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A 30-YEAR (1964–1993) DAILY RAINFALL DATA BASE FOR THE SPANISH MEDITERRANEAN REGIONS: FIRST EXPLORATORY STUDY

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ABSTRACT

A dense daily precipitation data base, extending from 1964 to 1993, has been created for the Mediterranean regions of Spain. It is composed of complete and homogeneous series at 410 raingauge stations (347 in the coastal fringe of peninsular Spain, and 63 in the Balearic Islands). The region offers an interesting scenario for mesoclimatological studies on time and spatial rainfall variability: geomorphologically, it is characterized by important coastal relief units and complex distribution of sea and land masses, leading to different exposures to the rain-bearing maritime winds; climatically, the western Mediterranean is subject to strong seasonal variability, since it is a transition zone between the midlatitude low pressure belt and the subtropical highs as a result of its latitude (between 36° and 44° N). In this study, we exploit the data base and present a first pluviometric characterization of the area by means of yearly and seasonal mean products. The results reveal clear and coherent spatial patterns that we interpret, based on typical storm tracks and land, sea, and relief distributions. In addition, a partition of the 30-year period into three decades (1964–1973, 1974–1983, 1984–1993) has been considered in order to assess the possible existence of any trend. A successive drying of the most sensitive areas to the winter Atlantic depressions (western Catalonia, and central and west Andalucía) is observed. In contrast, the second analysed decade is appreciably drier than the other two in the areas more dependent on the Mediterranean disturbances. The occurrence of anomalous autumns being the most responsible. This fact emphasizes the fundamental importance of the autumn season for the pluviometric balance of the considered area, especially in its eastern part where the major amount of precipitation during this season is produced by convective systems. © 1998 Royal Meteorological Society.

KEY WORDS: Western Mediterranean region; Spain; rainfall characterization techniques; climate variables; interpolation; rain days; extreme rainfall; wet/dry periods

1. INTRODUCTION

The western Mediterranean region is defined as the portion of the Mediterranean Sea enclosed by Spain, France, Corsica, Sardinia and north Africa, and the surrounding lands (Meteorological Office, 1962). That part of the Mediterranean Sea is surrounded by important mountain ranges with notable foothills reaching the coast line. Figure 1 shows a smoothed orography of the region. The most relevant and known ranges are the Atlas mountains in north Africa, Penibetic and Iberic Systems in Spain, Pyrenees between Spain and France, Central Massif in France, and Alps between France and Italy. Even the islands, regardless of their small size, emerge abruptly from the sea (Balearic Islands, Corsica, Sardinia, Figure 1). The topography configures the western Mediterranean as a closed basin isolated from other regions except through the valleys and narrow straits; for example the Gulf of Lyons area, where Atlantic

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flows can be channelled, or the Gibraltar Strait, that opens the Mediterranean Sea toward the Atlantic Ocean (Figure 1).

Of course, that topographic configuration becomes decisive for the pluviometry of the region. At the local scale, it assists the development of clouds at fixed zones or to enhance precipitation from preexisting cloud systems, leading to pronounced rainfall differences between uplands and lowlands, or between slopes with different exposures to the maritime winds. At larger scales, it acts to transform the atmospheric disturbances that approach from the Atlantic, frequently generating secondary cyclones over the Mediterranean, mainly in the lee of the Atlas, Pyrenees and Alps (Reiter, 1975). In fact, the western Mediterranean has the world's highest density of cyclogenesis (Petterssen, 1956). Synoptic and mesoscale flows can be generated or redirected, focusing rainfall in favorably exposed areas and supressing it in other more sheltered areas. Numerical simulations of several heavy precipitation events have demonstrated the primary role exerted by the topography of the region (Romero *et al*., 1998a,b).

The latitude of the region (between 36° and 44° N), imposes extreme contrasts between warm and cold seasons. During the warm season, the region is persistently affected by the Azores anticyclone (Font Tullot, 1983) and the weather is hot and very dry, although mid-afternoon convection usually occurs in mountainous areas as well as in convergence zones produced by local sea breezes or by the typical thermal low of the Iberian peninsula (Alonso *et al*., 1994). During the cold season, however, travelling disturbances associated with the mid-latitude westerlies can easily reach those latitudes and the weather becomes temperate and moderately humid.

On the other hand, the closed characteristic of the Mediterranean Sea and the high insolation received during the summer lead to high sea surface temperatures during the summer and autumn. This aspect ensures strong water vapour availability in the Mediterranean environment and, in fact, during that period the Mediterranean air masses present frequently convective instability (Meteorological Office, 1962; Ramis, 1995). This is premonitory of the torrential character of rainfalls during the late summer and autumn when, under favorable synoptic conditions, this instability is eventually released in the form of organized convection over the coastal areas (Font Tullot, 1983; Riosalido, 1990).

All the above mentioned aspects contribute to define the western Mediterranean as an independent climatic entity, very interesting for mesoclimatological studies. It is an ideal laboratory where geophysical aspects such as land/sea partitions and topography are fundamental, by themselves or as a result of their interactions, for the climatic characterization of the region, particularly for their spatial pluviometric regimes. It experiences pronounced seasonal rainfall variability (rainfall is moderate and more continuous in winter and spring, practically absent during the summer, and often torrential in autumn), and therefore it is an area especially sensitive to a possible shift of climatic zones.

In this work, we will focus our attention on the Mediterranean subdomain composed by the Spanish Mediterranean regions (Catalonia, Valencia, Murcia, Andalucía and Balearic Islands; see Figure 1). Figure 2 shows that area and the names of some geographical units in order to facilitate subsequent discussions. The region measures approximately 1000 km along N–S and E–W directions. In some areas of the Pyrenees and Penibetic System, not too far from the sea, terrain heights exceed 3000 m.

Our first objective is to create a homogeneous and complete daily rainfall data base for the region, with an appropriate density to effectively capture spatial variabilities. We have considered the 30-year period 1964–1993, since earlier rainfall data are limited in number and quality. Our second objective is to make use of the created data base and to give a first pluviometric characterization of the region, which is going to be complemented in other future statistical studies. In this case, we are interested in examining and interpreting spatial and seasonal differences in rainfall character and amount that result from mean maps, while also looking for possible changes during the 30 years considered. For that reason we have split the period into the three decades, i.e. 1964–1973, 1974–1983, and 1984–1993.

It has to be noted that historically, precipitation has been the meteorological variable of greatest concern in this area due to its manifestation as a deficient resource over long periods (notable are the droughts at the beginning of the 1980's), but also as a catastrophic agent during other episodes (floods occur every year in this area, and Font Tullot (1983) showed that daily rainfalls exceeding 200 mm have been recorded at most of the observatories of Catalonia and Valencia).

We have structured the paper in four parts. Section 2 describes the methodology followed for the data base construction and Section 3 describes the derived maps that have been considered for the analysis. Results, discussion and the most relevant maps are contained in Section 4, and Section 5 gives our main conclusions.

2. DATA BASE CONSTRUCTION

The raw data consisted of the 3366 available daily precipitation records from the Spanish Mediterranean regions during some period between 1951 and 1995, provided by the Instituto Nacional de Meteorología (INM). A first selection was made to consider only stations with a minimum of 1000 data values (almost 3 years), which yielded a set of 2842 raingauges.

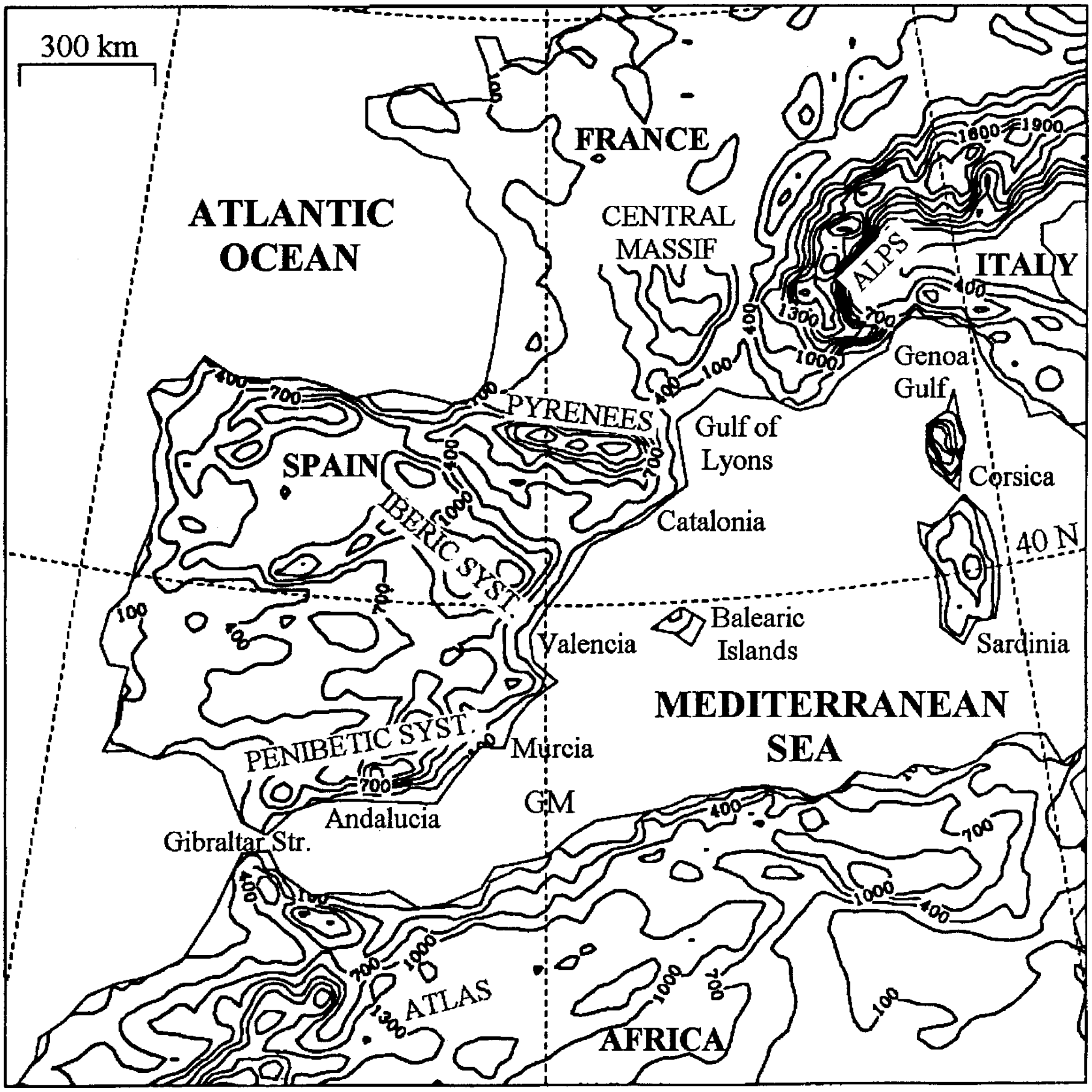

Figure 1. The western Mediterranean region and its smoothed orography (contour interval is 300 m starting at 100 m). The sites mentioned in the text are indicated

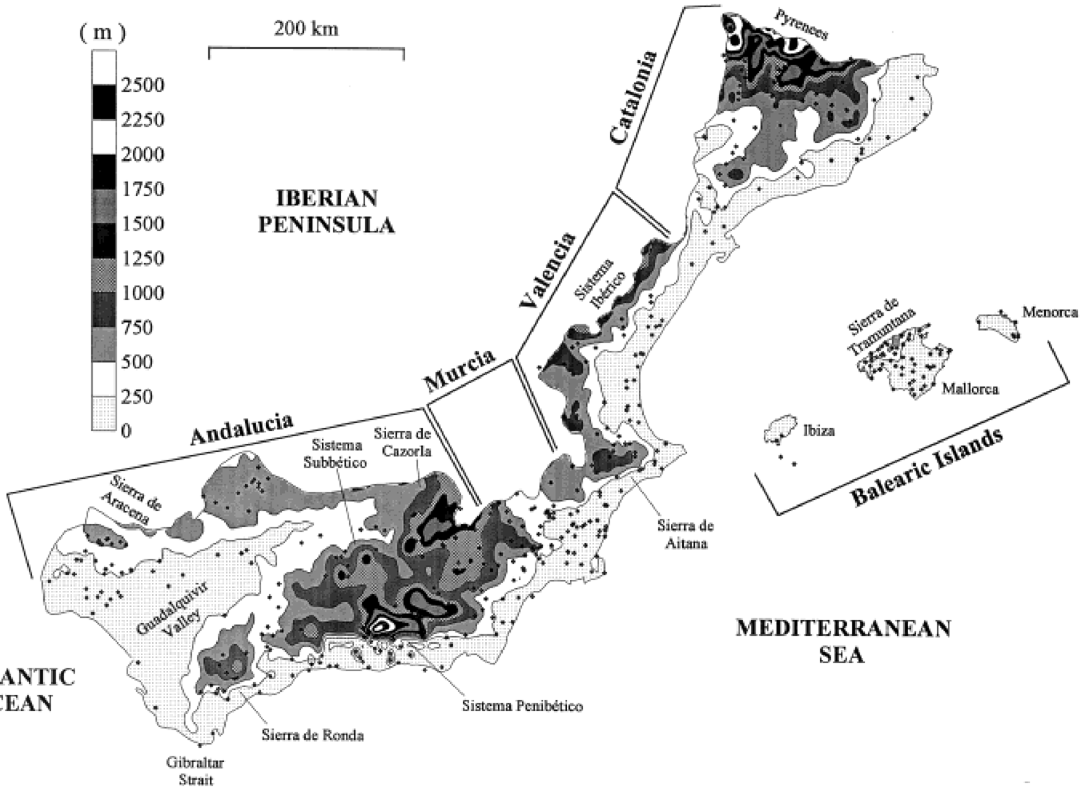

Figure 2. The Spanish Mediterranean area under study, formed by Catalonia, Valencia, Murcia, Andalucía, and Balearic Islands. It includes a smoothed version of its orography, the position of the definitive data base stations (410 in total), and some geographical references mentioned in the text. The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

The inventory of the data showed a great variety of record lengths, with only five stations with no missing data. Then, a search was performed to choose the longest subperiod of 1951–1995 having the highest number of stations with tolerable completion. The final decision was to keep all stations with 90% of data available during 1964–1993 (30 years). As a consequence, the final number of stations in the data base was reduced to 410, for the period 1964–1993. Its spatial distribution is shown in Figure 2. As can be observed, the resulting coverage is globally satisfactory (exceptional in Mallorca), although it is poor within the Guadalquivir valley, in mountainous areas of Andalucía, north of Valencia, and some areas of Catalonia.

The following task was to check the quality of the data, as well as to fill the missing data by interpolation from the surrounding stations. The need for a suitable method for data homogenization and quality control has been a constant concern of investigators dealing with climatological data (e.g. Shearman, 1975; De Ruffray *et al*., 1981; Spackman and Singleton, 1982; Baker *et al*., 1995). The average between-site distance for the 410 stations is 15 km, whereas that distance reduces to only 7 km when all the 2842 stations are considered. It seems, therefore, that although our requisite of minimum completion is only reached by 410 stations, there is still very useful information in the remaining stations that can be used for the interpolation task. We considered it opportune, then, to use all this information. We developed an iterative method.

First of all, a new complete record p^{*n}_i (i, station; n, day) was calculated for each of the 2842 stations for the whole period 1951–1995:

$$p^{*n}_i = \frac{\sum_{j=1}^{J} \alpha_{ij} (p'^n_i)_j}{\sum_{j=1}^{J} \alpha_{ij}} \quad (1)$$

Here, p^{*n}_i is a weighted average of the J estimated values at position i, noted as $(p'^n_i)_j$. The J reference stations are all stations which, lying within a radius of 0.5° around the target station i, have a common observing period of at least 1000 daily values with station i, and have no missing data on the target day n. The radius for acceptance was chosen large enough as to yield several stations even in areas with small raingauge density.

The estimated values $(p'^n_i)_j$ in Equation (1) are formulated as

$$(p'^n_i)_j = p'^n_j q_{ij} \quad (2)$$

where p^n_j is the observed precipitation at reference site j, and q_{ij} is the ratio between accumulated rainfalls at stations i and j:

$$q_{ij} = \frac{\sum_{k=1}^{K} p^k_i}{\sum_{k=1}^{K} p^k_j} \quad (3)$$

which is evaluated over the common observing period of K days. As implied by the previous arbitrary threshold, K is never less than 1000, ensuring the statistical significance of q_{ij}.

The criterion expressed by Equation (2) is based on the idea of interpolating normal ratio precipitations rather than absolute data, which was used by Paulhus and Kohler (1952) to eliminate the influence of orographically enhanced precipitation. But we cannot compute homogeneous station normals until the precipitation series is completed. Therefore, we use ratios of precipitation totals for the common observing period for each pair of stations. A simplified form of regression is then applied in which the independent term has been removed, and the regression coefficient can then be calculated as the ratio between the accumulated data of the dependent and independent variables (p_i and p_j, respectively). This simpler regression form has the advantage of being more robust as it is less influenced by outliers, and it is, in fact, the ratio method proposed by Conrad and Pollack (1962) to reduce precipitation averages to a common observing period. We applied the same technique but for the estimation of individual data.

Much discussion has been raised with respect to the functional form of the weighting factors (α_{ij} in Equation (1)). Some authors perform the weighting as an inverse function of the distance, while others prefer a function of the correlation coefficient. When looking to a plot of correlation coefficients versus distance or to mapped correlation fields (e.g. Sumner *et al.*, 1995b), it is clear that for close stations any of the methods may be applied with good results. For longer distances, however, pairs of stations separated by similar distances may have a wide range of correlation coefficients, and stations related with similar correlations may be separated by quite different distances. Moreover, while the correlation coefficient has the ability to account for geographically induced anisotropies, the distance may introduce more consistency in the analysis of highly variable fields such as the daily precipitation. We have adopted a compromise between both methods:

$$\alpha_{ij} = \frac{r^2_{ij}}{d^2_{ij}} \quad (4)$$

where the correlation coefficient r_{ij} and distance d_{ij} between stations i and j are squared to enhance the preeminence of the closer stations (both in spatial and correlation terms). This is especially useful in areas with a high density of stations, where close reference data could otherwise be masked by many farther stations.

More sophisticated interpolation techniques as multiple correlation, optimal interpolation, kriging, or spline-surface fitting have been proposed (Gandin, 1963; Creutin and Obled, 1982; Young, 1992). Their estimations were sometimes better when compared with simpler methods, but with the cost of a higher bias and reduction of variance.

Once the precipitation series p^{*n}_i were calculated, relative deviations (original datum minus calculated one, divided by the mean yearly calculated precipitation) were computed for each of the 2842 stations, and used to test the original data. Relative deviations series showed high variances and very leptokurtic frequency distributions. Only original data with relative deviations beyond seven times the standard deviation of its series were rejected and substituted by the calculated value. This process was performed iteratively, starting each new cycle at Equation (1), until no rejections were given. Ten iterations were needed, and less than 0.07% of the original data were rejected as a result of the whole process. Finally, the precipitation series calculated in the last iteration were used to fill the holes present in the records of the 410 selected stations.

3. ANALYSED PRODUCTS

The products described below have been computed separately for the three decades 1964–1973, 1974–1983 and 1984–1993. We distinguish between yearly products (those using accumulated quantities at the stations during the ten whole years), and the associated seasonal products (those restricted to particular seasons: winter, spring, summer and autumn). The periods included within each season follow the climatological criterion usually adopted by the meteorological agencies of the region, rather than the astronomical definition. Hence, winter is composed of December, January and February months; spring by March, April and May; summer by June, July and August; and autumn by September, October and November.

First of all, we have calculated yearly and seasonal mean precipitation (in mm). The second product accumulates, both for the whole decade and for the four individual seasons, the number of daily rainfalls greater or equal than some arbitrary threshold. In particular, following the World Meteorological Organization (WMO) standards, with a threshold of 1 mm we fix the number of days with rain. For large values of such threshold (say 100 or 200 mm), we quantify the occurrence of extreme rainfalls.

The third product is designed to compute the mean rate of rainfalls (in mm day^{-1}), and is given by the division of mean precipitation by the mean number of rainfalls. Then, this is not an independent parameter, but its direct visualization can be useful to determine precipitation character.

The next considered product is the mean duration of wet episodes (in days), where a wet episode is understood as an interval of consecutive days with rain (≥ 1 mm). This field reveals the degree of dispersion of rainy days throughout time. Analogously, we have also calculated the mean duration of dry episodes (a dry episode is understood as an interval of consecutive days with no rain, i.e. < 1 mm).

In addition to the previous yearly and seasonal products, we have also computed recurrence intervals for each decade (in years). This has been done for several daily precipitation levels (50, 75, 100, 150, 200 and 250 mm), using the Gumbel distribution function (Gumbel, 1958), and the Chow method (Chow, 1964) to estimate the distribution parameters.

Using the kriging interpolation method, which performed the best compared with other tested techniques, high resolution regularly spaced grids were generated for all fields and contoured. All maps were carefully examined and the principal results are given in next section. Only the essential maps are shown, however, for the sake of brevity.

4. RESULTS AND DISCUSSION

4.1. Mean precipitation

Figure 3 shows the yearly mean precipitation for the three decades. The main characteristics are high amounts around Sierra de Ronda (in the form of an almost circular area with more than 700 mm and peak values in its center exceeding 1700 mm), appreciable amounts also along Pyrenees, around Sierra de Aracena, Sierra de Cazorla, Sierra de Aitana and the north of Mallorca, contrasting with a general decrease toward inland areas, and very low values in a vast area of the Southeast (south of Valencia, Murcia and eastern Andalucía). In a general sense, the spatial patterns of Figure 3 reflect a general precipitation gradient along the SE–NW direction. This feature seems to be connected, apart from the orography, to the degree of proximity to the Atlantic waters from where the majority of storms arrive. The northwest of Catalonia and west of Andalucía (which in fact are more Atlantic than Mediterranean),

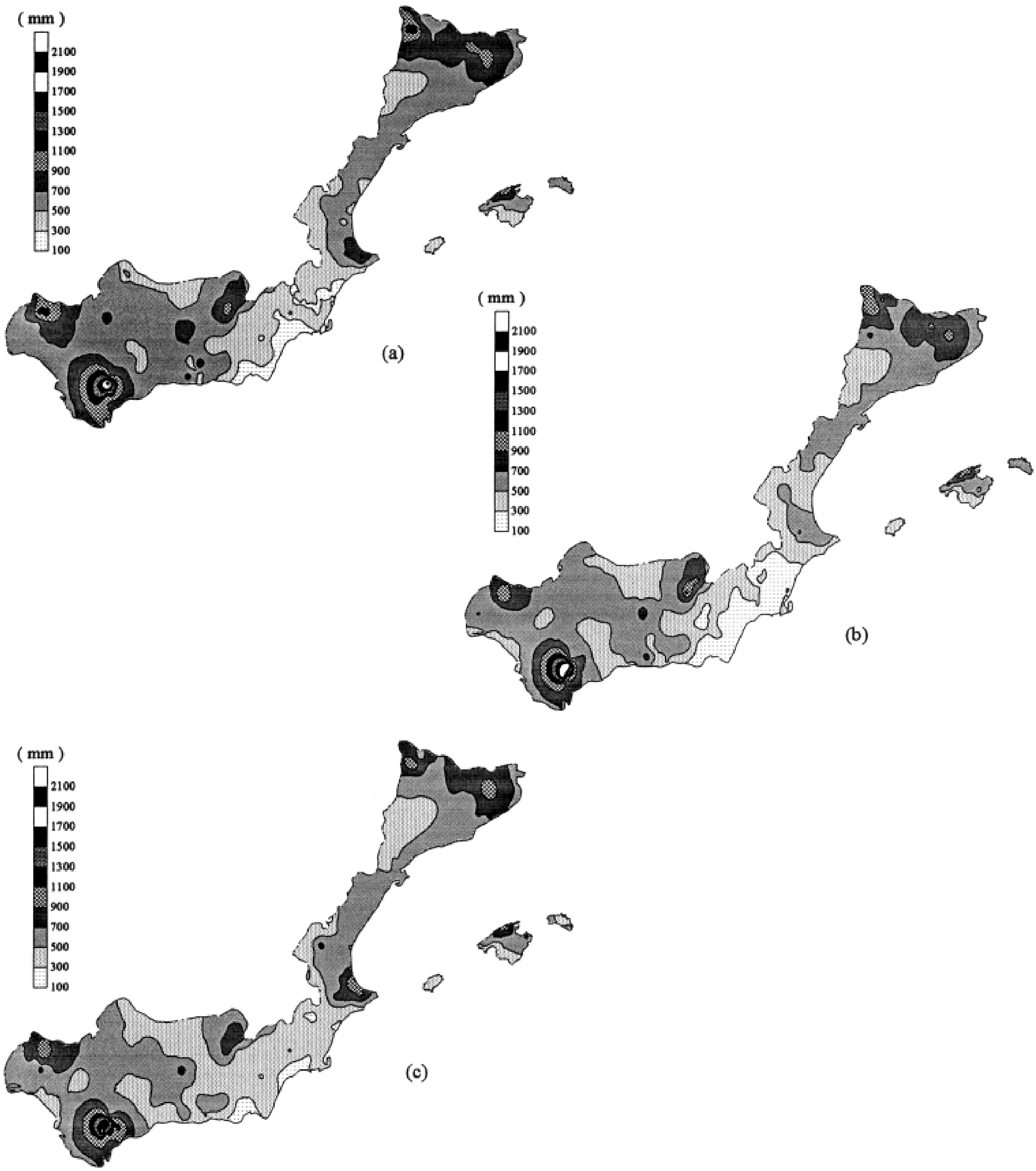

Figure 3. Yearly mean precipitation for (a) first decade; (b) second decade; and (c) third decade

are favourably exposed to the Atlantic fronts, whereas the Southeast is a depressed area sheltered by the extense plateau of the Iberian Peninsula (Figure 1), and where many fronts do not arrive. This last area is the most arid zone of Spain and even possesses some limited deserts. Colloquially, it is here that the Sahara desert is knocking at Europe's door.

The eastern part of the region has its own idiosyncrasy, since it is well exposed under purely Mediterranean flows and cyclones, these last having normally meso-α dimensions. With cyclones in the north of the Mediterranean basin, as the famous Genoa Gulf cyclones (Reiter, 1975), then the northeast of Catalonia and north of the Balearics are favoured. With cyclones in the south of the Mediterranean (for example the Algerian cyclone; Reiter, 1975), then practically all the area receives the induced southeasterly to northeasterly humid winds. Observe, however, that the arid southeastern fringe is only favoured under very specific flows: southerly flows descend from the dry African continent (Figure 1), whereas if winds with an excessive north component develop, the area lies downstream of the important Sierra de Aitana mountains (Figure 2).

In a more local sense, the internal variability registered in Balearic Islands (see Figure 2) is notable. There is a marked transition from southern Mallorca, which behaves similarly to Ibiza, toward the uplands of Sierra de Tramuntana in the north. The island of Menorca is wetter than Ibiza and reaches quantities comparable to those of the centre and east of Mallorca.

The orographic signature is quite clear in Figure 3, especially in the Sierra de Ronda domains where both easterly and winter southwesterly to northwesterly winds impinge directly. On the contrary, and probably influenced by its low stations density (see Figure 2), the effect of the still higher Sistema Penibético is almost unimportant in the obtained mean precipitation. This fact may seem unexpected in a first analysis, but becomes logical when it is noted that the mentioned flow regimes are hardly effective in this case. Winds with perpendicular incidence, from the south, have only a short path over the Mediterranean waters (Figure 1).

With respect to significant changes between the three decades (Figure 3), the main conclusions are: a successive drying of central Andalucía, the same tendency in western Catalonia and some places of western Andalucía, and a significant drying during the second decade in the Southeast (observe the important advance of the 300 mm isohyet), Valencia, and northeast Catalonia. But during the third decade, these last areas not only recovered the state of the first decade, but were even wetter. The Balearic Islands, except Menorca, keep apart of these changes, showing similar values during all decades.

We have selected the third decade (1984–1993) to show the rainfall distribution mode among the four seasons (Figure 4). During winter, western Andalucía benefits most, where more than 200 mm are registered in a wide region and large values are obtained in Sierra de Aracena and Sierra de Ronda (Figure 4(a)). Other important signals are obtained in the proximity of Sierra de Aitana, and in the mountainous north of Mallorca. The less favoured areas in this season are the Southeast and the interior of Catalonia.

Winter maps for the first and second decade (not included), show that still larger values occur in mountainous areas of Andalucía, and the 200 mm isohyet arrives at the western edge of the domain and extends farther east occupying practically all central Andalucía, this change is more pronounced in the first decade than in the second. Other seasons, however, behaved similarly to central Andalucía. Therefore, it is mainly the successively drier winters, probably as a result of a lesser incidence of the Atlantic depressions, that are responsible for the yearly rainfall decrease in this area. Correspondingly, western Catalonia, which also depends on the Atlantic 'activity', shows a similar behaviour to central Andalucía and as a result its last decade becomes the driest one. On the contrary, the Southeast and Valencia were wetter during winters of the third decade. These contrasts between Atlantic sensitive areas and Mediterranean sensitive areas could be explained by a major incidence of Mediterranean regimes and a less incidence of Atlantic regimes during the third decade. But this is only an hypothesis that should be further investigated. The Balearic Islands do not show remarkable differences through the three decades.

The spring seasons show similar mean precipitation patterns in all three decades (that displayed in Figure 4(b) is for 1984–1993). In this season, the mean precipitation field is rather uniform, with not so strong contrasts between different areas. Orographic signatures in Andalucía, Valencia and Mallorca

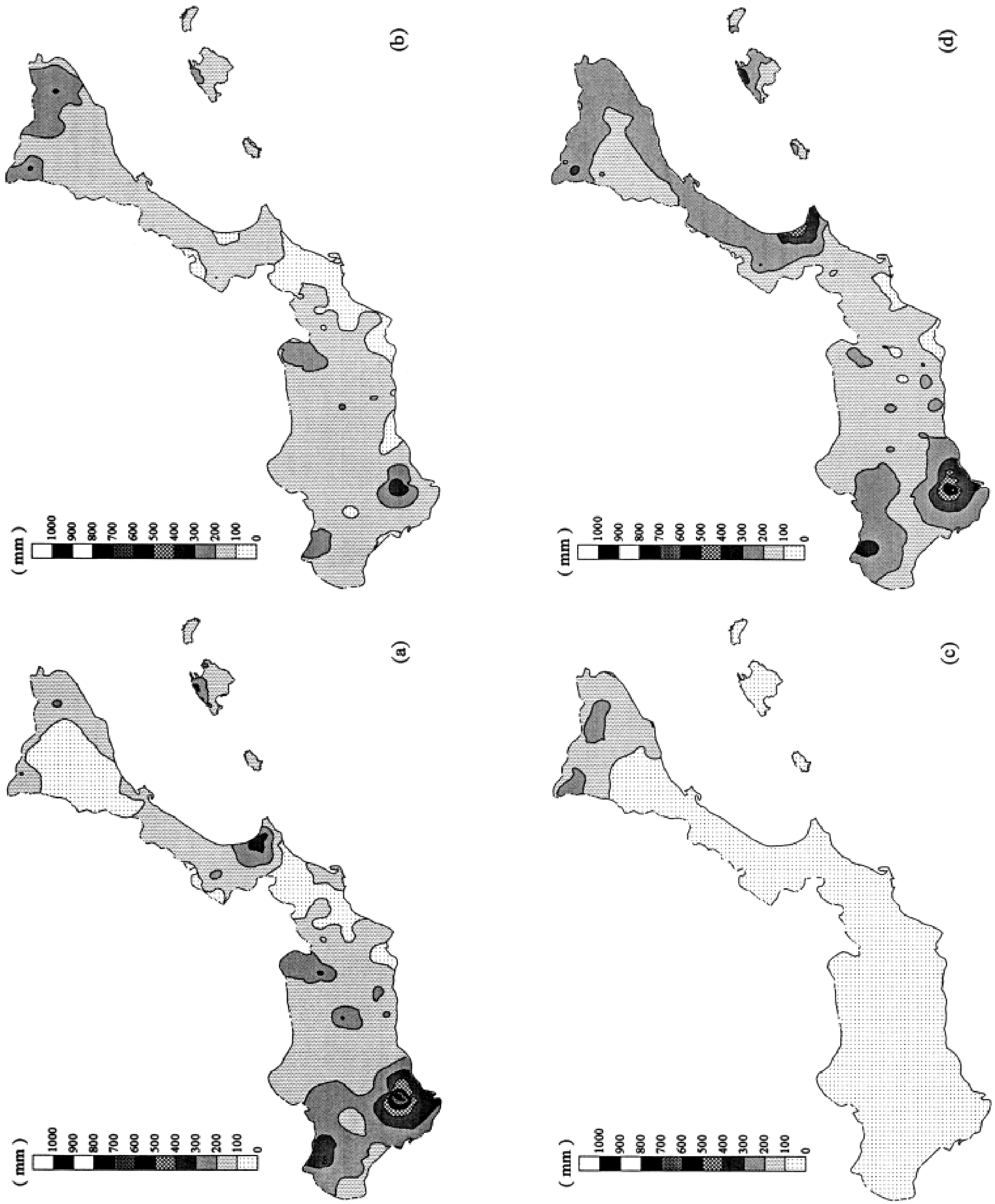

Figure 4. Seasonal mean precipitation for the third decade: (a) winter; (b) spring; (c) summer; and (d) autumn

weaken appreciably, but that associated with the Pyrenees enhances. Although the Southeast exhibits again as a distinctive drier zone, the same does not hold in this case for the interior of Catalonia. In this season, meteorological changes follow very rapidly and scattered showers are frequent. The important land heating in the plains and the presence of the orography are both important for triggering convection.

As Figure 4(c) shows, the summer is very dry (less than 100 mm during June, July and August) in all the territory except in the northern half of Catalonia, particularly in the Pyrenees (more than 200 mm). Although the so called Mediterranean air mass possesses high specific humidities and often presents convective instability (Meteorological Office, 1962), synoptic conditions are supressive for significant cloud developments in this season. It is a period with a determinant latitudinal dependence. In the centre and south, rainfalls can occur during June and the second half of August, but are rare during July and the beginning of August. Only some mid-afternoon thunderstorms sustained by the Iberian thermal low (Alonso *et al*., 1994) develop in mountainous areas (especially in Sistema Ibérico), but they have usually very low precipitation efficiencies. However, northern Catalonia can be still affected by the extremes of some rain fronts. In addition, thunder storms over the Pyrenees slopes, fed by the recurrent sea breezes along the Catalan coast, occur almost every afternoon. Maps from the other two decades (not shown) reflect to a greater degree the positive signal of Catalonia and Pyrenees.

Figure 4(d) displays an essential contribution of the autumn season in eastern Andalucía, Murcia, Valencia, Catalonia and Balearic Islands. Effectively, comparing with Figure 4(a, b and c), it is observed that the autumn is the wettest season in those regions. In central and western Andalucía the autumn contribution is not so decisive, generally similar to the spring contribution and clearly smaller than the winter contribution. This is what in fact the maps from the previous decades (not included) show, but an exception to that rule occurs for the third decade: in western Andalucía (but not in its center), the autumns were abnormally wet and more similar to the winters, helping to compensate for the drier winters discussed before.

The eastern part of the domain, including the Balearic Islands, responds precisely to the typical Mediterranean pluviometric regime, characterized by a maximum in the autumn season. This maximum is the result of the high sea surface temperatures and the major occurrence of cold intrusions and Mediterranean depressions that often develop long-lived, highly organized mesoscale convective systems with exceptional precipitation efficiencies (Riosalido, 1990). Almost all Mediterranean heavy precipitation events and associated floods cited in the literature occurred in these months, but they are not exclusive of this season. Consider as an example the heavy rains in Valencia and the Southeast (totals of almost 400 mm in Sierra de Aitana) during 1–4 February 1993 (Doswell *et al*., 1998; Romero *et al*., 1998a,b).

The significant drying found in the peninsular eastern domain during the second decade (discussed earlier), can be explained comparing the autumn mean precipitation of the second decade (not shown) with that of the third decade (Figure 4(d)). Large differences between the two decades (about 100 mm in general but reaching 300 mm in the slopes of Sierra de Aitana), are found in this part of the domain. We can conclusively say that abnormaly dry autumns during the second decade (notably during 1981, 1982 and 1983), made the decade as a whole the driest one of the studied period in eastern Spain. An exception is again the Balearic Islands, although the above mentioned years were also very dry.

4.2. Days with rainfall over different thresholds

It is interesting to examine the spatial patterns of the variable 'number of wet days' and their changes through the seasons. Figure 5 contains the map for the third decade. The absolute maximum is found in the Pyrenees, with almost 1/3rd of wet days. The minimum occurs in the interior of Catalonia and Southeast areas, as with the yearly mean precipitation field (Figure 3(c)). Nevertheless, there is no equivalence between mean precipitation (Figure 3(c)), and number of wet days (Figure 5). In particular, the strong signals given by Figure 3(c) around Sierra de Aitana and Sierra de Ronda are not so well contrasted in Figure 5. This lack of correspondence between both maps is a consequence of having different predominant rainfall intensities among the different subdomains. In the next section, this point will be discussed in detail by studying the mean rates of rainfalls.

In agreement with the tendencies observed for yearly mean precipitation in the last section, maps of wet days during first and second decade (not shown), confirm a progressive diminution of wet days in western and central Andalucía, and a minimum during the second decade in the Southeast and Valencia.

A general examination of the seasonal maps for the 1 mm limit (not shown) display clear differences between summer and colder seasons. During summer the number of wet days is very low in the southern half of the region and Balearic Islands (less than 1/10th). Summer has two local maximums around Sierra de Cazorla and Sistema Ibérico where afternoon thunderstorms related with the thermal low are frequent, and experiences a rapid increase from northern Valencia toward the Pyrenees (1/3rd is exceeded in its western part). In winter, spring and autumn, distinct behaviours exist depending on the zone: in central and western Andalucía there is a marked positive tendency along autumn–spring–winter (*ca.* 1/5th–1/4th–1/3rd in mountainous areas; and 1/7th–1/6th–1/5th in the remaining areas). In the Southeast, the three seasons attain similar low values (1/9th in the coastal territory and 1/8th inland).

In Valencia and south of Catalonia we find an opposed tendency to that in Andalucía, with a slight increase of wet days along winter–spring–autumn (maximum values are *ca.* 1/5th, 1/6th in the north and mountainous areas). However, in the north of Catalonia the positive tendency goes along winter–autumn–spring, with all seasons giving a strong gradient toward the Pyrenees peaks similar to that shown in Figure 5. In this case we find values ranging between 1/7th and 1/3rd in winter, 1/6th and 1/3rd in autumn, and 1/5th and 1/3rd in spring. The Balearic Islands have a weak spring–autumn–winter positive tendency, giving maximum values in the northern mountains of Mallorca (1/4th), and minimum values in the south of Mallorca and Ibiza (less than 1/6th).

We also examined yearly and seasonal maps for the 10 and 25 mm limits (maps not shown). These maps reveal a general tendency to increase the relative importance of the coastal territories (especially the uplands of Sierra de Aracena and Sierra de Aitana) as the precipitation limit rises, but a loss of relative weight in distant areas from the sea, this loss being very pronounced in western Pyrenees. Significant daily rainfalls have a clear preference, therefore, for the exposed coastal areas.

Focussing the attention on the 100 mm limit, we can assess the incidence of extreme daily rainfalls. Note, however, that as a consequence of our rainfall basic time unit (1 day), it is not possible to distinguish between heavy continuous rainfalls (e.g. 100 mm in 12 h) and torrential rainfalls of short duration (e.g. 100 mm in 2 h). Although the effect of both types of rainfalls is certainly different, we should work with rainfall registers with a resolution comparable to the convective time scale (e.g. 1 h), in order to make such distinctions. Figure 6 shows yearly and seasonal maps for the 100 mm limit. For these

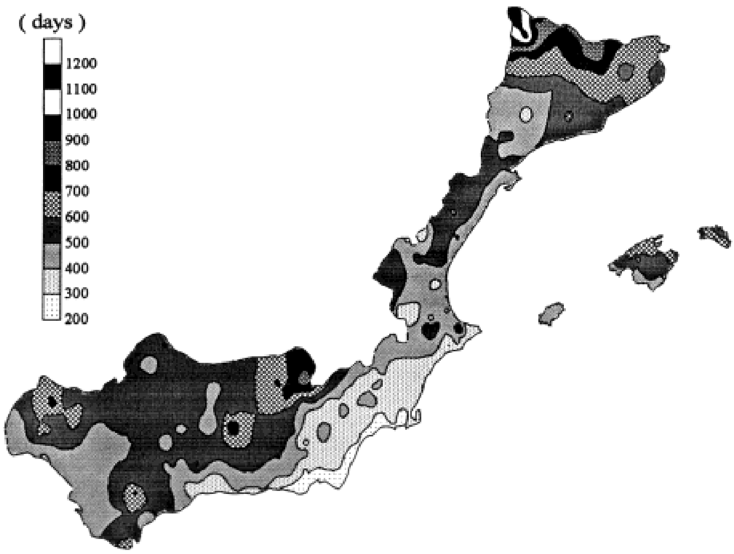

Figure 5. Days with precipitation (≥ 1 mm) during the third decade

plots, a representation based on a previous gridded data analysis was found inopportune, because the very localized maximums we want to highlight were partially damped. Instead, at the station coordinates we centered a circumference with a diameter scaled as a function of different predefined categories.

Figure 6(a) shows that extreme rainfalls tend to concentrate in coastal areas, and secondarily, in mountainous interior areas. The maximum values are found in Sierra de Ronda, where a station attains the 21–25 days category. The 26–30 and 31–35 categories are reached in this zone during the wetter second and first decades, respectively. Valencia and Murcia define an extensive area where 100 mm occurrences (in general in the 1–5 or 6–10 ranges) are given by most of the stations, although such distinction is not as strong during the drier second decade, and during the first decade in Murcia. The high amount of 100 mm days given by the stations located close to Sierra de Aitana is notable. This zone has been classically considered the most torrential in Spain. Observe how the peninsular arid Southeast participates actively in this case.

Extreme rainfalls are also frequent in the island of Mallorca along Sierra de Tramuntana, and in its eastern part where a minor topographic ridge exists. Ibiza and the two stations of the adjacent island of Formentera also registered 100 mm rainfalls. The same occurred in Menorca, but not during this decade.

With respect to the seasonal distribution (Figure 6(b, c, d, e)), most of the 100 mm rainfalls are concentrated in the torrential autumn season. Winters occupy the second place, followed by springs. Extreme rainfalls are rare during summer. The 200 mm events (maps not shown) are almost exclusive of autumn, although they also tend to occur during winter in Sierra de Ronda. None of the 410 stations registered such an event during the 30 summers.

4.3. Mean rates and recurrence intervals

An additional notion about the precipitation characters in the region can be obtained by means of yearly and seasonal mean rates maps. Specifically, this variable measures the relative importance of significant rainfalls with respect to total rainfalls, but nothing is said about its absolute importance. This last question is only answered using the maps of last section. In this case the question is asked: When it rains, how much, on average, does it rain? In summary, stations with strongly positively skewed rainfall frequency distributions will lead to low mean rates; on the contrary, stations with less positively skewed distributions will give greater values of this variable. We are interested in detecting this last type of stations where the heavy precipitation component (normally convective), has a major relative importance.

Figure 7(a) (third decade) shows that yearly rates greater than 10 mm day^{-1} are found in western Andalucía, in alternate areas of the South and Southeast, and in a continuous coastal band extending from Sierra de Aitana to the northeast of Catalonia. These values are also found in Ibiza and Mallorca, but not in Menorca. The alternate structure of the South and Southeast seems to respond to the complex orography of that area, whereas the continuous structure of Valencia and Catalonia lies parallel to the coastal ridges. Rates exceeding 12.5 mm day^{-1} are practically restricted to Sierra de Aracena, proximity of Gibraltar Strait and Sierra de Ronda, coastal locations of the South and Southeast, Sierra de Aitana area, northeastern Catalonia and Sierra de Tramuntana. As expected from the results of previous sections, Sierra de Ronda and Sierra de Aitana areas define the two most important centres of torrentiality.

Similar structures are found for the first and second decades (not shown). The only remarkable differences are: higher values in Sierra de Cazorla, in the interior of Catalonia and about the boundary between Valencia and Catalonia during both decades; lower values during the second decade in the coastal band extending from eastern Andalucía to northern Valencia where the autumns were dry (see previous sections).

The yearly patterns and maximums positions in Figure 7(a) can be also identified, in general, in the wet seasons maps (Figure 7(b, c, e)). However, since the summer is governed by long dry periods combined with irregular and isolated thunderstorms, the structures obtained for this season are noisy (Figure 7(d)), and quite different from one decade to another. Among the wet seasons, the most significant differences are related to the patterns intensity. Springs present the lowest rates, followed by winters, and the maximums rates are found in autumns, especially in the eastern regions. The same seasonal variability of

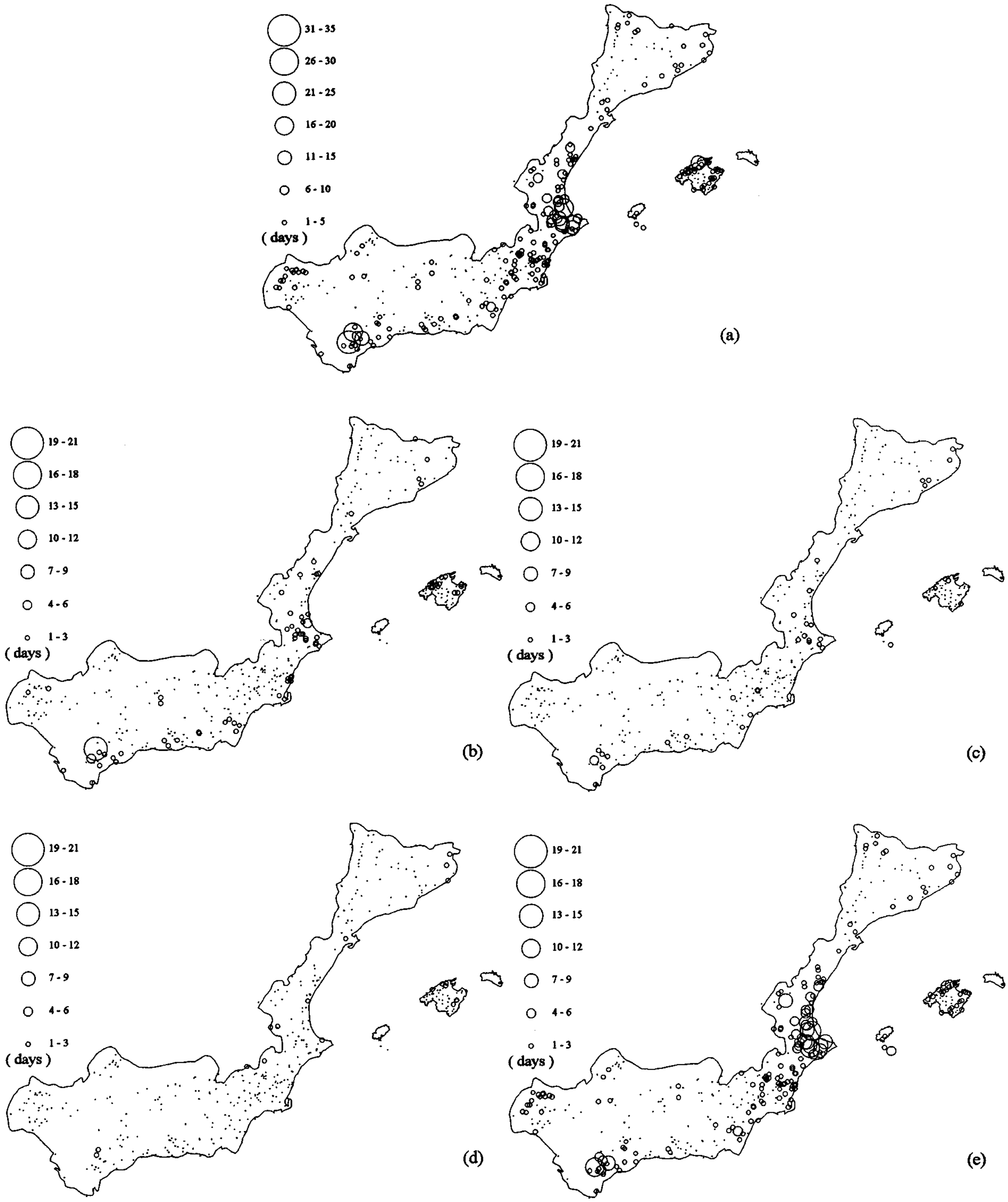

Figure 6. Days with extreme rainfalls (≥ 100 mm) during (a) third decade; (b) winters of third decade; (c) springs of third decade; (d) summers of third decade; and (e) autumns of third decade. Note the different scale of (a) and the other maps. The dots represent the position of the stations where extreme events were not registered

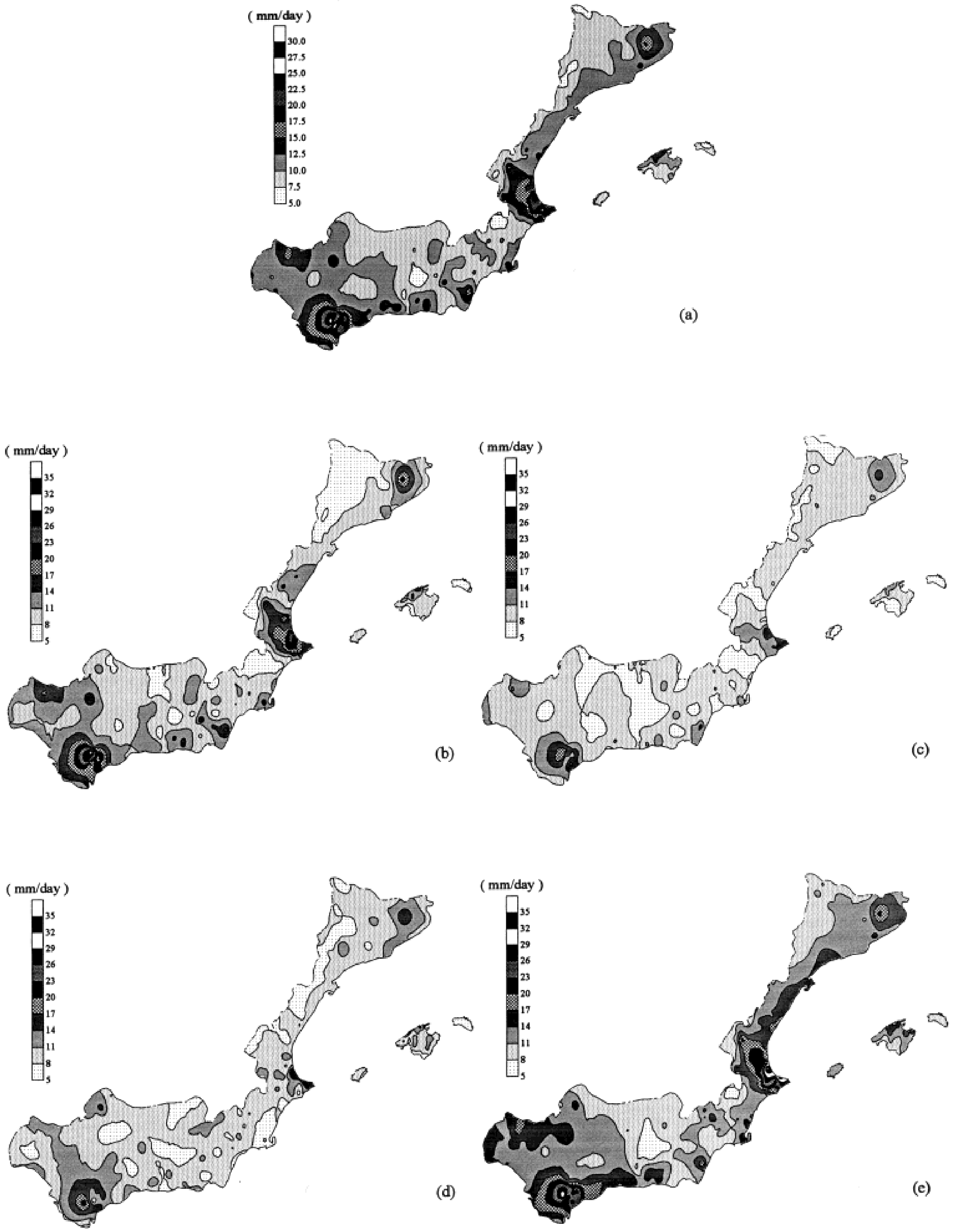

Figure 7. Mean rates of daily rainfalls, computed from (a) third decade; (b) winters of third decade; (c) springs of third decade; (d) summers of third decade; and (e) autumns of third decade. Note the different scale of (a) and the other maps

the precipitation character results for the second decade. However, during the first decade some particularities arise: the maximum rates in western Andalucía are found in winter; in the eastern part of the domain, winters and springs are more similar in this case, but autumns intensify their rates still more.

A direct demarcation of the torrential zones of Mediterranean Spain can be done by visualizing the calculated recurrence intervals. In this case, we only display recurrence intervals for the third decade, but the other decades are also considered. For 100 mm daily rainfalls (Figure 8(a)), recurrence intervals less than 5 years are obtained around Sierra de Aracena, in a wide zone around Gibraltar Strait, in very localized zones of eastern Andalucía close to the coast or at high altitudes, in Murcia and Valencia, in the littoral of northern and southern Catalonia, zones of Pyrenees, and north and east of Mallorca. For 200 mm (Figure 8(b)), periods smaller than 75 years are in general restricted to coastal lowlands and exposed slopes. In summary, the most torrential zones, invariably obtained in all decades, are: Sierra de Aracena area, slopes around Sierra de Ronda facing toward the Mediterranean or Atlantic ocean, Gibraltar Strait area, elevated areas of Sistema Subbético and Sistema Penibético, coastal zones in the South and Southeast, Murcia and Valencia in general except in the interior, coastal zones of southern Catalonia, northeast of Catalonia, and Sierra de Tramuntana.

4.4 Mean duration of wet and dry episodes

Finally, in this section we analyze the yearly and seasonal averaged persistence of wet and dry periods. Figure 9, corresponding again to the third decade, shows that on the yearly average, the most persistent wet periods occur in the Atlantic subordinate areas of the west and north, with maximums in the mountains. Two-days persistences are exceeded in Sierra de Aracena, Gibraltar Strait/Sierra de Ronda, Sierra de Cazorla, Sistema Subbético and Pyrenees. An exception is again Sistema Penibético. Sierra de Aitana area, Menorca and north of Mallorca have also relatively important values. As expected, the sheltered Southeast and interior Catalonia areas are mainly controlled by occasional rainfalls. In the Southeast, this characteristic is still more evident at first and second decade maps (not shown).

In Andalucía, areas with persistences over 1.95 days were even more extensive in the previous decades. On the contrary, in the Southeast, Valencia and Balearic Islands, the third decade precisely gives the longest wet periods (about 0.20 days longer). The general lower persistences in the pure Mediterranean zones of the east (notably during the first and second decades), can be explained by two factors: Mediterranean cyclones are normally small in size and consequently evolve rapidly; under the longer Atlantic regimes, intermission of wet days frequently occurs because these regimes are not very effective in that area.

An inspection of seasonal maps (not shown), determines that: the lowest wet persistences in all zones are obtained during summer, with the maximum values occurring in the mountains; in central and western Andalucía the longest wet episodes occur in winter (averages of up to 2.5 days in Sierra de Aracena, Sierra de Ronda, Sierra de Cazorla and Sistema Subbético), followed by spring and autumn. In the Pyrenees, the persistence maximum is found in spring; the rest of the territories do not reveal a uniform hierarchy of seasons, but in general there is a preference for autumn and winter.

Figure 10(a) displays the yearly mean duration of dry episodes during the third decade. The highest persistences (greater than 12 days) occur in the southern extreme of the region, practically in all the Southeast, and in the south of Valencia. But dry period durations greater than 10 days are general except in mountainous interior areas, major part of Catalonia, centre and north of Mallorca, and Menorca. Similar patterns can be deduced from previous decades (not shown).

It is noteworthy that the mountainous north of Mallorca presents as low values as the Pyrenees. But this is not unexpected since the north of Mallorca and Menorca can positively participate in the many frontal systems coming from the west and northwest. In addition, northerly to northeasterly winds produced by frequent cold season Genoa Gulf cyclones, induce orography-enhanced rainfalls in these exposed areas.

Winter, spring and autumn maps (not included) show a general decrease of dry persistences from southeast (10–15 days) to west and north (the most extreme values are found in western Pyrenees, with less than 5 days). The second decade drier autumns also affect this variable in the form of a general

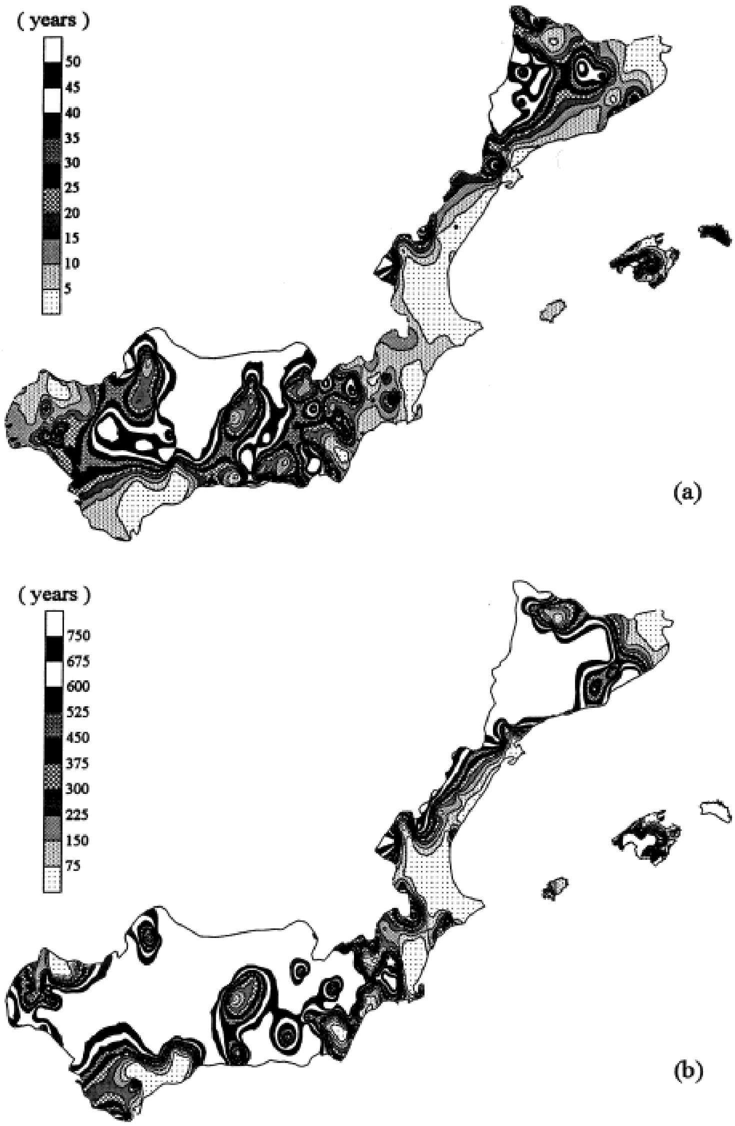

Figure 8. Recurrence intervals computed from the third decade: (a) for 100 mm events; and (b) for 200 mm events

increase of almost 5 days in the persistences, except in northern Catalonia and Balearic Islands. The high persistences obtained (in general in the 5–15 days range) reflect that Mediterranean wet periods are very limited in number and quite concentrated in time. Typically, these wet periods are interrupted by Atlantic blocking anticyclones that remain over several days or weeks.

Exceptional spatial differences are found during the summer season (Figure 10(b)). There is a strong north–south gradient. Average dry periods lasting as much as 40–50 days are found in southern Andalucía, whereas in the Pyrenees mountains similar or even smaller values to those of the other seasons are obtained. As expected, therefore, this field is critically dependent on latitude and it is not exaggerative to affirm that rainfalls simply do not occur in southern Andalucía during the full summer. Nevertheless, the summer droughts were not so severe, especially in Andalucía, during the previous decades (maps not shown).

In general, the yearly averaged dry presistences of Figure 10(a) are the result of a balance between the latitude-modulated summer persistences, and the relative incidence of the cold season precipitating systems. Thus, the Southeast, where low-latitude high persistences during summer combine with a dominant sheltering effect during the cold seasons, presents the highest yearly values (Figure 10(a)). Although the summer is still more critical in southwest Andalucía, the cold seasons are so substantial there, that the yearly averages are not so bad. Since the wet Pyrenees area remains unaffected by the summer droughts (see Figure 10(b)), we find therein the lowest dry persistences (less than 6 days in its western part, Figure 10(a)).

5. CONCLUSIONS

A daily rainfall data base for the 1964–1993 period has been compiled for the Mediterranean regions of Spain, based on 410 regularly distributed raingauge stations. The coverage was found to be suitable to permit studies on rainfall spatial and time variability. In this paper we have analysed, individually for three consecutive decades (1964–1973, 1974–1983, 1984–1993), the spatial distributions of yearly and seasonal means of different parameters that characterize, in an average sense, the rainfalls of the region: their cumulative amounts, frequencies, intensities, and persistence or absence. Special attention has been directed to delimit the heaviest precipitation zones. For that purpose, recurrence intervals have been also calculated.

The results obtained have permitted a broad intercomparison among geographical zones in which the relevant geophysical and seasonal factors exert a variable influence. The first source of contrast is found between favorably exposed uplands (e.g. Sierra de Ronda, Sierra de Aracena, Sierra de Cazorla, Sistema Subbético, Sierra de Aitana, Sierra de Tramuntana and Pyrenees), and sheltered lowlands (interior of Catalonia and Southeast principally). A larger scale differentiation can be made between zones where Atlantic influences are quite substantial (western and northern Andalucía, northern Catalonia), and those others which principally rely on the Mediterranean dynamics (from eastern Andalucía to southern Catalonia especially). Despite the temptation to include the Balearic Islands among these last zones, such connection is not clear from some of the analyzed products. In some respects, northern Mallorca and Menorca are more similar to central and northern Catalonia, since both regions are affected by the

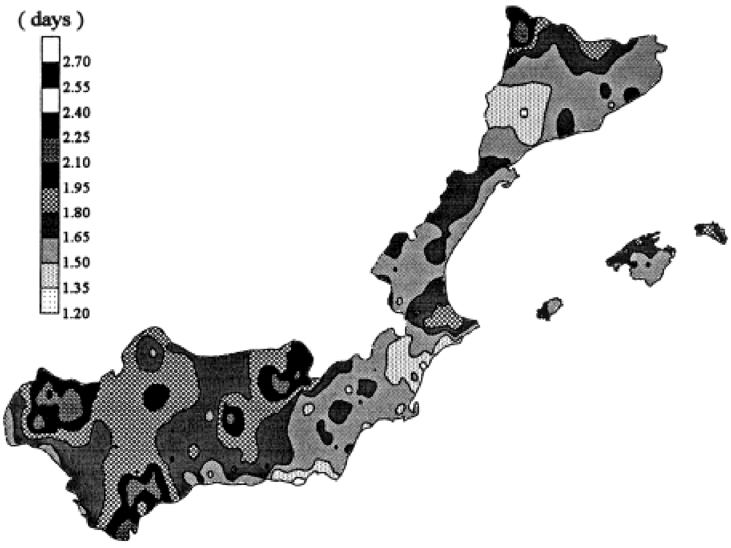

Figure 9. Mean duration of wet episodes, for third decade

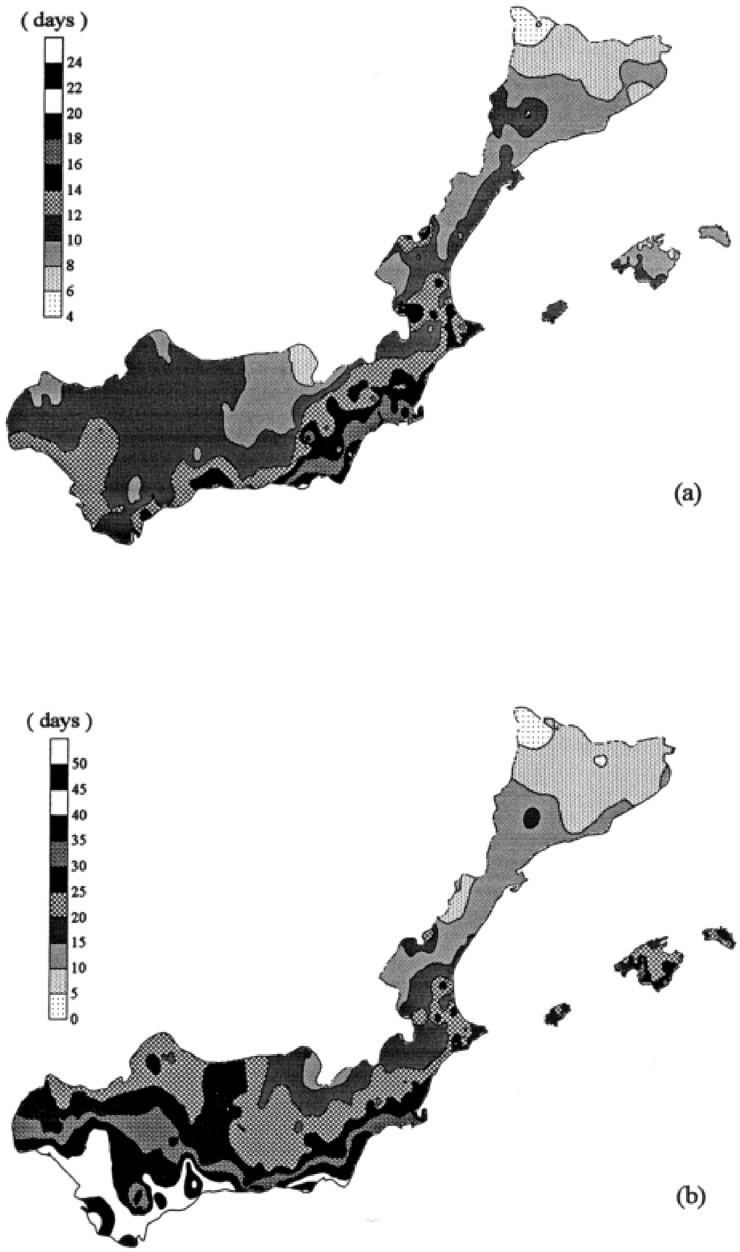

Figure 10. Mean duration of dry episodes: (a) for third decade; and (b) for summers of third decade. Note the different scale of the maps

low-pressure systems circulating at higher latitudes. An additional distinction should be made between coastal areas and interior zones. In the former, and especially during the convective fall, rainfalls often adopt a torrential character; this characteristic is especially maximized about Sierra de Ronda and Sierra de Aitana. Finally, a sharp transition from extremely dry zones of southern Spain toward the wet Pyrenees is imposed by latitude during summer.

With respect to relevant changes along the three decades, the main findings can be reduced to: a successive drying in western Catalonia, and central and western Andalucía; dry 1974–1983 decade in Mediterranean-governed zones (except Balearic Islands) because of anomalous autumns. We are aware, however, that a 30-year period is not enough to fully encompass any climatic variability signal, so those changes should be cautiously considered.

In the last years, with the increasing water demand by agricultural and industrial activities, and more importantly by intense summer tourism, the hydrological debate has become an affair of first order in this semiarid region. Paradoxically, appreciable damages on the infrastructures and several deaths occur every year as a result of torrential episodes. The 'desertification' process is an authentic problem in the Southeast, where prolongated dry periods are suddenly interrupted by highly erosive torrential rains. The first step to assess any evidence of climatic change in the future, or to anticipate water management strategies, is an objective characterization of the recent climate by means of its elements, in this case the precipitation. This paper is a contribution to that task, but future work is certainly needed.

The results obtained, for their coherence and interpretability, are encouraging in terms of the possibilities that the region offers for complementary studies concerning with its pluviometric regionalization, as well as the identification of the main daily rainfall spatial patterns and responsible synoptic situations. Such studies (under development at present) have to deal with daily rainfall which, as opposed to the integrated quantities considered in this paper, is a very complex variable subjected to extreme space and time variability. Undoubtedly, application of modern techniques of principal component analysis and cluster analysis (e.g. Bonell and Sumner, 1992; Fowell and Fowell, 1993; Sumner *et al*., 1993; Cacciamani *et al*., 1994; Kidson, 1994a,b; Gong and Richman, 1995; Sumner *et al*., 1995a,b) will help to deal with the problem.

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