1999a) derived the main spatial patterns for significant daily rainfalls in the region. This was accomplished by subjecting the between-day correlation matrix for the 3941 significant days (defined as those days during the period, in which at least 5% of the stations registered more than 5 mm) to principal components analysis (PCA) and

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by performing cluster analysis (CA) on the most relevant extracted principal components. The 11 clusters or rainfall patterns (RPs) that were obtained appear in Figure 2. Visual inspection of the RPs, and comparison with the relief of the area (Figure 1), shows that a clear regionalization emerges based largely on the complex topography of the region. Romero *et al.* (1999a) also derived eight characteristic rainfall patterns for the 449 torrential events (defined when at least 2% of the stations register more than 50 mm), which occurred during the 30-year period (referred to as torrential patterns, TPs; Figure 3).

This paper attempts to identify the main atmospheric circulation patterns associated with RPs and TPs identified by Romero *et al.* (1999a), in order to develop a more detailed precipitation climatology for Mediterranean Spain. A primary aim has been to identify which RPs are more frequent for a given atmospheric pattern. This hopefully yields results that are potentially useful for regional forecasting and may complement conceptual forecasting models already in use in the region. In addition, the results may permit the construction of much more detailed forecasts of rainfall activity using GCM predictions of the large-scale circulation.

There are several studies in the literature that have illustrated and interpreted statistical connections between synoptic atmospheric patterns and certain surface weather and/or environmental parameters. In his book, Yarnal (1993) offers multiple examples of synoptic classifications, ranging from subjective

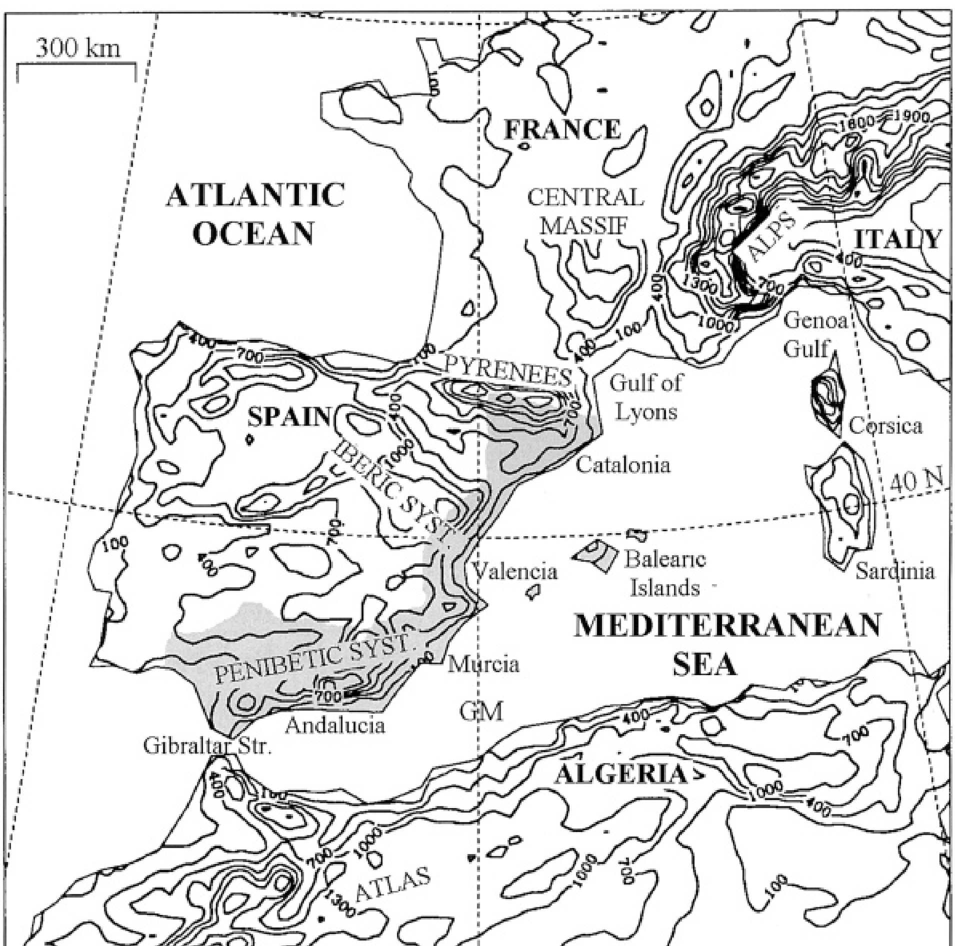


Figure 1. The western Mediterranean and the Spanish Mediterranean area (shaded), formed by the administrative regions: Catalonia, Valencia, Murcia, Andalucía and Balearic Islands. The map includes a smoothed version of the topography and the location of places mentioned in the text

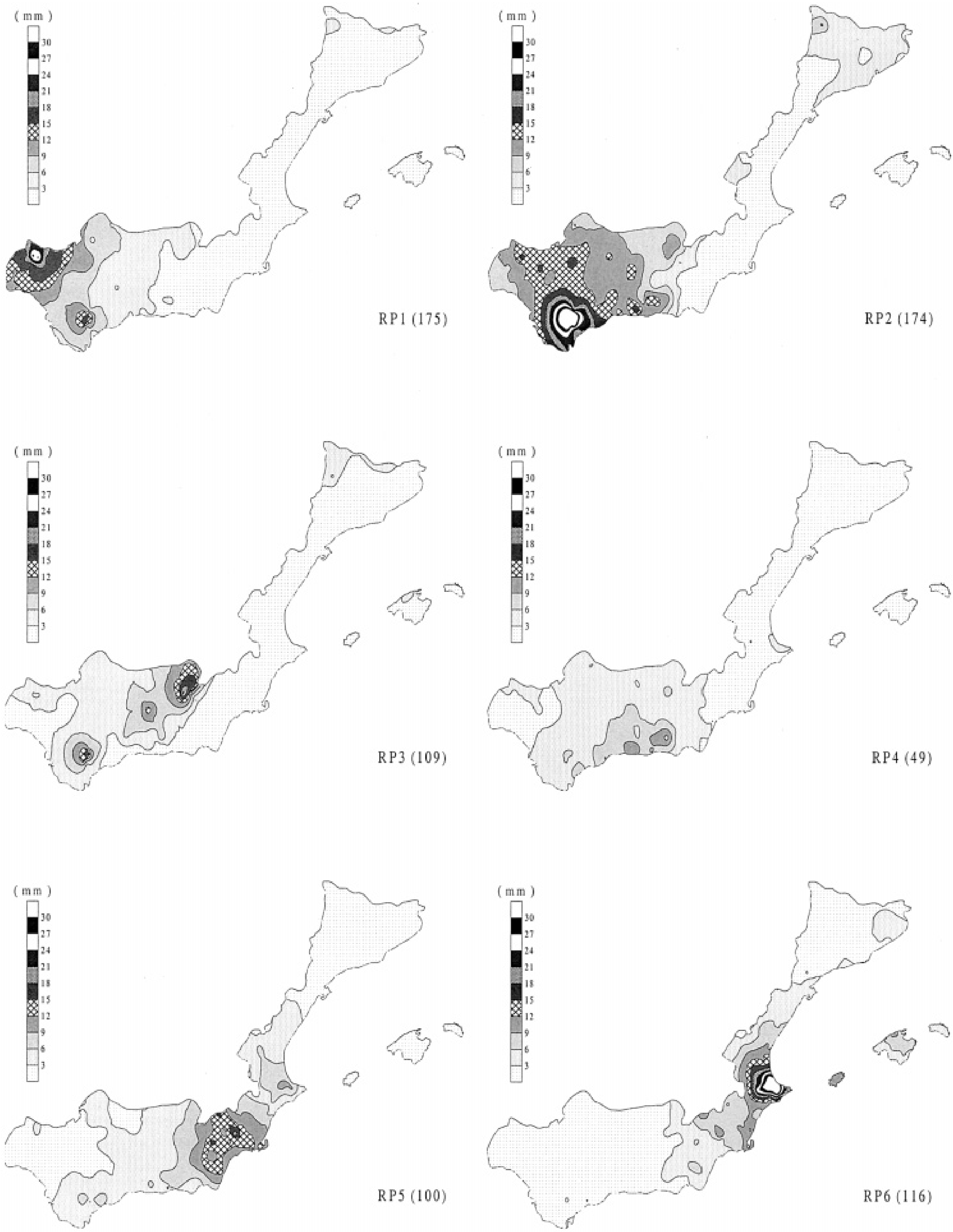


Figure 2. Daily rainfall composites for the 11 typical patterns of significant rainfall (RPs) in Mediterranean Spain (from Romero *et al*., 1999a). The number of days for the decade 1984–1993 included in each pattern group is indicated in parentheses (total 1275)

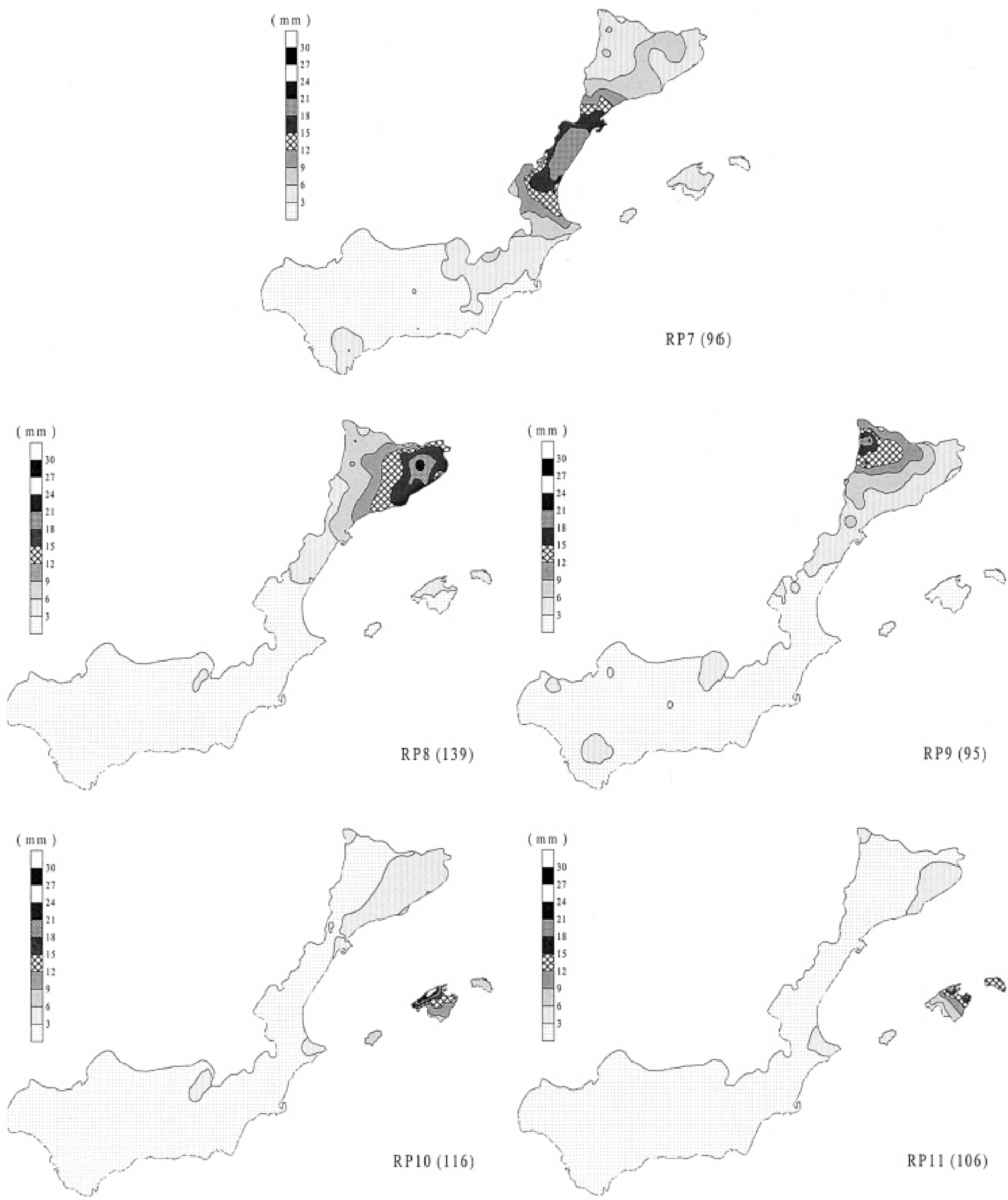


Figure 2 (*Continued*)

manual classifications to outputs from eigenvector-based techniques. Worked examples are used to determine how well these classifications relate to four environmental scenarios in the Pennsylvania area (urban air quality, acid rain, agriculture and fluvial hydrology). Kidson (1994a,b) uses an automated procedure for the identification of synoptic types over the New Zealand region, and tests the classification

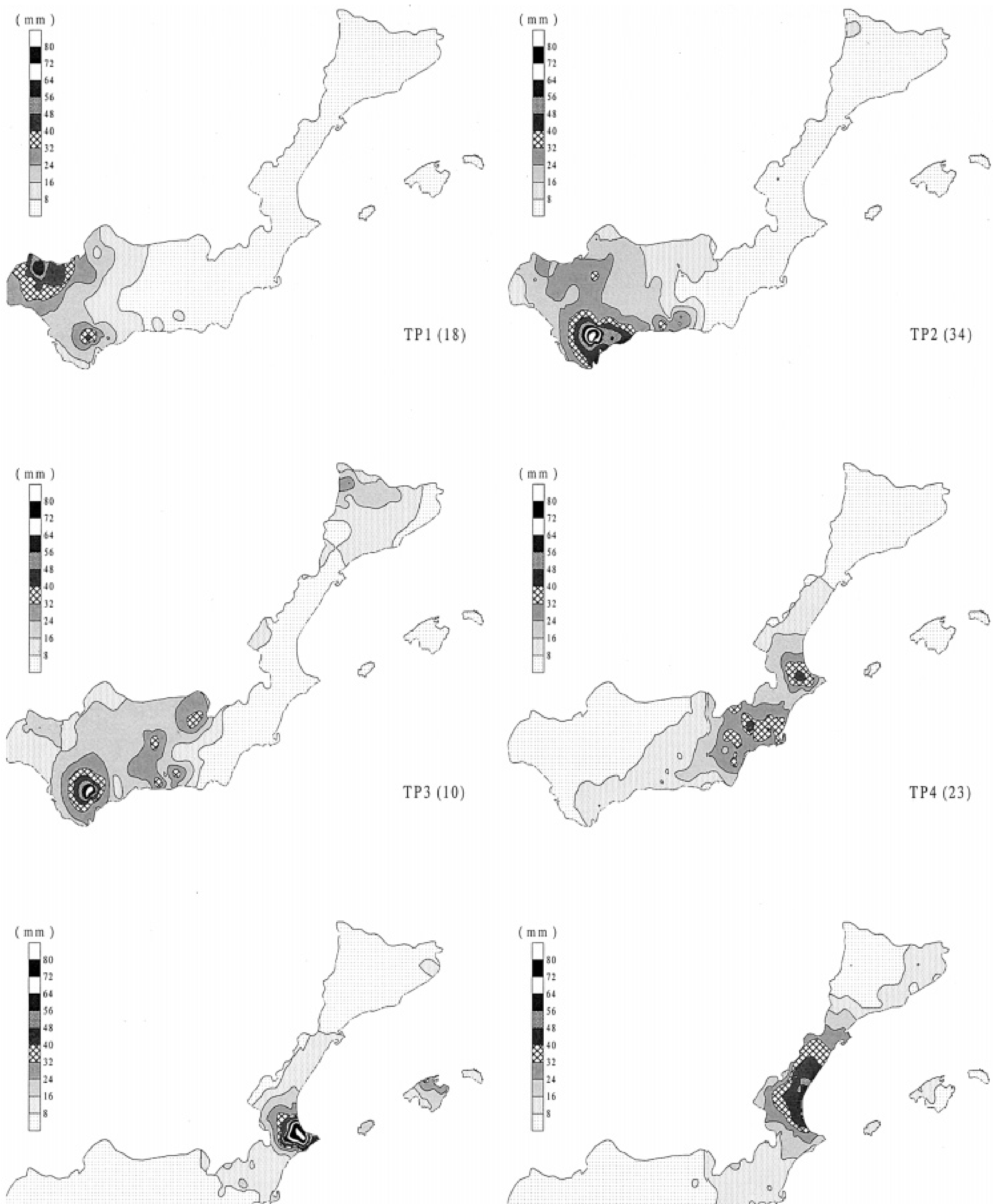


Figure 3. Daily rainfall composites for the eight typical patterns of torrential rainfall (TPs) in Mediterranean Spain (from Romero *et al*., 1999a). The number of days for the decade 1984–1993 included in each pattern group is indicated in parentheses (total 165)

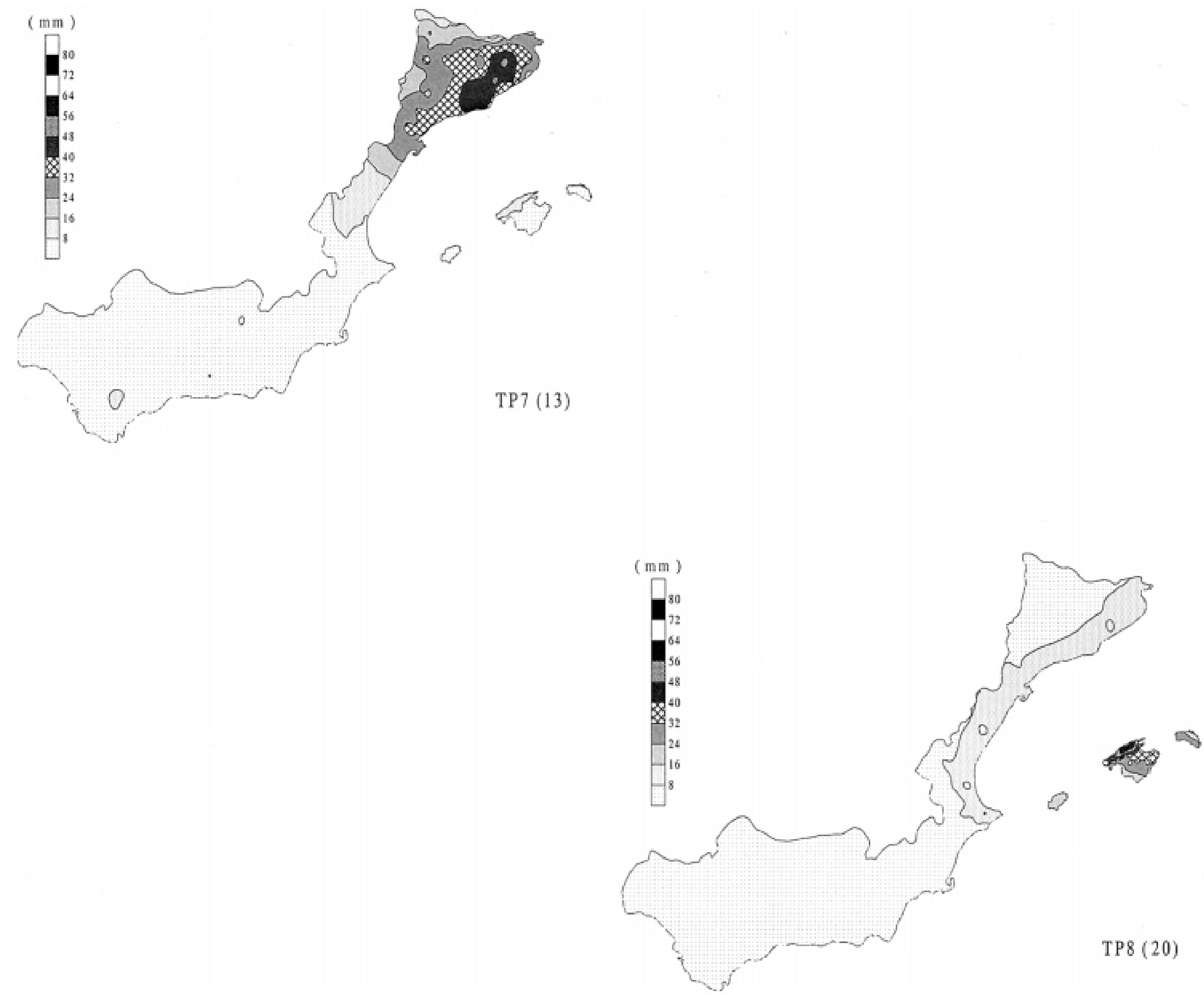


Figure 3 (*Continued*)

through its relationship with daily and monthly variations in temperature, precipitation, sunshine and daily wind run. Bonell and Sumner (1992) establish, using S-mode PCA and CA, the main daily precipitation affinity areas for Wales according to surface wind direction. Hawksworth (1998) expands this analysis using other atmospheric circulation classifications. Sumner *et al.* (1995) associate the distribution of significant rainfalls over the island of Mallorca with recognized dominant surface circulation types. However, although they have been conceptually recognized for a long time, and have become apparent through numerous case studies (notably of heavy precipitations in eastern Spain; see Doswell *et al.*, 1998 and references mentioned therein), climatology based scenarios of rainfall distribution for defined synoptic types have still not been derived for Mediterranean Spain. The current work represents a new effort in this direction.

2. DATA BASE AND METHODOLOGY

The meteorological data available to carry out the synoptic classification are the European Centre for Medium Range Weather Forecast (ECMWF) grid analyses of geopotential height, temperature, relative humidity and horizontal wind components at 11 standard pressure levels. The spatial resolution of these analysis is 0.75° in both latitude and longitude. Since the ECMWF has only been operative since 1979, the meteorological data base has been restricted to the last decade of the 30 years of the original rainfall data base (1984–1993). During that decade, 1275 days were identified as significant rainfall days (as previously defined) in Mediterranean Spain. Of these, 165 were also classified as torrential (previously defined). The classification of atmospheric circulation thus utilizes 1275 unique circulation patterns.

ECMWF data are available at 00:00, 06:00, 12:00 and 18:00 UTC, whereas rainfall data correspond to the 07:00–07:00 UTC time interval. An important source of uncertainty arises when trying to select the most representative time of the synoptic situation giving rise to each rainfall event. In the absence of any further information about the actual time span over which the precipitation developed, it is reasonable to select the synoptic situation at 18:00 UTC, since this is approximately the central time in the 07:00–07:00 interval. However, in order to approximate better the selected time, the authors applied two further provisos. If the immediately preceding day was also a significant day, and its rainfall distribution fell within the same RP, then the selected time was moved to 06:00 UTC. Similarly, if the day following exhibited a rainfall distribution within the same RP, then the selected time was moved to 00:00 UTC, the next day.

Circulations were classified using PCA and CA, also used in the derivation of RPs (Figure 2, Romero *et al.*, 1999a). The classification was carried out using data only within the interior rectangular geographical window shown in Figure 5. This extends between 33.75 and 45.75°N, and between 11.25°W and 6.00°E. It thus comprises 408 grid points. The window dimensions are similar to those used in other works (e.g. El-Kadi and Smithson, 1996), and seem consistent with the meso-scale nature of the RPs and their strong dependence on the interaction between the basic flow and the local topography. Classifications based on larger windows encompassing much larger geographical areas were also tested, but associations with rainfall patterns were very poor, because the classifications were strongly influenced by circulation features of regions remote from Mediterranean Spain.

The classification of the 1275 circulation patterns within the selected geographical area was obtained by subjecting a T-mode (day-by-day) correlation matrix of the data to PCA (Richman, 1986; Yarnal, 1993), and then subsequently carrying out CA of the days based on the retained principal component loadings. As defined in Everitt (1986), the CA is the application of an algorithm devised for grouping the objects (days in this case, described by their meteorological fields) into a number of classes such that objects within classes are similar in some respect (in the PC loadings sequence, in this case) and unlike those from other classes. When more than one field was considered, e.g. using geopotential heights at two levels, PCA was carried out for each level and a sole CA applied to the total set of collected loadings. This method is essentially a correlation-based technique (see El-Kadi and Smithson, 1992), but the PCA ensures that only the most important modes of spatial variation in the meteorological field are considered for the clustering process. The method is the analogue to that applied in regionalization studies, where an S-mode (site-by-site) correlation matrix is used instead (e.g. White *et al.*, 1991; Bonell and Sumner, 1992; Sumner *et al.*, 1993; Gong and Richman, 1995).

This methodology was applied to all relevant data (geopotential heights, specific humidity, total precipitable water, etc.) singly and together using data for the 1275 significant rain days. The optimum classification linking meteorological parameter(s) to RPs then had to be determined. The finally selected meteorological classification must be one that yields clusters showing strong associations with RPs, but also retaining a simple yet comprehensive solution. Classifications were derived using the circulation at 500 hPa (using geopotential height), low-level circulation (using geopotential height at 925 hPa, since at lower levels the topographic perturbation may be considerable and very complex), the thickness between 500 and 925 hPa heights, the lapse rate between these levels, and moisture variables (the specific humidity at 925 hPa, and precipitable water in the atmospheric column between 1000 and 200 hPa). In addition, the mean surface wind direction for the 12 daily rainfall affinity areas of Mediterranean Spain derived in a recent regionalization study (Romero *et al.*, 1999b). In this case the CA was applied directly with the 24 original variables (the two normalized wind components in the 12 regions).

The most satisfactory results were obtained from a combination of the circulations at 500 and 925 hPa. This is not surprising, since these fields contain already, either explicitly or implicitly, essential informa-

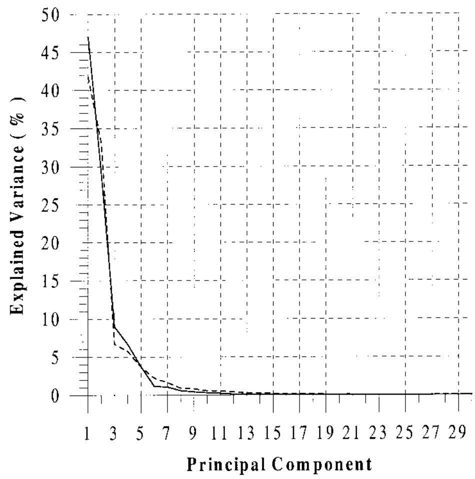


Figure 4. Principal components scree plot for the geopotential field at 500 hPa (full line), and the geopotential field at 925 hPa (dashed line). Only the first 30 components of the resulting 407 are shown

tion about important dynamic and thermodynamic physical processes behind precipitation generation and distribution: the dynamic forcing for vertical motion by advection of vorticity at upper levels; the presence of cold pools aloft; the sign and intensity of low tropospheric temperature advection; the interaction of the low-level flow with the topography; and the moisture content of surface air masses possessing long paths over the Mediterranean Sea or Atlantic Ocean.

Figure 4 shows the scree plots resulting from the PCA of the geopotential fields at 500 and 925 hPa, respectively. Application of the classical scree test of Cattell (1966) suggests the retention of six PCs in the first case (accounting for 96.7% of the total variance), and eight PCs in the second case (95.7% of the total variance). Thus, 14 variables were used in the CA. The clustering algorithm used was the non-hierarchical k-means method (Anderberg, 1973), as implemented in the STATISTICA (1994) utility. Gong and Richman (1995) showed that non-hierarchical methods, such as the one used, out-perform hierarchical techniques. Nevertheless, hierarchical tree plots generated by Ward's method (Ward, 1963) were consulted to decide the number of clusters to be selected. Solutions involving seven, 11 and 19 clusters were clearly indicated. The former two solutions produced too dilute an association with rainfall distributions, and an appropriate compromise for a still relatively simple collection of patterns, but with enough meaningful associations was found in the 19 cluster solution. These clusters (referred to as atmospheric patterns, APs) are presented and discussed in next section (see Figure 1 for geographical locations).

3. EMERGENT ATMOSPHERIC PATTERNS AND DISCUSSION

Figure 5 shows the composites of the 19 emergent APs, and their main features are summarized in Table I. These APs must be compared with each other in terms of both 500 and 925 hPa circulation dissimilarities within the considered geographical window. In some cases, the structures at 500 hPa, which are smoother, are relatively similar, but the surface circulations exhibit quite substantial differences (e.g. compare AP7 with AP11, or AP16 with AP18). In other cases, both levels show very similar aspects in some areas, but in other areas important differences in the position, orientation, size or depth of the disturbance appear (compare AP1 with AP4, or AP7 with AP9).

The associations between the 19 derived APs and the 11 RPs are shown in Table II. Visual inspection of the plot reveals that each of the APs is reflected significantly in only a few RPs. Given the nature of the two datasets, where daily rainfall is accumulated through a 24 h period, and atmospheric circulation is measured at a specific time during that period, and considering that only two circulation parameters are

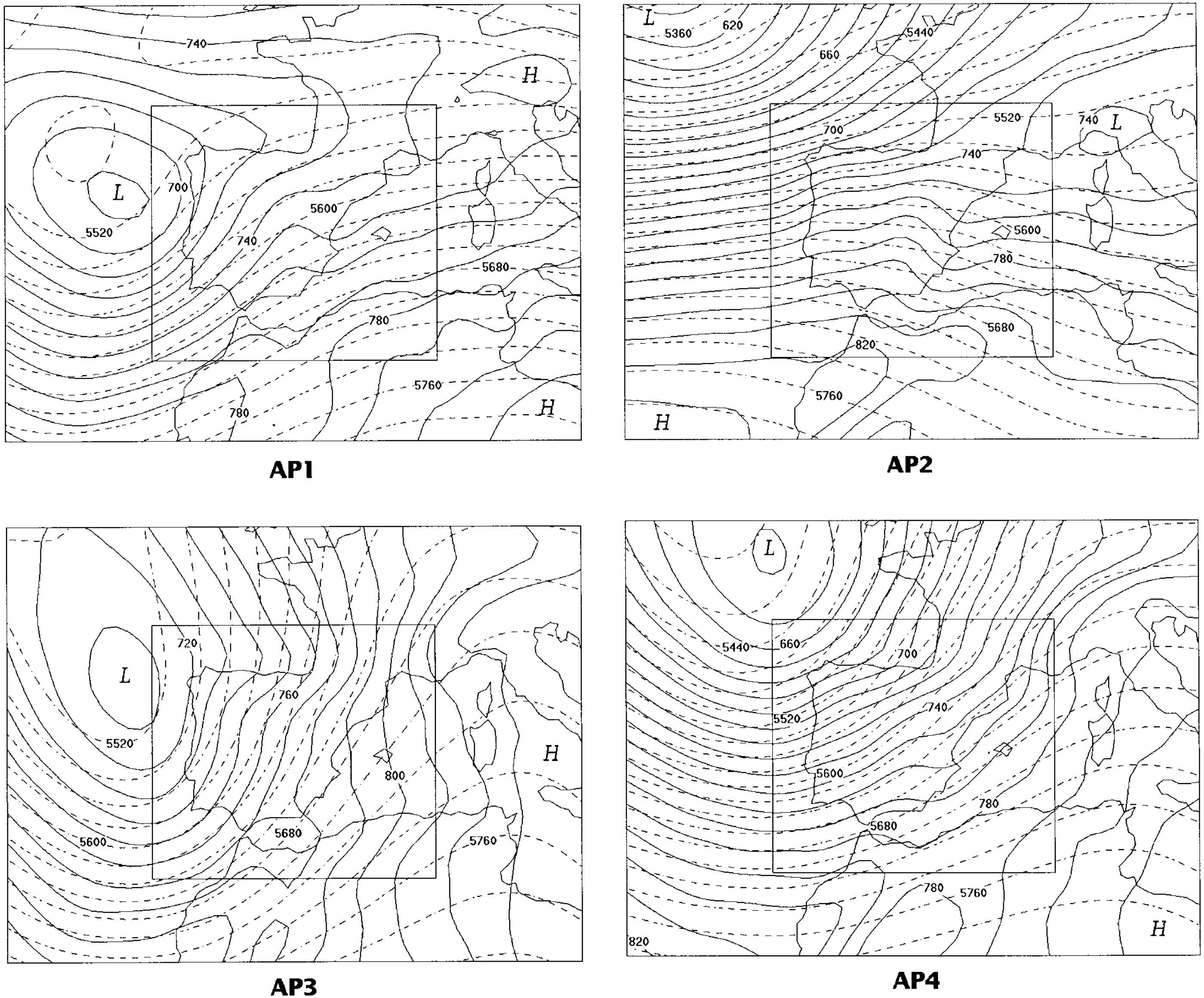
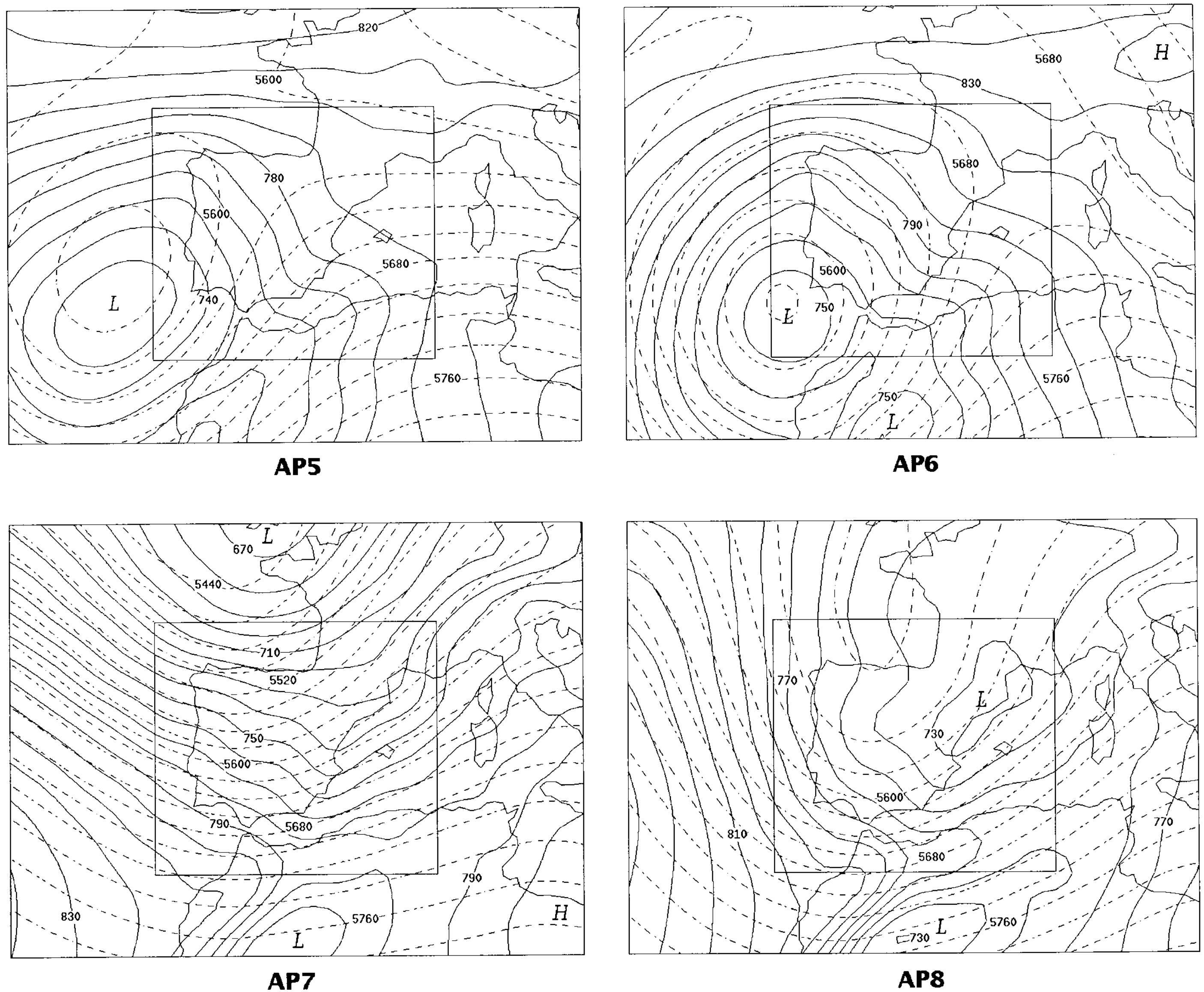


Figure 5. Composites of the 19 APs associated with significant daily rainfall in Mediterranean Spain. The continuous line represents the geopotential field at 925 hPa (contour interval is 10 m), and the dashed line that at 500 hPa (contour interval is 20 m). Surface lows and highs are indicated. The interior rectangle represents the geographical window used for the patterns classification



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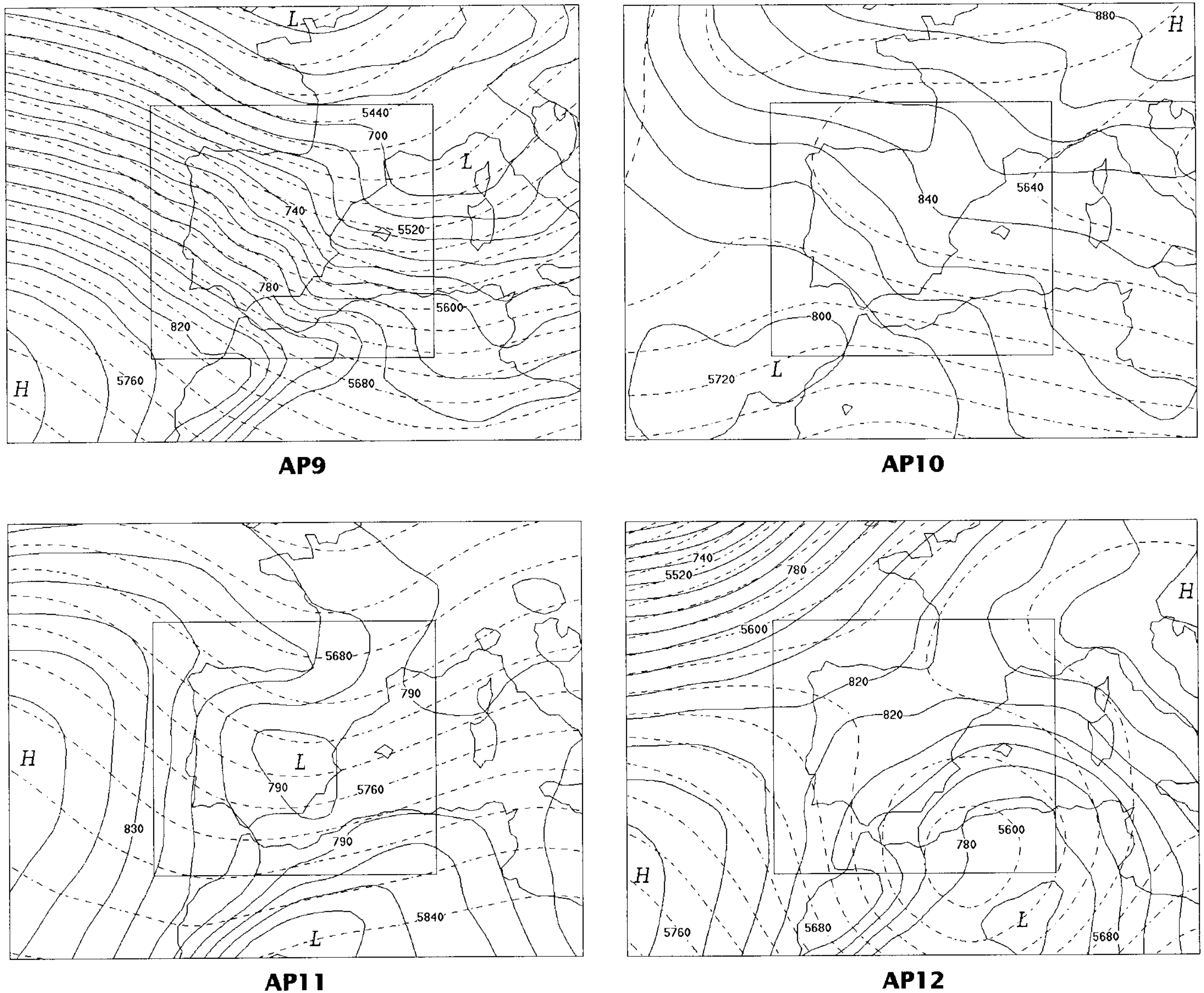

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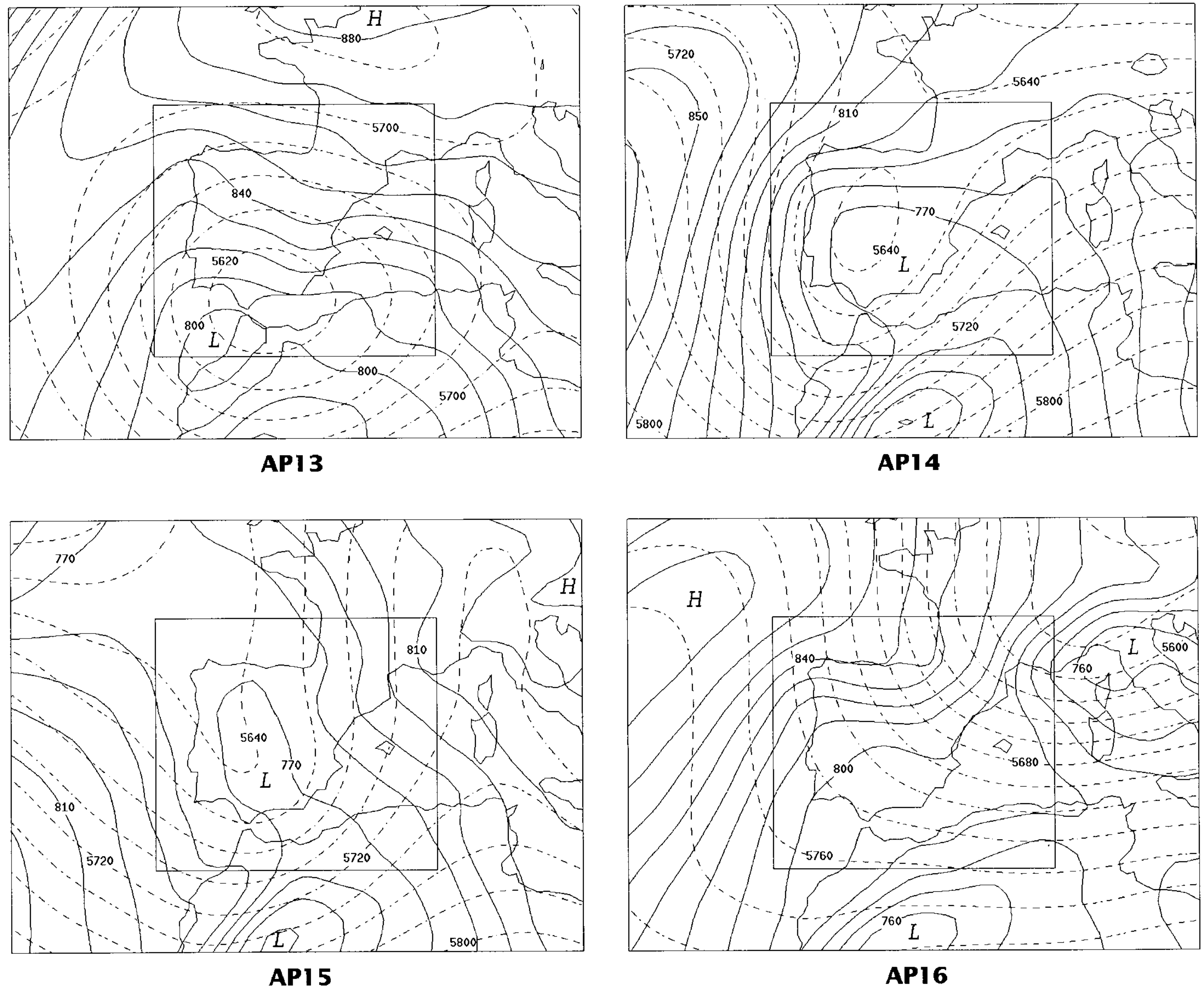

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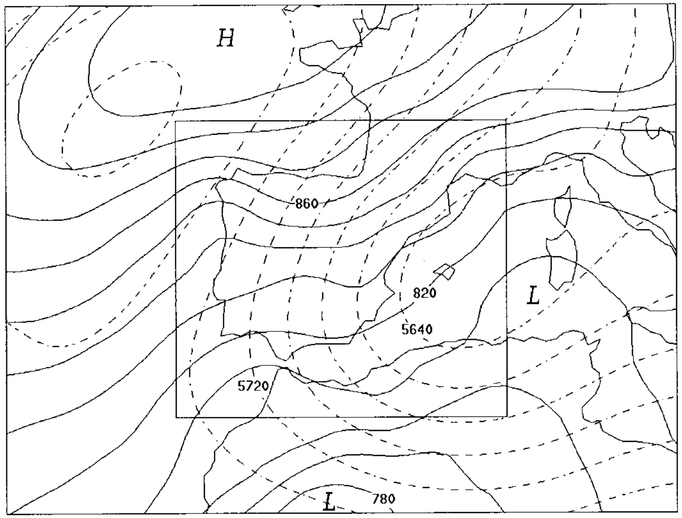
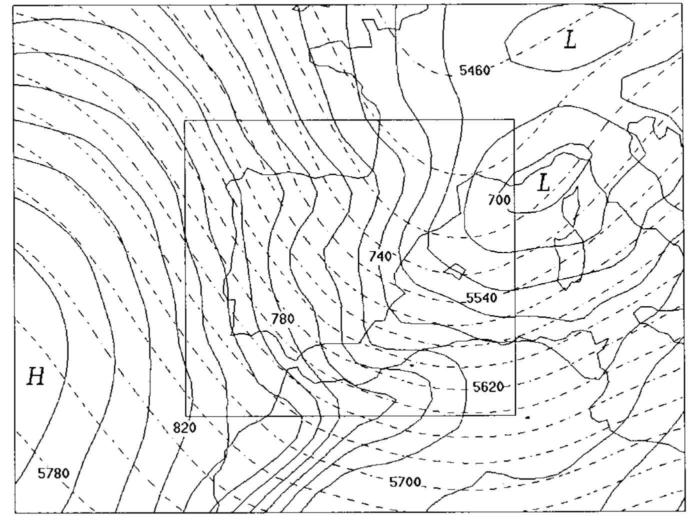
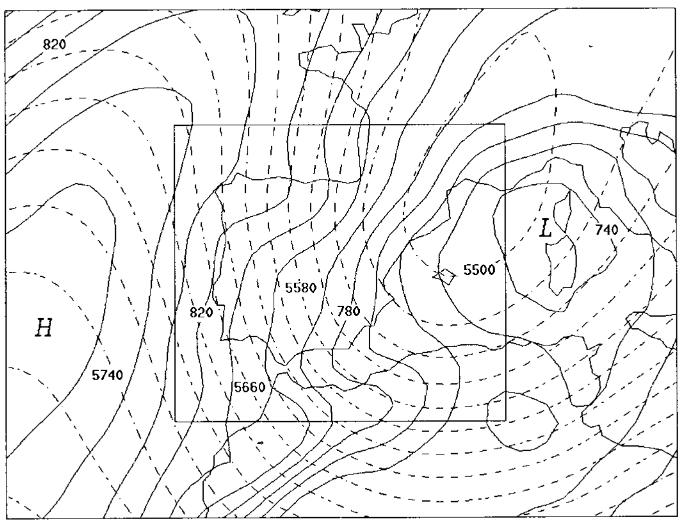


AP17



AP18



AP19

Figure 5 (*Continued*)

used, this result is encouraging, since precipitation, being the final result of a wide range of atmospheric scales and their interactions, is a very complex variable. It would be unrealistic to expect an exact relationship to emerge between atmospheric patterns and rainfall patterns. This analysis can only be expected to deliver general relationships, sacrificing small-scale detail for their essential aspects.

The following discussion of the emergent APs is not only based on the structure of the composites shown in Figure 5, but also on the individual daily circulations contained within in each AP cluster. There is some divergence of individuals from the overall mean pattern shown in Figure 5, but relatively few at the margin of each cluster set whose actual pattern differs significantly from the overall mean. Again, this is encouraging, since it suggests that the number of cluster groups selected is near the optimum for the exercise.

Pattern AP1 consists of occasions when a short wavelength trough lies to the west over the Atlantic, and when there is a surface low off the west coast of the Iberian Peninsula. This configuration produces

Table I. Summary of the 19 APs, with an indication of their major synoptic features and influence zones relative to Mediterranean Spain

Atmospheric pattern	Major synoptic features	Main influence zones
AP1	Short wavelength troughs and surface lows to the west	Western Andalucía
AP2	Highly zonal flows produced by disturbances to the north	West and north-centre of Andalucía
AP3	Low pressure centres located to the west-north-west inducing southerly flow	Western Andalucía and north-eastern part of Iberian Peninsula
AP4	Southwesterly flows associated with low pressures to the northwest of Spain	Western Andalucía and north of Mediterranean Spain
AP5	Upper level and surface lows to the west-south-west	Andalucía except northern part, Murcia, Valencia and Pyrenees
AP6	Extensive upper level cold-core lows and surface lows over the southwest part	Andalucía; and especially the eastern flank of Iberian Peninsula
AP7	Passage of cold fronts over the Iberian Peninsula	West and mountainous interior of Andalucía and Catalonia
AP8	Accentuated surface frontal lows over north-eastern Spain	Central part of Andalucía, north Valencia and Catalonia
AP9	West to northwesterly winds following the passage of cold fronts	Mountains of Andalucía; Catalonia and Balearic Islands
AP10	General easterly flows over Mediterranean Spain	Exposed areas of Andalucía; eastern part of Mediterranean Spain
AP11	Relative low pressures over the southeast of Iberian Peninsula, and thermal lows	North-eastern regions of Spain
AP12	Cut-off cyclones and surface lows to the south-east, inducing northeasterly winds	Exposed coastal mountains of Valencia
AP13	Cut-off cyclones over the southern part, inducing easterly flows at low levels	Eastern Andalucía, Murcia, Valencia and south Catalonia
AP14	Short baroclinic waves over Spain, with easterly flows over the northeastern coast	Mountains of Andalucía, eastern Spain and Pyrenees
AP15	Short baroclinic waves over Spain, with south-easterly flows over the east coast	South of Andalucía, southeast, north Valencia, Pyrenees and Balearics
AP16	Main low pressures centres over northern Italy, with relative lows in south Spain	South Andalucía, Murcia, Valencia, eastern Catalonia and Balearics
AP17	General northeasterly surface winds, with the troughs aloft over the Mediterranean	Murcia and south Valencia; Balearic Islands
AP18	General northerly winds by low pressure centres in the Genoa Gulf area	East Catalonia and Balearics
AP19	General northeasterly winds by low pressure centres to the east of the Balearics	East Catalonia and Balearics

Table II. Percentage frequency of the 11 daily RPs within the 19 APs (in bold, percentages greater than 15%) and seasonal distribution of the APs (in bold, percentages greater than 30%)

Atmospheric pattern	Number of days	RP1	RP2	RP3	RP4	RP5	RP6	RP7	RPO	RP9	RP10	RP11	Winter	Spring	Summer	Autumn
AP1	51	**49.0**	**33.3**	0.0	2.0	0.0	0.0	5.9	5.9	2.0	0.0	1.9	**43.1**	17.6	5.9	**33.4**
AP2	71	**46.5**	**23.9**	**15.5**	0.0	1.4	0.0	0.0	2.8	1.4	4.2	4.3	**54.9**	18.3	1.4	25.4
AP3	84	**35.7**	**36.9**	0.0	1.2	4.8	1.2	8.3	8.3	2.4	0.0	1.2	20.2	19.0	6.0	**54.8**
AP4	105	**30.5**	**36.2**	4.8	0.0	0.0	1.0	8.6	2.9	12.4	1.9	1.7	25.7	29.5	3.8	**41.0**
AP5	58	**22.4**	**25.9**	0.0	12.1	**15.5**	5.2	8.6	0.0	6.9	1.7	1.7	25.9	**36.2**	0.0	**37.9**
AP6	78	**17.9**	**15.4**	5.1	7.7	**21.8**	9.0	**17.9**	3.8	0.0	0.0	1.4	29.5	**33.3**	9.0	28.2
AP7	100	13.0	9.0	**25.0**	4.0	3.0	2.0	2.0	14.0	**25.0**	2.0	1.0	22.0	**35.0**	8.0	**35.0**
AP8	76	2.6	13.2	**15.8**	1.3	3.9	0.0	10.5	**23.7**	**21.1**	6.6	1.3	7.9	**42.1**	23.7	26.3
AP9	86	2.3	8.1	**41.9**	3.5	0.0	1.2	2.3	**16.3**	4.7	10.5	9.2	**45.3**	29.1	9.3	16.3
AP10	28	3.6	10.7	0.0	0.0	10.7	14.3	14.3	**28.6**	3.6	7.1	7.1	**46.4**	10.7	0.0	**42.9**
AP11	70	1.4	1.4	4.3	2.9	4.3	11.4	11.4	**30.0**	**20.0**	7.1	5.8	5.7	**30.0**	**41.4**	22.9
AP12	23	0.0	0.0	0.0	8.7	4.3	**69.6**	0.0	4.3	0.0	8.7	4.4	**47.8**	17.4	0.0	**34.8**
AP13	66	1.5	3.0	0.0	3.0	**28.8**	**40.9**	12.1	4.5	1.5	4.5	0.2	**53.0**	19.7	3.0	24.3
AP14	56	3.6	3.6	8.9	3.6	**17.9**	**16.1**	**21.4**	3.6	14.3	5.4	1.6	8.9	**35.7**	**33.9**	21.5
AP15	25	4.0	8.0	0.0	**16.0**	**20.0**	4.0	**24.0**	0.0	8.0	8.0	8.0	16.0	**32.0**	12.0	**40.0**
AP16	73	4.1	4.1	0.0	9.6	**16.4**	8.2	6.8	**20.5**	0.0	**17.8**	12.5	12.3	28.8	**38.4**	20.5
AP17	52	0.0	3.8	0.0	5.8	9.6	**36.5**	0.0	1.9	0.0	**19.2**	**23.2**	**30.8**	23.1	15.4	**30.7**
AP18	86	2.3	2.3	8.1	0.0	4.7	7.0	2.3	**17.4**	2.3	**24.4**	**29.2**	26.7	**41.9**	8.1	23.3
AP19	87	0.0	1.1	1.1	4.6	1.1	5.7	1.1	10.3	1.1	**37.9**	**36.0**	**34.5**	**40.2**	4.6	20.7
Total	1275	13.7	13.6	8.5	3.8	7.8	9.1	7.5	10.9	7.5	9.1	8.3	28.2	29.9	12.1	29.8

humid southwesterly flows, near or behind warm fronts linked to the Atlantic low, over the exposed topography of western Andalucía and therefore favours RP1 and RP2 (see Table II). Other rainfall patterns are rare because areas are more sheltered from such flows, or lie under the influence of a northwest–southeast oriented ridge. This circulation pattern is not very frequent (51 members; see Table II) and has a peak occurrence during the winter and autumn (Table II).

Pattern AP2 possesses a very high zonal index, at both 500 and 925 hPa. This pattern again produces warm and humid advection from the Atlantic, but is associated with Atlantic lows at a higher latitude and of larger size than lows associated with AP1. The coastal near-surface trough over eastern Spain, produced by barotropic conversion of vorticity as zonal flows override the Iberian plateau, is nicely captured by the geopotential field at 925 hPa. As for other Atlantic regimes, rainfall mostly favours areas RP1 and RP2. However, in contrast with AP1, RP3 is also favoured under these situations (15.5% frequency; Table II) because the mountains of central, interior Andalucía are much more exposed to westerly flows than they are to southwesterly flows. AP2 comprises 71 events, most of which are concentrated in the winter season.

AP3 is characterized by deep depressions centred to the west of the Iberian Peninsula. At upper levels, the nearly meridionally oriented trough axis implies a general southwesterly flux and advection of positive vorticity over practically the whole of the region. At low levels, the flow is southwesterly over southwest Spain, so favouring again, and in similar proportions, the precipitation distributions RP1 and RP2, but inhibiting RP3. In the eastern part of the region, there is warm and humid advection from the south-southeast. This also sometimes favours rainfall development over the exposed areas of eastern Spain (distributions RP5 and RP7) and Catalonia (RP8). Pattern AP3, which is comparatively frequent in the current data base (84 members), exhibits its maximum occurrence during the autumn (55%), well above values during winter and spring, which are only around 20% (see Table II).

Circulation AP4 is the most frequent of the patterns (105 members), and represents southwesterly flows at all levels associated with low pressure to the northwest of Spain. Characteristically, the geopotential fields indicate the presence of weak cold fronts moving into the Iberian Peninsula from the west. Apart from the Atlantic rainfall patterns RP1 and RP2, rainfalls in the northern sector of the region are also favoured (RP7 and RP9). As for AP3, this circulation pattern is also more frequent in autumn than in winter or spring.

AP5 is characterized by relatively small upper level lows close to the western coast of the Iberian Peninsula. The associated low pressure centre at low levels provides warm south-southwesterly flows over western Andalucía, and rather warm easterly on-shore flows over southeastern Spain as a result of an embedded trough along the African coast. This trough is a lee effect, as the upper levels flux almost perpendicularly crosses the Atlas Mountains, and it has been recognized as an important agent for the development of heavy precipitation in eastern Spain (e.g. Ramis *et al.*, 1999). With the support of upward dynamic forcing over southern Spain induced by the 500 hPa vorticity centre, the aforementioned humid flows interact with the terrain features to produce rainfall distributions RP1, RP2, RP4, RP5 and RP6 (Table II). Rainfall patterns RP7 and RP9 may also be favoured, since these areas are subject to warm and humid southeasterly winds under these conditions. The AP5 pattern is most frequent in autumn and spring, but it is not overall a very frequent occurrence (58 members).

Cluster AP6 represents the occurrence of an extensive cold-core low at 500 hPa, centred near the southwest corner of the domain, and associated with strongly diffluent flow over the northeastern part. The surface circulation is similar to that for AP5, but in this case the secondary trough over the southern Mediterranean is much more evident and extends its influence further north, since the flow over the Atlas Mountains is more perpendicular for this configuration. The low-level warm air advection towards the Mediterranean coast from the east-southeast is quite strong. As may be expected, typical rainfall patterns are basically similar to those that characterized AP5, but in this case the Andalucían patterns RP1, RP2 and RP4 lose some weight in favour of the eastern patterns RP5, RP6 and RP7 (Table II). The AP6 configuration is relatively frequent in the data base (78 members), and shows a regular distribution throughout the cold season (about 30% each in winter, spring and autumn; Table II).

AP7, which has the second largest cluster membership (100 members), is characterized by weak troughs in the westerlies at upper levels lying over western Spain, but with no appreciable tilting. At the surface, the northwesterly winds associated with the passage of cold fronts may interact with the northwesterly facing ridges of Andalucía, and therefore, rainfall pattern RP3 is much more frequent in this case (25%). Rainfalls in Catalonia, which lies ahead of the 500 hPa trough axis, and within the area affected by the surface frontal trough, are also favoured under this situation (RP8 and RP9). Rainfall distributions RP1 and RP2 in western Andalucía, which lies almost behind the 500 hPa trough, can also occur but are significantly less frequent than for the preceding APs because the surface flow is not so favourable. AP7 situations tend to occur in spring and autumn (35% on each season).

AP8 (76 members) contains occasions when short baroclinic waves occur over the Iberian Peninsula. The general structure is similar to the previous atmospheric pattern, but in this case the wave is much deeper and the surface frontal troughing is better defined. The wind over the western part of Iberia is more from the north (RP1 is not favoured under this situation), and cold air advection over the Iberian Peninsula is quite strong (the northwest winds favour RP2 and RP3). Rainfalls in the northern part of Mediterranean Spain (RP7–RP10) are largely activated by this pattern since that area is affected by maximum positive vorticity advection at 500 hPa (especially Catalonia). In addition, moisture from the Mediterranean is available ahead of the cold front. AP8 tends to appear in spring, followed by autumn and summer, but it is infrequent during winter (less than 8% of the cases).

The AP9 composite basically represents west to northwesterly winds at all levels following the passage of cold fronts from the Atlantic to the Mediterranean. This appears to be an ideal situation for the development of orographically enhanced rainfalls of type RP3. Distribution RP2 is also possible. The northeastern regions (Catalonia and the Balearic Islands) are close to the cold front and this is reflected in a significant occurrence of patterns RP8–RP11 in Table II. AP9 is a quite frequent situation (86 members) and it is typical of winter and spring (see Table II).

Pattern AP10 represents a strongly Mediterranean regime, with easterly warm surface flows feeding large quantities of moisture onto the Mediterranean coasts of Spain. This surface circulation is associated at 500 hPa with the presence of troughs or low pressure areas in the north of the study area. The AP10 configuration is infrequent (only 28 members), and is characteristic of winter and autumn, and obviously associated with rainfall activity in areas exposed to near-surface on-shore flows (RP2, RP5–RP8, RP10 and RP11).

Pattern AP11 (70 members) possesses relative low pressures over the southeast of the Iberian Peninsula, with weak troughs aloft just west of the Mediterranean coast. This configuration combines dynamic forcing at upper levels with surface easterly flows rich in moisture over the northeastern part of Spain induced by cyclonic circulation in the south, favouring rainfall development in RP6–RP11. Rainfall patterns RP3, RP4 and RP5 may also occur. The fact that this atmospheric pattern tends to occur during the warm season (the maximum frequency is in summer; Table II) suggests that the AP11 cluster may include a significant proportion of Iberian thermal low events. This has been verified by visual inspection of the individual maps included in this cluster. Under thermal low conditions, afternoon convection is often triggered by the important Iberic System and Pyrenees mountain ranges (Romero *et al.*, 1998), and this can be sometimes reflected in significant daily rainfalls of type RP7, RP8 and RP9 (Table II).

Cluster AP12 captures the relatively rare occasions when cut-off cyclones at 500 hPa dominate over the southeastern part of the domain. A nearly symmetric circulation exists at low levels, with a low pressure centre near the Algerian coast providing warm northeasterly flows over the Valencia region. Such flows are very effective for concentrating rainfalls in this area's highly exposed coastal mountains, and consistent with this, there is a strong association with type RP6 rainfalls (70% of the cases) within this cluster. Obviously, other rainfall distributions along the Mediterranean coast and in the Balearics are also possible (RP4, RP5, RP8, RP10 and RP11). Pattern AP12 has the lowest incidence of all APs in the data set (only 23 members), and tends to develop in winter and autumn.

AP13 represents the presence of large and intense cut-off cyclones over the southern part of the domain. The associated surface circulation imposes a general easterly regime over the domain. The Spanish Mediterranean coast is highly exposed to continuous moisture supply under this situation, and therefore the rainfall distributions RP5, RP6 and RP7 are the most probable (especially the first two which are closer to the upper level cold pool). Cluster AP13 is composed of 66 members, more than half of which occurred during winter.

AP14 (56 members) is characterized at 500 hPa by an accentuated trough with a positively tilted axis which is restricted to the central part of the Iberian Peninsula. The area with the maximum advection of vorticity is the southeast and east, which also benefits from the warm and humid Mediterranean flows induced by the surface pressure distribution. Accordingly, this circulation pattern tends to favour rainfall in RP5, RP6 and RP7. Rainfalls in the interior of Andalucía, which is the nearest zone to the centre of the disturbance and receives the favourable surface northwesterly winds, are also produced (pattern RP3). Rainfalls can also occur in the exposed Pyrenees (pattern RP9), but other rainfall distributions are much less frequent. As AP11, this circulation pattern exhibits its maximum frequency in spring and summer, and the 925 hPa field indicates relatively low pressure over the Iberian and African plateaux. However, only a few thermal low events have been identified in this cluster.

The meteorological situation AP15 is similar to AP14 at 500 hPa, since it is also characterized by shortwave troughs over the Iberian Peninsula, though now with opposite tilting. As with AP14, this pattern also possesses southeasterly warm, humid flows from the Mediterranean at low levels induced by low pressure over the south of Spain. Thus, again, RP5 and RP7 distributions are largely favoured, but not RP6, which needs a greater easterly or northeasterly component to the near-surface wind. Other favoured rainfall patterns are RP2 and RP4 in the south, and RP9–RP11 in the northeast. There are very few AP15 cases (only 25 members), and most occurred during autumn and spring.

AP16 (73 members) mostly contains occasions when vigorous depressions at 500 hPa are centred to the northeast of the domain. The circulation at lower levels is characterized by cold advection from the north over northeastern Spain, induced by a low pressure centre to the east of this area, but with easterly flows in the southern part of the Mediterranean as the low pressure area elongates towards the southern part of the domain. Rainfalls in eastern Catalonia and the Balearic Islands are often favoured under northerly flows associated with low pressures in the Gulf of Lyons and Gulf of Genoa areas (Romero *et al.*, 1998), and this is reflected in Table II by important associations between pattern AP16 and rainfall modes RP8, RP10 and RP11. In addition, the northeasterly and easterly flows over the rest of the Mediterranean coast may activate rainfall patterns RP4–RP7. This atmospheric circulation pattern tends to occur from spring to autumn.

Pattern AP17 contains occasions when upper level lows occur over the western Mediterranean, with the trough axis is approximately aligned along the Spanish Mediterranean coast. The corresponding 925 hPa circulation has a general southeast–northwest pressure gradient, which imposes a northeasterly current over the Mediterranean basin. As mentioned above, such a wind direction is commonly associated with rainfall development in the exposed coastal mountains of Valencia (see Figure 1), and this explains the strong association obtained between this atmospheric state and rainfalls of type RP6 (Table II). Of course, rainfall is also highly probable in the Balearic Islands, which lie just under the 500 hPa minimum, again reflected in RP6, and also in RP10 and RP11. Other favoured rainfall patterns are those of the southern coasts (especially RP4 and RP5). AP17 is not very frequent (52 members) and it tends to occur in winter and autumn.

Pattern AP18 has some similarity with AP16, but the northerly component in the flow at low levels is general over the whole of the domain. As expected with a surface low pressure centre over the southern French coast, the most probable rainfall development under AP18 occurs in RP8, RP10 and RP11. RP5–RP7 are less probable in this case. The significant association obtained with pattern RP3 can be once again attributed to the northwesterly winds over the mountains of Andalucía. With these winds the southern coast remains sheltered and this explains the lack of RP4 rainfalls in this case. AP18 is a quite frequent configuration (86 members) and tends to appear evenly during the cold season.

Finally, cluster AP19 comprises 500 hPa lows over the Gulf of Lyons with the associated low-level cyclone to the east of the Balearic Islands, providing northerly winds over the domain. Almost 75% of the cases developed rainfalls in the Balearic Islands through patterns RP10 or RP11 (Table II). Significant associations with distributions RP8, RP6 and RP4 are also found. This circulation pattern is quite numerous frequent (87 cases), and is more frequent in spring and winter than in autumn.

Table III. Distribution of torrential days[a] for the 19 APs, and percentage frequency of the eight TPs within the APs (in bold, percentages greater than 25%)

Atmospheric pattern	Torrential days	% of total	TP1	TP2	TP3	TP4	TP5	TP6	TP7	TP8
AP1	8	15.7	**25.0**	**62.5**	12.5	0.0	0.0	0.0	0.0	0.0
AP2	8	11.3	**37.5**	**25.0**	**25.0**	0.0	0.0	0.0	0.0	12.5
AP3	21	**25.0**	**33.3**	**52.4**	4.8	4 8	0.0	4.8	0.0	0.0
AP4	16	15.2	**25.0**	**31.3**	12.5	0.0	0.0	6.3	24.9	0.0
AP5	10	17.2	20 0	**50.0**	0.0	10 0	0.0	10.0	0.0	10.0
AP6	18	**23.1**	0.0	22.2	0.0	**33.3**	11.2	**33.3**	0.0	0.0
AP7	2	2.0	0.0	0.0	**100.0**	0.0	0.0	0.0	0.0	0.0
AP8	6	7.9	0.0	16.7	0.0	0.0	0.0	16.7	**66.6**	0.0
AP9	3	3.5	0.0	0.0	**66.7**	0.0	0.0	0.0	0.0	33.3
AP10	3	10 7	0.0	0.0	0.0	**33.3**	**33.3**	**33.3**	0.0	0.0
AP11	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AP12	5	**21.7**	0.0	0.0	0.0	0.0	**80.0**	0.0	0.0	20.0
AP13	25	**37.9**	0.0	4.0	0.0	**32.0**	20.0	24.0	8.0	12.0
AP14	11	19.6	0.0	0.0	0.0	**36.4**	**27.3**	**27.3**	0.0	9.0
AP15	8	**32.0**	0.0	0.0	0.0	12.5	0.0	**62.5**	0.0	**25.0**
AP16	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AP17	7	13.5	0.0	0.0	0.0	14.3	**71.4**	0.0	0.0	14.3
AP18	4	4.7	0.0	0.0	0.0	0.0	0.0	0.0	**50.0**	**50.0**
AP19	10	11.5	0.0	0.0	0.0	0.0	10.0	10.0	10.0	**70.0**
Total	165	12.9	10.9	20.6	6.1	13.9	12.7	15 8	7.9	12.1

[a] Also shown as a percentage of the total number of significant days; in bold percentages greater than 20%.

4. ATMOSPHERIC PATTERNS AND TORRENTIAL RAINFALL

As a further refinement of the analysis carried out for this paper, the days producing torrential rainfall were extracted, and their association with atmospheric circulation has been investigated. The eight TP distributions are shown in Figure 3. Table III shows how the subset of 165 torrential rain days are distributed amongst the derived 19 atmospheric patterns. The same table shows, for each AP, how the torrential events distribute among the eight TPs.

Circulation patterns AP11 and AP16 were not associated with any torrential event. By contrast, AP13 is associated with the development of torrential rains on almost 40% of occasions (see Table III). Also noteworthy are AP3, AP6, AP12, AP14 and AP15, with the incidence of torrential rain exceeding 20%. As can be observed from Figure 5, these more torrential APs are characterized in the middle troposphere by closed cyclonic circulations or very accentuated shortwave troughs located in the south of the domain. At low levels, they exhibit a significant level of warm advection towards some area of Mediterranean Spain. These conditions have been observed in most studies of severe rainfall events in Mediterranean Spain (e.g. Ramis *et al*., 1986; Ramis *et al*., 1994, 1999; Fernández *et al*., 1995; Romero *et al*., 1997; Doswell *et al*., 1998)

Table III, although obtained from only 165 torrential events, is quite informative and complements the result for significant rainfalls expressed in Table II. As for the significant rainfalls, the distributions shown in Table III are physically consistent with the dynamic processes contained in the corresponding APs. Focusing the attention on the most torrential APs, AP3 favours torrential patterns TP1 and TP2 in western Andalucía, AP6 favours TP4 and TP6 and in a lesser extent TP2 and TP5, AP12 projects almost exclusively on TP5, AP13 and AP14 favour significantly torrential rainfalls in Murcia, Valencia and the Balearic Islands through TP4, TP5, TP6 and TP8, and AP15 produces TP4, TP6 and TP8.

5. CONCLUSIONS

A total of 19 fundamental synoptic types has been derived that explain the development of significant daily rainfalls in the Spanish Mediterranean area. This has been done by performing cluster analysis of the 1275 significant rainfall days in the area during the 1984–1993 decade, based on the main spatial modes of the 500 hPa and 925 hPa geopotential fields. A clear, and useful, association between the 19 atmospheric circulation patterns and the previously derived 11 typical daily rainfall distributions has been established.

In a general context, it is possible to argue that the synoptic types obtained summarize four main more general scenarios producing significant rainfall in Mediterranean Spain. First, a large scale disturbance lies to the west or northwest of the Iberian Peninsula producing humid Atlantic flows that encourage rainfall development in the bulk of western Andalucía. The second occurs with the passage of cold fronts over the Iberian Peninsula linked to higher latitude low pressure systems. This scenario favours the development of rainfalls in northeastern Spain and in the inland mountainous areas of Andalucía. In the third case, relatively small lows at 500 hPa are found about the southern part of Spain, and the associated low-level flux over the Mediterranean is warm and humid from the east-southeast. This configuration leads to rainfalls over the eastern flank of Spain, including the Balearic Islands. Finally, for the fourth type, upper and low level disturbances are located to the east of the Iberian Peninsula in the Gulf of Genoa area, inducing strong flows with a pronounced northerly component over Spain. This last scenario generates significant rainfalls in the northeast of the Iberian Peninsula and in the Balearic Islands.

Such a general picture was already subjectively inferred by Romero *et al.* (1999a) in a first attempt to explain the 11 rainfall patterns. However, the four-scenario representation is obviously too simple. The present more objective study has produced a much more accurate division of the atmospheric patterns. The classification obtained has succeeded in capturing the dependence of well-defined rainfall regimes (described through a few rainfall spatial patterns) upon a few, clear aspects of the synoptic circulation. The combination of important topographic enhancement of rainfall for moist Atlantic or Mediterranean airflows, or both, and dynamic factors associated with an upper level disturbance, in fact render the physical interpretation of the relationship between atmospheric and rainfall patterns quite straightforward.

A study of the torrentiality of the derived atmospheric patterns reveals that some of them, although important for explaining significant rainfalls, are irrelevant for the occurrence of torrential rainfalls in the region. The situations characterized by disturbances located about the south of the Iberian Peninsula, although not very frequent, exhibit a high propensity towards the development of torrential rainfalls focused on the eastern flank of the Iberian Peninsula and the Balearic Islands.

The results obtained here should be most valuable in providing a more detailed forecast of rainfall activity in Mediterranean Spain within the context of synoptic numerical weather prediction, and as a complement for meso-scale resolution models. The assessment of the long-term rainfall variability in the region may also benefit from these results.

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