

# REGIONALIZATION OF PENINSULAR SPAIN BASED ON THE LENGTH OF DRY SPELLS

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## ABSTRACT

Firstly, the number of dry spells made up of consecutive dry days with thresholds more than or equal to 0.1, 1.0 and 10.0 mm have been taken into account, as well as the days comprising them, from 35 observatories in Peninsular Spain, for the period 1951–1990 and they have been represented on maps. In a like fashion, the longest spells, of length equal to or greater than 7, 15, 30, 60, 90 and 120 days, and the number of days comprising them, for a threshold of 0.1 mm, have been taken into account and mapped. In a great part of Spain, the mean and maximum lengths of the dry spells are very high. Secondly, Markov chains of different orders, up to the tenth-order, have been used to fit the duration of dry spells of different lengths, with a 0.1 mm threshold. The adjustment of the general distribution of the dry spells according to their length and the adjustment of the longest spells, those that exceed 1, 2 or 3 months duration, have been considered. The goodness (or not) of the adjustments permits regionalization of the country, showing up three types of behaviour: one, a Markovian in which the adjustments are acceptable, in the north of Spain; a second, with good general adjustment, but with notable discrepancies between the empirical values and those estimated for the longest spells, in a central area; and a third, in which both adjustments have to be rejected, and so drought can not be considered a Markovian phenomenon, in the south. Copyright © 1999 Royal Meteorological Society.

KEY WORDS: dry spells; Markov chains; regionalization; Spain; drought

## 1. INTRODUCTION

The definition of dry spells based on the length of the sequences consisting of days without precipitation has been widely used. The advantage of this procedure rests in the clarity of the criteria and in the ease of applying statistical or specific stochastic analysis to dry spells or dry periods of different resultant length. This type of analysis can be done on dry spells that use different rainfall thresholds in the definition of a dry day, such as more than or equal to 0.1, 1.0, 10.0 mm, etc. Using thresholds such as 10.0 mm eliminates the excessive weight that some isolated rainy days with small amounts have in breaking the long dry spell, without really putting an end to the drought.

In the case of Mediterranean Spain (Martín-Vide, 1994), the duration of dry spells reaches very high values, in accordance with total rainfall measurements, which are generally modest and spread over a few days of intense precipitation. Moreover, the subtropical Mediterranean dynamics themselves, in a very dry summer, assure the existence in a great part of the country, almost every year, of long dry spells greater than one or more months.

Amongst the most frequently used stochastic procedures for the treatment of wet and dry spells are the Markov chains of different orders. In fact, for wet spells, the results obtained through them show a close fit as numerous studies since the 1960s confirm (Gabriel and Neumann, 1962; Caskey, 1963; Eriksson, 1965; Todorovic and Woolhiser, 1975; Haan *et al.*, 1976; Chin, 1977; Katz, 1977; Buishand, 1978; Stern,

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1982; Cárdenas, 1989; Dahale *et al.*, 1994; Moon *et al.*, 1994). On the contrary, they have been used much less frequently for dry spells (Berger and Goossens, 1983; Nobilis, 1986; Douguedroit, 1987), because of the high persistence of days without precipitation in many climatic zones, which reduces the goodness of the adjustments.

In Spain, the first climatological studies that make use of Markov chains are those of Domínguez (1973), Burgueño (1981), Martín-Vide (1981) and Raso (1982), which calculate the probabilities of the occurrence of rainy days and other conditional probabilities for Malaga, Barcelona, the south Mediterranean coast of the Iberian Peninsula and Palma de Mallorca, respectively. Their exclusive application in the case of dry spells has been carried out by authors since the 1980s (Martín-Vide and Moreno, 1985; Martín-Vide *et al.*, 1992; Conesa and Martín-Vide, 1993; Gómez, 1997).

In the present work, Markov chains of different orders, up to the tenth-order, have been used to adjust the duration of dry spells of different lengths, adopting a threshold of  $\geq 0.1$  mm to define a rainy day. The goodness or not of the fit permits regionalization of the country and considers the drought as Markovian or not. By using daily data, regionalization through Markov chains increases the seasonal resolution of regionalizations based on annual totals, and permits showing similar behaviour in the persistence of dry days. This parameter is of great importance in dry or arid areas. If the length of the dry spells does not adjust to Markov models, it remains evident that the length of the drought is great, which denotes the subtropical character of the precipitation.

In order to evaluate the suitability of the Markovian models, two criteria are considered in each observatory: (i) the adjustment of the general distribution of dry spells according to their length and (ii) the adjustment of longer periods, i.e. those that exceed a determined number of days, such as 1, 2 or 3 months. In this way it is possible to distinguish three types of behaviour: one, Markovian, in which the two fits are significant; a second, with good general adjustment but with notable discrepancies between the empirical values and those estimated by the model for the longer spells; and a third, in which both adjustments have to be rejected and, therefore, the drought cannot be considered a Markovian phenomenon.

In the case of the first-order Markov chain, the probability that a dry spell will last exactly  $n$  days is given by:

$$Q_n = p_{00}^{n-1} \cdot p_{01} = p_{00}^{n-1} \cdot (1 - p_{00}),$$

where  $p_{00}$  is the probability of a dry day following a dry day and  $p_{01}$  the probability of a rainy day following a dry day.

In the second-order Markov chain, the same probability is expressed as:

$$Q_n = p_{100} \cdot p_{000}^{n-2} \cdot p_{001}, \quad \text{for } n \geq 2$$

$$Q_1 = p_{101},$$

where  $p_{100}$  is the probability of a dry day following a dry day and the day before is rainy;  $p_{000}$  is the probability of a dry day after two dry days; and  $p_{001}$  the probability of a rainy day after two dry days.

For the third-order Markov chain:

$$Q_n = p_{1000} \cdot p_{0000}^{n-3} \cdot p_{0001}, \quad \text{for } n \geq 3$$

$$Q_2 = p_{1001}$$

And so on.

Therefore, the first-order Markov chain only takes into account the state—wet or dry—of the day preceding a given one. In the same way, the second-order considers the states of the two preceding days, the third-order, of the three preceding days, and so on. Consequently, the greater the order of the chain, the greater the consideration of the persistence of each one of the states. Markov chains of up to order ten have been applied. Raising the order increases unnecessarily the task of calculations without incorporating new observatories to the group of those that show Markovian behaviour.

## 2. SELECTED OBSERVATORIES AND DATA

Thirty-five observatories of the Instituto Nacional de Meteorología (Spanish Institute of Meteorology) were selected for the period 1951–1990, being representatives of the different types of climate existing in peninsular Spain. The complex and divided Spanish orography is not, however, well-reflected in the selection of observatories, because the number of observatories with reliable data in middle and high mountain areas is low. With the spatial cover guaranteed, preference was given to the observatories with the most continuous and reliable records, with a maximum of 14610 values of presence or absence of precipitation (Table I and Figure 1). It was decided not to complete the gaps in the data, given that since it was a question of dealing with daily values in some latitudes where the precipitation is of a character more convective than generalized, the correlations between the observatories are very low and not significant. Moreover, the Markov method uses only the dichotomic value of the existence (or not) of daily precipitation, with the chosen threshold, and not its quantity. At all events, the sample of 12648 days used for Vigo, the observatory with fewest data (about 87% of the possible maximum) is sufficiently wide for its results to be used in the whole analysis.

Table I. Observatories, code map and number of analysed days

Observatory	Code map	Number of days
Albacete	1	14 610
Alicante	2	14 600
Almeria	3	14 610
Avila	4	13 483
Barcelona	5	14 535
Burgos	6	14 610
Caceres	7	14 610
Cadiz (San Fernando)	8	14 610
Ciudad Real	9	14 610
Cordoba	10	13 789
Coruña, La	11	14 610
Cuenca	12	14 610
Gerona	13	14 013
Gijon	14	14 590
Granada	15	14 610
Huelva	16	14 610
Huesca	17	14 569
Leon	18	14 610
Lerida	19	14 610
Logroño	20	14 610
Madrid	21	14 610
Malaga	22	14 610
Murcia	23	14 610
Orense	24	12 907
Pamplona	25	13 879
Salamanca	26	14 610
San Sebastian	27	14 610
Santander	28	14 561
Seville	29	14 610
Soria	30	14 610
Tortosa	31	14 610
Valencia	32	14 500
Valladolid	33	14 576
Vigo	34	12 648
Zaragoza	35	14 610

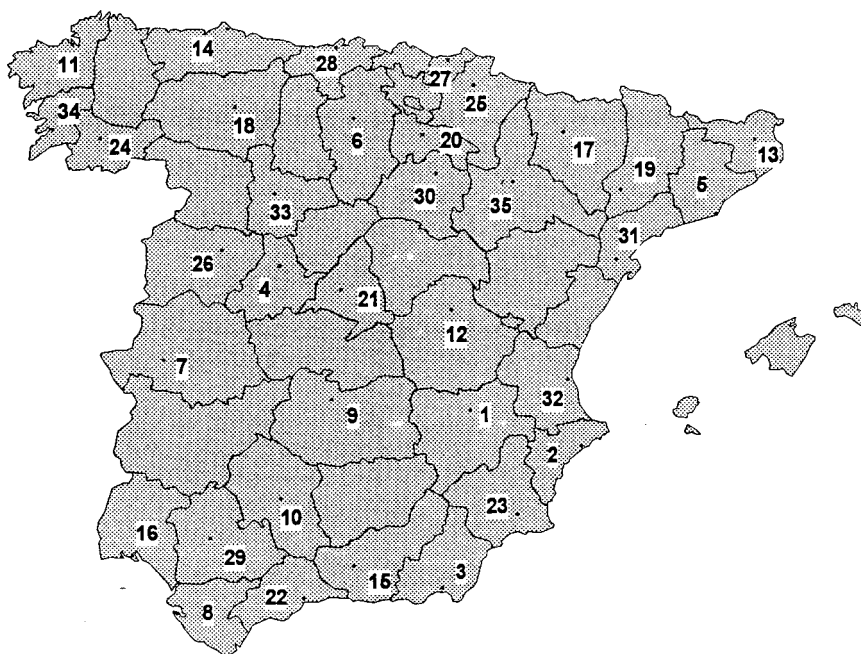


Figure 1. Location of the observatories

### 3. MEAN LENGTH OF DRY SPELLS WITH A 0.1 mm THRESHOLD

With a 0.1 mm threshold, the minimum quantity of precipitation that the official pluviometer in Spain records, the percentage of dry days in the northern fringe with oceanic climate is less than 65% of total days, with the minimum in San Sebastian (48.5%). At the opposite extreme, the southeast of the Iberian Peninsula, which is the driest area, has more than 85% of dry days, with the maximum in Almeria (88.1%). A great part of peninsular Spain has a percentage of days without precipitation lying between 65 and 85%. The isopleths show a certain latitudinal disposition in the west of Spain and parallel to the Mediterranean coast in the east. (Figure 2)

The mean length of dry spells with a 0.1 mm threshold gives a good idea of the great pluviometric variation existent in Spain. While in the northern fringe, the length of the dry spells does not exceed 5 days, with less than 4 on the Cantabrian coast, on the south Mediterranean coast the dry periods exceed an average of 10 days. Along the approximately 800 km length of the meridian 2°W, the dry spells multiply their duration by 3.5, from 3.1 days in San Sebastian to 12.1 days in Almeria. The increase in length from north to south is clear, with the isopleths adopting a quasi-zonal disposition (Figure 3).

### 4. MEAN LENGTH OF DRY SPELLS WITH 1.0 mm AND 10.0 mm THRESHOLDS

With the 1.0 mm threshold, the percentage of dry days increases between 3% and somewhat less than 13% with respect to the corresponding 0.1 mm threshold figures. Now it is the 70% isopleth that limits the northern ocean fringe from the rest of Spain. In the southeast of Spain the number of dry days with the new threshold exceeds 90% of the total. Extreme values are given once again in San Sebastian (59.8%) and in Almeria (92.1%) (Figure 4).

The mean length of the dry spells with the 1.0 mm threshold presents values of less than 6 days in the northern oceanic fringe, to equal to or more than 14 days in the southeast. The duration increases by four times between San Sebastian (3.7 days) and Almeria (16.2 days). The isopleths present a subzonal

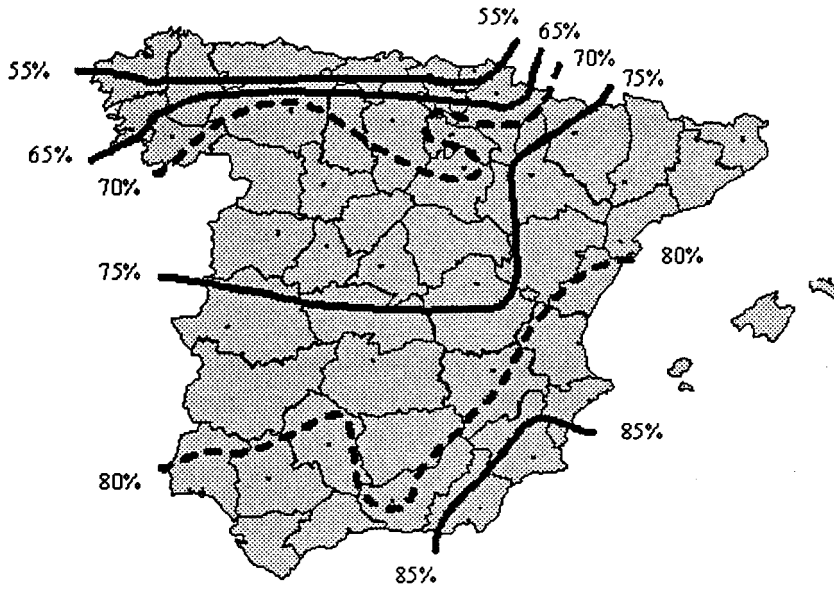


Figure 2. Percentages of the dry days with the  $\geq 0.1$  mm threshold

disposition that reflects the increase in drought conditions from the north of Spain to the southeast of the country, where the driest places of continental Europe are found (Figure 5).

With the 10 mm thresholds, in the whole of peninsular Spain, except in two Cantabrian observatories, San Sebastian and Santander, and in Vigo, on the Galician coast, the percentage of dry days exceeds 90% of the total. The extremes are found in Vigo (82.4%) and Almeria (98.2%) (Figure 6).

The mean length of dry spells with the 10.0 mm thresholds aggravates the pluviometrical differences between north and southeast, with less than 10 days (8.7 in San Sebastian and 9.2 in Vigo) to more than 50 days (59.3 in Almeria), respectively, as extreme cases. In the corresponding map (Figure 7), the

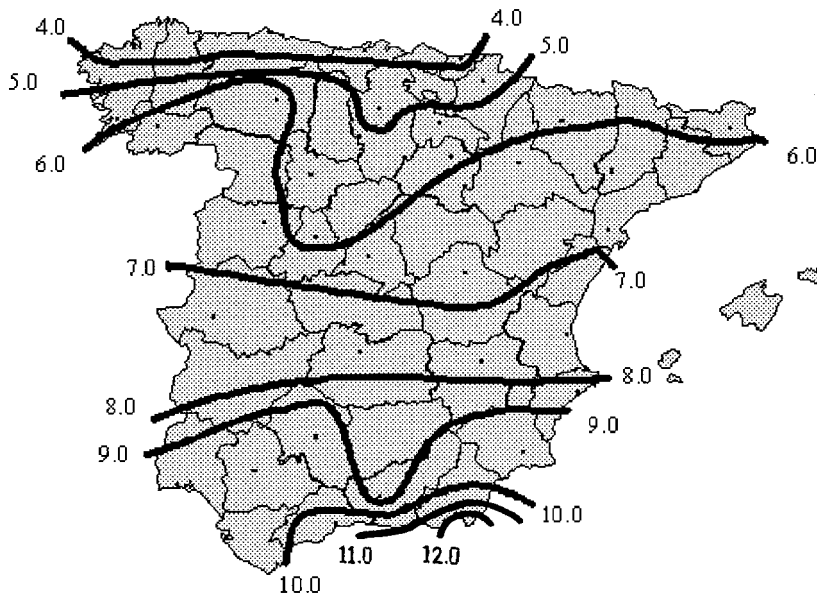


Figure 3. Mean length, in days, of the dry spells with the  $\geq 0.1$  mm threshold

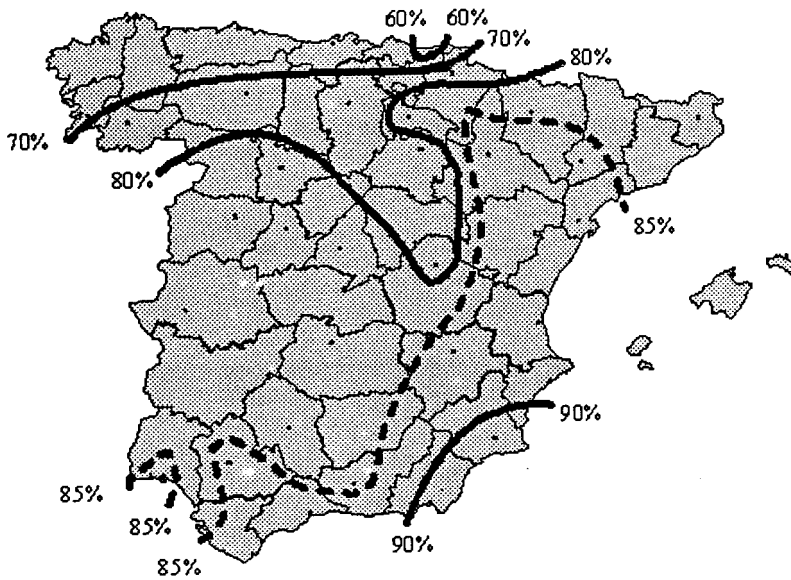


Figure 4. Percentages of the dry days with the  $\geq 1.0$  mm threshold

relatively low values for west Andalusia, compared with east Andalusia and the southeast are notable. This reflects the great difference in the productive mechanisms of the precipitation between one area and another. While in the southwest of Spain, the rains are copious and persistent with southwesterly and westerly Atlantic gales during the cold half of the year, the southeast of the country lies to leeward of the Atlantic influence, there being numerous dry spells in the depths of winter with the 10 mm threshold.

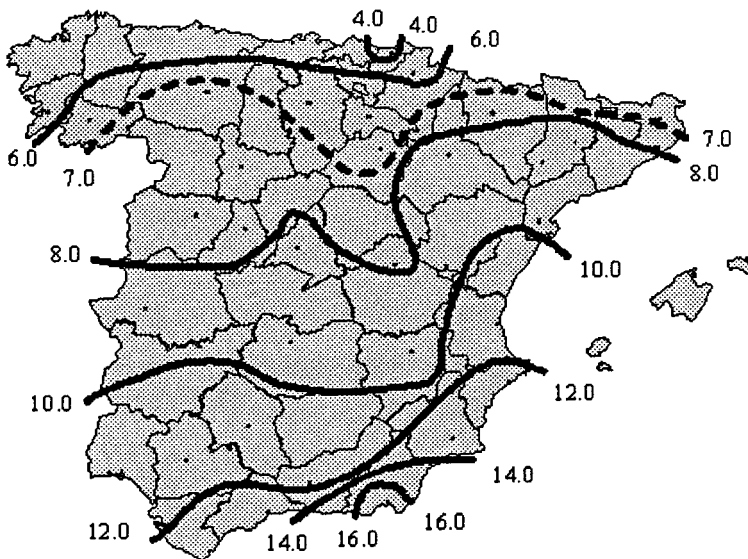


Figure 5. Mean length, in days, of the dry spells with the  $\geq 1.0$  mm threshold

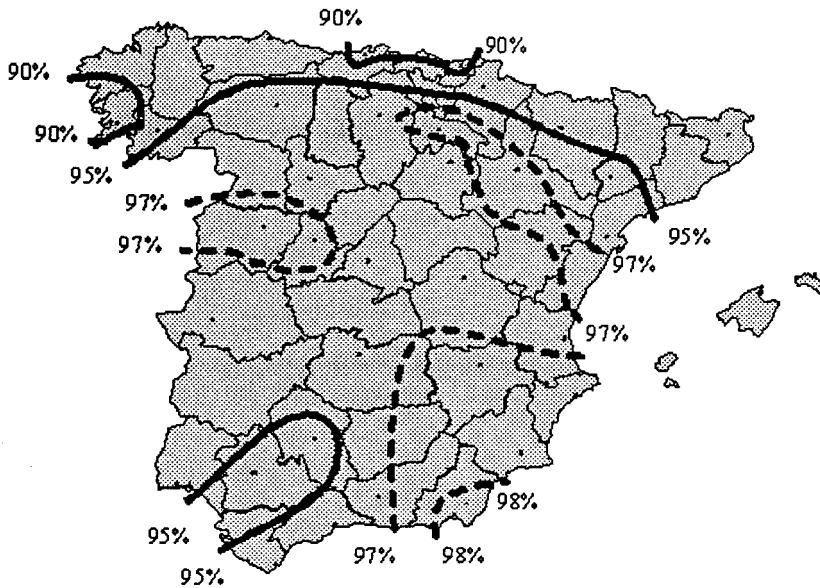


Figure 6. Percentages of the dry days with the  $\geq 10$  mm threshold

### 5. THE MAXIMUM LENGTHS OF THE DRY SPELLS

The maximum lengths of the dry spells with the three thresholds of 0.1, 1.0 and 10.0 mm are compiled in Table II. Most outstanding is the extraordinary lengths of the dry spells in Andalusia and in other parts of the southern half of Spain. Based on the values shown for the 0.1 mm threshold, it can be affirmed that in the said region there have been episodes of more than 4 months, and even of more than 5 months, without any appreciable pluviometrical record. There are eight analysed observatories where the greatest dry spell exceeds 4 months duration: Caceres (126 days), San Fernando (129), Albacete (138), Seville (140)

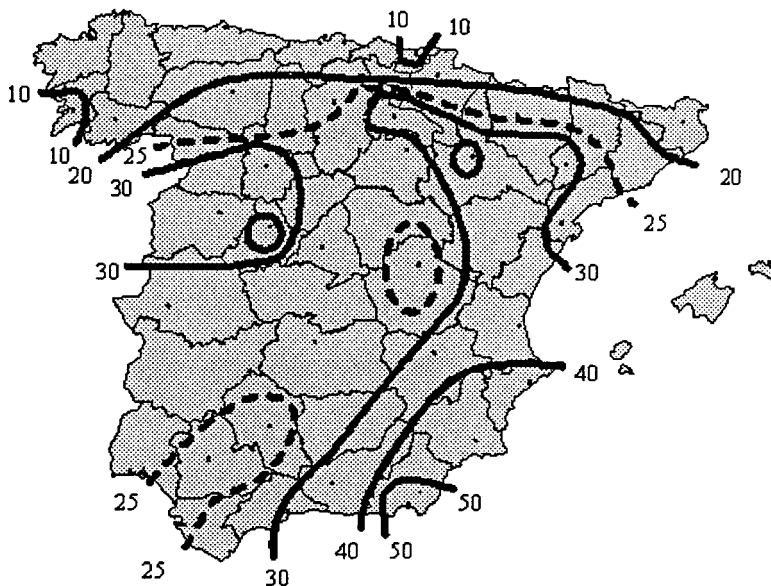


Figure 7. Mean length, in days, of the dry spells with the  $\geq 10$  mm threshold

Table II. Maximum length (in days) of the dry spells with the 0.1, 1.0 and 10.0 mm thresholds

Observatory	Thresholds (mm d <sup>-1</sup> )		
	0.1	1.0	10.0
Albacete	138	138	263
Alicante	96	106	343
Almeria	156	179	363
Avila	77	98	306
Barcelona	59	66	180
Burgos	59	77	189
Caceres	126	112	206
Cadiz	129	153	231
Ciudad Real	96	96	326
Cordoba	144	150	205
Coruña, La	35	46	192
Cuenca	75	86	192
Gerona	51	74	117
Gijon	37	52	178
Granada	112	130	237
Huelva	169	176	265
Huesca	66	72	169
Leon	64	64	208
Lerida	79	102	234
Logroño	63	74	299
Madrid	102	122	205
Malaga	166	190	247
Murcia	96	123	299
Orense	74	74	167
Pamplona	63	80	162
Salamanca	71	82	274
San Sebastian	30	40	63
Santander	39	61	112
Seville	140	155	219
Soria	54	63	245
Tortosa	61	76	227
Valencia	61	120	288
Valladolid	69	81	233
Vigo	42	93	132
Zaragoza	80	92	275

and Cordoba (144), besides Almeria, Malaga and Huelva, which exceed 5 months duration. Almeria has a dry spell of 156 days, Malaga one of 156 and another of 166, and Huelva the longest, with 169 days. On the contrary, in San Sebastian, the longest period without appreciable precipitation did not exceed a month.

With the 1.0 mm threshold, the maximum length of the dry spells exceeds 5 months in the southern zone of the Iberian Peninsula, the extreme value being given in Malaga, with one spell of 190 days, more than half a year without even 1 mm falling in a day. On the contrary, the longest spell of this type in San Sebastian was 40 days.

Finally, with the 10 mm threshold, two observatories in southeast Spain, Alicante and Almeria have had droughts lasting more than 11 months in which 10 mm was not reached in any one day. Alicante has a dry spell of this type of 343 days and Almeria of 363, practically a whole year without measuring 10 mm or more of precipitation.

## 6. THE LONGEST DRY SPELLS WITH 0.1 mm THRESHOLDS

In the analysis of the daily structure of the drought, the longest dry spells are those that present the greatest interests. It is then a question of analysing the tails of the general distribution of the dry spells according to their length. As regards the adjustments by using Markov chains, only the results for a threshold of 0.1 mm are going to be presented.

The numbers of dry spells of length equal to or more than 7, 15, 30, 60, 90 and 120 days as well as the total number of days comprising them are compiled in Table III. With respect to the number of dry spells equal to or more than a week long, most of them are found not in the southeast of the Iberian Peninsula, but in the Ebro valley, with more than 600 cases during the period of analysis in Zaragoza and Tortosa (Figure 8(a)). This shows up the arid conditions in the middle of the Ebro basin. The values are not very different, because the 7 days duration is a relatively small threshold, that does not discriminate well between the pluviometrical differences between the north and south of Spain. Nevertheless, on taking into account the total number of days that form part of the dry spells of 7 days or more duration the values obtained do show the pluviometrical contrasts of the country, with minimum in San Sebastian (2389 days) and maximum in Almeria (11406 days) (Figure 8(b)).

For the dry spells of a half month or more in length, the extreme number of cases and total days are found in the same observatories, San Sebastian (24 spells and 438 days) and Almeria (276 spells and 9051 days). The Cantabrian coast has recorded less than 50 cases, while a great part of the south Mediterranean and southeast coast, more than 8000.

All the observatories analysed have at least one dry spell lasting equal to or more than a month. From one single case 30 days long, recorded in San Sebastian, to 104 spells totalling 5497 days in Almeria. The north-south gradation is clear (Figure 9(a) and (b)) with less than five spells in oceanic climate Spain to more than 75 in a great part of Andalucia and with less than 100 days on the Cantabrian coast and north of Galicia to more than 5000 on wide stretches of the Andalusian coast.

On taking into account the dry spells of 60 days or more, nine observatories, all situated in the north of Spain, appear without a single case. That is to say, in them there is no period without precipitation of at least 2 months duration, in the 40 years analysed. On the contrary, more than ten cases, that is to say more than one episode every 4 years, appear in the southern one third of the country, with more than 30 cases in west Andalucia, to the maximum in Huelva (38). With this threshold, the peninsular southeast leaves the leadership, as regards extreme values, to the southwest sector. The southern one third of the country gives a total of 1000 days of this type of dry spell, with maxima greater than 3000 in Malaga and, above all, in Huelva (3651 days). Although bathed by the Atlantic, the climate of the southwest of Spain is as Mediterranean as that of the southeast of the country. This explains why the number of long dry spells, for certain thresholds, in the southwest can be as high as or higher than the number in the southeast. The practical absence of precipitation in two months is very common in the southwest of the country.

In the period analysed there is no recorded dry spell of at least 90 days in the approximate northern half of peninsular Spain. On the contrary, droughts lasting three months or more are recorded with a return period of 2 years in Huelva (21 cases) and in Malaga (22 cases) (Figure 10(a)). Such spells have totalled more than 2300 days in the said cities (Figure 10(b)). This result emphasizes the significance and intensity of dry spells in the south of Spain, in accordance with the subtropical nature of its climate, reflected especially in a very dry summer. It has to be noted, however, that Huelva and Malaga have annual amounts close to 500 mm, far removed from the minima, less than 250 mm for southeast Spain. Likewise, it is worthy to remember that not far from the said cities there are some very outstanding pluviometrical nuclei. Particularly outstanding is the Grazalema mountain range, between Cadiz and Malaga, with an annual mean of 2300 mm, where the number of long dry spells has to be very high, because the summer is very dry, by the predomination, as in the rest of the south of Spain, of anticyclonic subtropical conditions in the middle and upper troposphere. Grazalema has records of null precipitation in many months of July, and even in 2 and up to 3 consecutive months (López Muñoz, 1988). In this area, on the contrary, the winter precipitations are usually copious, caused by the relief barrier effect on the moist southwesterly winds that enter by the Gulf of Cadiz.

Table III. Numbers of dry spells of length equal to or more than 7, 15, 30, 60, 90 and 120 days (0.1 mm threshold) and the total number of days comprising them

0.1 mm d <sup>-1</sup>	Length (d)											
	7		15		30		60		90		120	
	No. dry spells	Total days	No. dry spells	Total days	No. dry spells	Total days	No. dry spells	Total days	No. dry spells	Total days	No. dry spells	Total days
Albacete	559	8927	221	5604	51	2164	5	409	1	138	1	138
Alicante	569	9779	241	6540	66	2991	9	671	3	280	0	0
Almeria	518	11 406	276	9051	104	5497	29	2421	9	946	1	156
Avila	463	6722	161	3851	32	1267	2	142	0	0	0	0
Barcelona	597	8182	185	4136	23	920	0	0	0	0	0	0
Burgos	480	6153	126	2740	12	491	0	0	0	0	0	0
Caceres	483	8991	222	6404	69	3345	15	1257	4	462	2	252
Cadiz	456	9635	194	7020	77	4698	34	2988	13	1423	2	258
Ciudad Real	505	8900	226	6144	61	2807	11	838	1	96	0	0
Cordoba	439	9196	219	7029	73	4131	26	2244	9	995	2	283
Coruña, La	374	4163	73	1411	1	35	0	0	0	0	0	0
Cuenca	516	7601	183	4348	36	1435	1	75	0	0	0	0
Gerona	543	7068	150	3281	18	684	0	0	0	0	0	0
Gijon	324	3351	38	726	2	71	0	0	0	0	0	0
Granada	503	9378	214	6571	77	3879	17	1461	7	709	0	0
Huelva	440	10 018	202	7705	76	5128	38	3651	21	2392	6	817
Huesca	587	7976	177	4003	29	1095	1	66	0	0	0	0
Leon	506	7484	180	4197	34	1403	2	128	0	0	0	0
Lerida	587	8428	192	4557	40	1598	3	208	0	0	0	0
Logroño	524	6615	148	3034	11	419	1	63	0	0	0	0
Madrid	503	7946	183	4780	44	1998	8	591	1	102	0	0
Malaga	481	10 694	236	8315	83	5213	33	3150	22	2369	4	585
Murcia	570	10 403	265	7339	68	3318	17	1216	1	96	0	0
Orense	419	6388	152	3845	36	1511	5	332	0	0	0	0
Pamplona	449	5307	91	1873	8	326	1	63	0	0	0	0
Salamanca	501	7793	196	4869	45	1815	5	320	0	0	0	0
San Sebastian	242	2389	24	438	1	30	0	0	0	0	0	0
Santander	295	3042	34	629	1	39	0	0	0	0	0	0
Seville	464	9944	225	7571	76	4580	34	2921	13	1365	1	140
Soria	516	6503	130	2831	15	550	0	0	0	0	0	0
Tortosa	617	8188	176	3898	26	1000	1	61	0	0	0	0
Valencia	598	9111	225	5446	50	1884	1	61	0	0	0	0
Valladolid	517	7313	165	3945	30	1194	2	134	0	0	0	0
Vigo	363	4650	106	2182	4	146	0	0	0	0	0	0
Zaragoza	609	8677	203	4721	35	1382	3	205	0	0	0	0

Finally, there are eight observatories, all in the southern half of Spain, in which dry spells have been recorded that equal or exceed 4 months duration: Seville, Almeria and Albacete have once exceeded 120 consecutive dry days; Caceres, Cordoba and San Fernando have two spells of this type; Malaga has four, totalling 585 days, and Huelva six, totalling 817 days. Of these spells, one exceeded 5 months duration in Almeria, another in Huelva (the longest, 169 days) and 2 in Malaga.

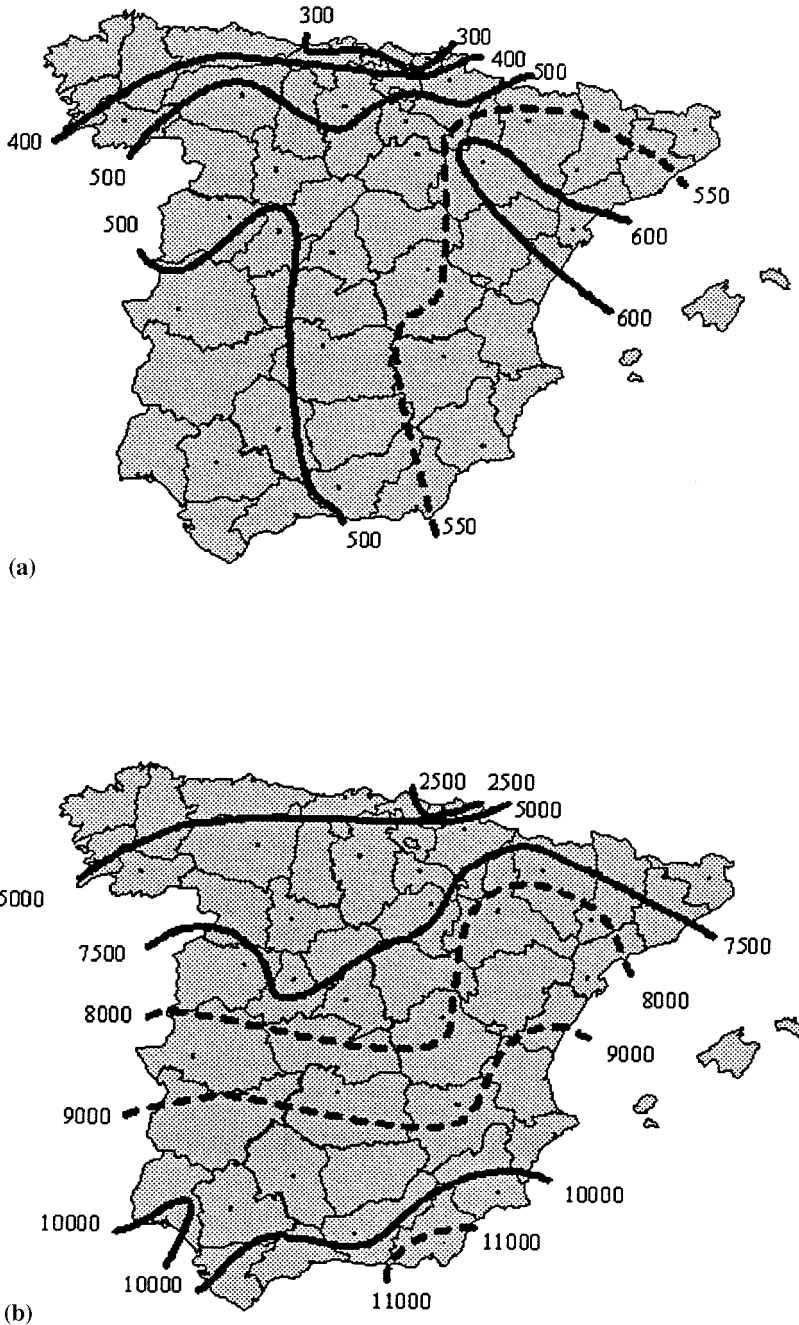


Figure 8. (a) Number of dry spells equal to or more than 7 days duration with the  $\geq 0.1$  mm threshold. (b) Total number of days that form part of the dry spells of 7 days or more duration

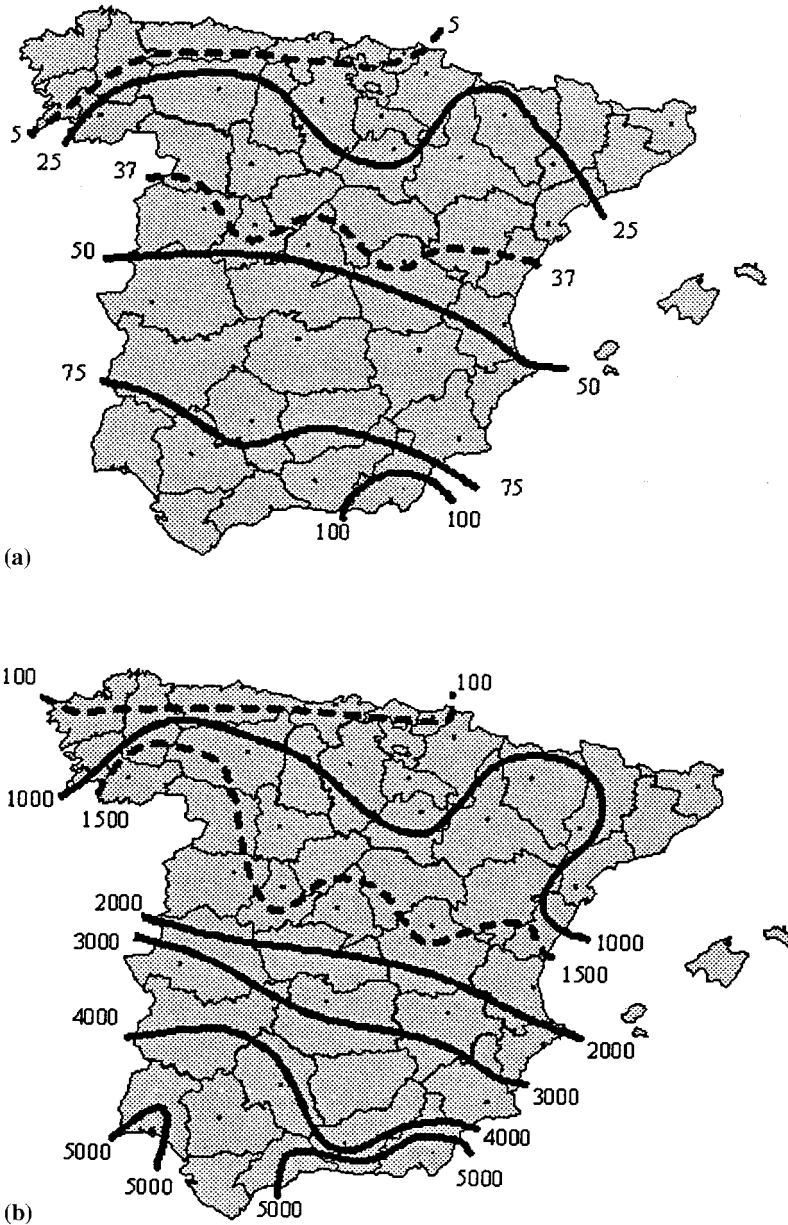


Figure 9. (a) Number of dry spells equal to or more than 30 days duration with the  $\geq 0.1$  mm threshold. (b) Total number of days that form part of the dry spells of 30 days or more duration

The longest dry spells usually occur in summer, although Martín-Vide and Moreno (1985) have already indicated that in the southeast, long dry spells (of 1 or more months in length) can happen in other seasons of the year.

### 7. THE GOODNESS OF FITS BY MARKOV CHAINS

Once the empirical distribution of frequencies of the dry spells according to their length is found, that is to say, taking into account the dry spells of length 1, 2, 3, . . . ,  $n$  days, for each observatory, the same

frequencies have been calculated using Markov chains. As the probability of a dry day after a dry day is high in a great part of Spain (Table IV) or, what is the same, the persistence of dry days is high, it will be difficult for a first- or second-order Markov chain to adjust the empirical distribution. On account of this, up to order 10 has been tested in each case. The adjustments have been verified by the  $\chi^2$  test, with  $\nu - 1$  degrees of freedom, once the spells with a frequency less than 5 are grouped, and to a level of significance  $\alpha = 0.05$ . The regionalization of peninsular Spain according to the lowest order of Markov chain that fits the general empirical distribution of the dry spells is shown in Figure 11. It is notable, in the first place, that none of the chains adjusts the empirical distribution in the southern one third of the

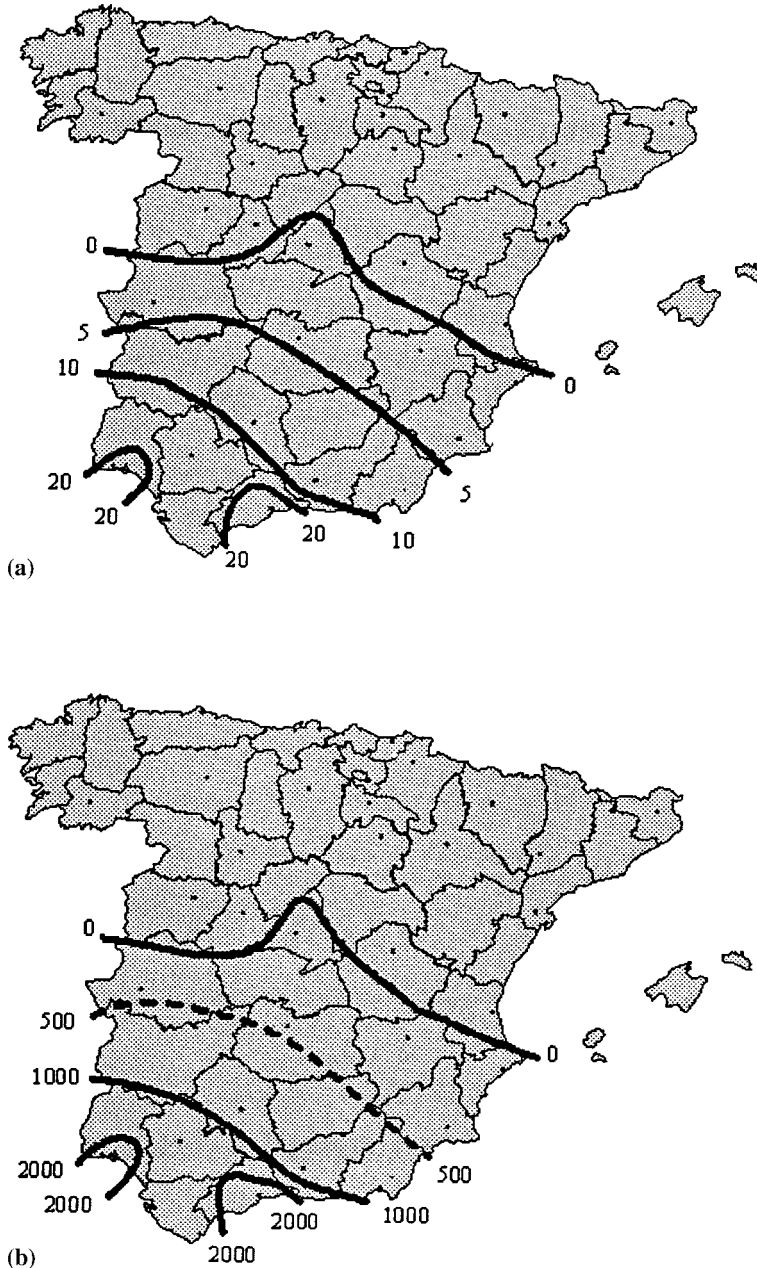


Figure 10. (a) Number of dry spells equal to or more than 90 days duration with the  $\geq 0.1$  mm threshold. (b) Total number of days that form part of the dry spells of 90 days or more duration

Table IV. Probability of a dry day after a dry day,  $p_{00}$  ( $\geq 0.1$  mm threshold) and first significant and best orders of Markov chains that fit the general distribution of the dry spells

Observatory	0.1 mm d <sup>-1</sup>		
	$p_{00}$	Significant fit	Best fit
Albacete	0.8605	4	8
Alicante	0.8831	8	9
Almeria	0.9174	—	—
Avila	0.8254	5	8
Barcelona	0.8440	—	—
Burgos	0.7922	4	7
Caceres	0.8726	10	10
Cadiz	0.8907	—	—
Ciudad Real	0.8687	7	8
Cordoba	0.8906	—	—
Coruña, La	0.7520	3	7
Cuenca	0.8359	4	8
Gerona	0.8271	3	8
Gijon	0.7154	3	4
Granada	0.8828	—	—
Huelva	0.8972	—	—
Huesca	0.8323	3	7
Leon	0.8362	5	8
Lerida	0.8445	4	8
Logroño	0.8046	3	8
Madrid	0.8471	—	—
Malaga	0.9082	—	—
Murcia	0.8938	—	—
Orense	0.8356	9	10
Pamplona	0.7802	3	7
Salamanca	0.8406	6	8
San Sebastian	0.6741	2	7
Santander	0.6979	3	7
Seville	0.8951	—	—
Soria	0.8057	3	7
Tortosa	0.8432	2	8
Valencia	0.8699	6	8
Valladolid	0.8294	4	8
Vigo	0.7999	4	8
Zaragoza	0.8501	4	8

territory, as well as in Madrid and Barcelona. From which it may now be concluded that the dry spells do not present a Markovian behaviour in the south of Spain. On the contrary, along a northern fringe (exemplified by nine observatories) a Markov chain of third-order is enough to obtain an acceptable adjustment. Even in two cases, San Sebastian and Tortosa, the latter observatory outside the said fringe, the second-order Markov chain fits well. To continue, in six observatories, the fourth-order is needed, in two the fifth-order, in another two the sixth, and in one more case each one of the seventh- to tenth-orders. Note that half of the observatories analysed are to be found amongst the second-, third- and fourth-orders, which endorses the usefulness and simplicity of Markov models for the study of dry spells in a great part of Spain (Table IV). The Markov chains estimate well the length of the dry spells in numerous observatories and, on dealing with low-orders, the calculations are always short and easy (products and powers). However, in general, the greater the latitude the smaller is the order of the chain, given that drought is less persistent.

If the order of chain that gives the best adjustment is considered, the seventh is outstanding for seven observatories located in the northern part of the country, and the eighth for 14 observatories. Only in one case, Gijon, on the Cantabrian Coast is the best adjustment obtained with a lower-order, the fourth (Table IV).

## 8. REGIONALIZATION

Once the adjustments had been made of the general distribution of dry spells (0.1 mm threshold) in each observatory, using different orders of Markov chains, the tails were studied, that is to say the longest dry spells or authentic droughts. To this end the empirical frequencies and the ones calculated by Markov chains of the dry spells of length equal to or more than 7, 15, 30, 60, 90 and 120 days have been compared. Three representative cases are shown in Table V. Note that in each case, different orders offer the best estimates for the stated lengths. In the first, Santander, whose general distribution was adjusted well by a third-order Markov chain, the 34 dry spells of length equal to or greater than half a month are estimated well by the fifth-order Markov chain, and the only spell of length equal to or more than a month does not differ much from the 0.67 spells estimated by the sixth-order chain. In consequence, in Santander drought is a low-order Markovian phenomenon.

In the second case, Ciudad Real, where the general distribution of the dry spells was adjusted by a seventh-order Markov chain, the empirical number of dry spells of 60 or more days duration, 11, differs appreciably from any of the estimates used, as a maximum 4.2, only a little more than one third. The only dry spell of 90 or more days duration is also very underestimated, in relative difference, by any of the chains. Therefore, the Markov chains forecast a number of long dry spells clearly below the empirical in Ciudad Real, so the tails of the distribution do not show Markovian behaviour.

In the third case, Malaga, where the Markov chains already did not fit the general distribution of dry spells, the tails also remain very badly estimated by the Markov models. Although the chain of order seven estimates perfectly the number of dry spells of 7 days or more, the adjustment has to be rejected because, for the longest dry spells,  $\geq 60$ , 90 and 120 days—the authentic droughts—it gives very small values with respect to the empirical ones. The persistence of dry days is such, that the Markov chains greatly underestimate the number of long droughts (22 spells of 90 or more days duration recorded against an estimated 4.4, or 4 of 120 or more days duration against 0.8). Therefore, drought in its daily structure is by no means a Markovian phenomenon in Malaga.

The three cases quoted exemplify three groups of observatories: (i) those in which the distribution of dry spells is adjusted well by a Markov chain and the longest spells are also estimated well by a determined order of the chains; (ii) those with a general distribution of dry spells adjustable by a Markov

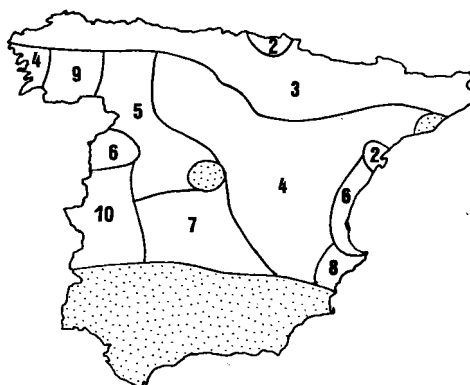


Figure 11. Regionalization of peninsular Spain according to the lowest order of Markov chain that adjusts the general empirical distribution of the dry spells

Table V. Empirical and calculated by Markov chains frequencies of the dry spells of length equal to or more than 7, 15, 30, 60, 90 and 120 days in Ciudad Real, Malaga and Santander (cM $n$ : Markov chain of order  $n$ )

	Dry spells	cM1	cM2	cM3	cM4.	cM5	cM6	cM7	cM8	cM9	cM10
Ciudad Real											
7	505	643.37	617.61	589.51	559.45	536.25	522.75	504.85	504.84		
15	226	208.66	233.27	243.64	248.06	248.54	247.77	245.74	245.64		
30	61	25.26	37.58	46.46	53.95	58.73	61.05	63.63	63.71		
60	11	0.37	0.97	1.66	2.50	3.20	3.61	4.14	4.16		
90	1	0.00	0.01	0.03	0.06	0.09	0.11	0.13	0.14		
120	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Malaga											
7	481	638.84	598.71	561.22	532.26	520.59	491.91	480.98	480.98	438.95	378.93
15	236	295.84	304.27	304.43	301.14	299.02	292.27	289.21	284.84	269.83	261.59
30	83	69.85	85.52	96.69	103.51	105.73	110.11	111.42	112.73	115.42	116.10
60	33	3.89	6.76	9.75	12.22	13.21	15.62	16.52	17.64	21.09	22.83
90	22	0.22	0.53	0.98	1.44	1.65	2.20	2.44	2.74	3.82	4.44
120	4	0.01	0.04	0.10	0.16	0.20	0.30	0.35	0.41	0.66	0.82
Santander											
7	295	267.39	296.85	304.39	304.55	301.30	291.94	294.95			
15	34	15.03	23.25	28.08	31.26	33.43	36.20	35.69			
30	1	0.07	0.19	0.31	0.41	0.51	0.67	0.63			
60	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
90	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
120	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00			



Figure 12. Final regionalization of peninsular Spain according to the adjustment of the general distribution and the estimation for the longest dry spells (see text)

chain but with notable discrepancies in the estimates for the number of the longest dry spells; and (iii) those in which neither the adjustment of the general distribution nor the estimate for the longest dry spells is acceptable.

In the first group, 14 observatories are included: Burgos, La Coruña, Cuenca, Gerona, Gijon, Huesca, San Sebastian, Logroño, Pamplona, Santander, Soria, Tortosa, Valencia and Vigo. These observatories occupy a northern zone with two incursions towards the south, by the Iberian mountain range and by the Mediterranean coast (Figure 12). In the second group there are 11 observatories: Albacete, Alicante, Avila, Caceres, Ciudad Real, Leon, Lerida, Orense, Salamanca, Valladolid and Zaragoza. These observatories occupy a relatively central position in peninsular Spain. Finally, the third group comprises ten observatories already mentioned in Section 7: Almeria, Barcelona, Cordoba, Granada, Huelva, Madrid, Malaga, Murcia, San Fernando and Seville. All these are located in the south of the Iberian Peninsula, except Madrid and Barcelona. This last city presents an atypical behaviour, given that the tails are estimated well, even although its general distribution is not adjusted by any chain. To simplify regionalization, it has been decided to include this city in the third group for not complying with the first adjustment, the most general one.

In general, the lower the latitude, the greater is the influence of the synoptic subtropical patterns, which express themselves in longer droughts, especially in summer. Thus, in the warm season, while in the north of Spain the succession of fronts or the moist winds from the Cantabrian Sea cause fairly frequent precipitation, especially in the Bay of Biscay, in the south the influence of the subtropical anticyclone in the middle and upper troposphere causes great atmospheric stability. The dry spells in the north of Spain are relatively short; that is to say, the persistence of dry days is low, and so the Markov models of low order estimate them well. In the south, the dry spells are so long, that is to say, the persistence of dry days is so high that the Markov models are incapable of giving acceptable estimates, for not taking into account the influence of the dry state many days before a given one. Even if the order of the chain were increased, the Markov models would not be acceptable in the south of Spain, because the relative improvement in the estimates of the long dry spells would be lost in the short ones.

## 9. CONCLUSIONS

The length of dry spells in a good part of Spain is very high, even with a threshold of 0.1 mm for defining a rainy day. Altogether, the mean length of the dry spells increases from north to south, from less than 4 days to more than 12, as extreme cases for the quoted threshold. With 1.0 mm threshold the number of dry days in the southeast of Spain exceeds 90% of the total number of days. The length of dry spells with a 10.0 mm threshold increases the pluviometrical differences between the north and southeast of the country, from less than 10 days to more than 50, respectively.

The maximum length of the dry spells in Andalucía and in other places in the southern half of Spain exceeds 4 and even 5 months, with the 0.1 mm threshold. The longest dry spells, in the period 1951–1990, have had a length of 169, 166 and 156 days, in the Andalusian cities of Huelva, Malaga and Almeria, respectively. With the threshold of 10.0 mm, two observatories in the southeast have recorded dry spells of almost a year in length (Almeria, 363 days, and Alicante, 343 days). The 35 observatories analysed have at least one dry spell of length equal to or greater than a month, although with very great differences; from one single case of 30 days in San Sebastian, on the Bay of Biscay, to 104 spells totalling 5497 days, in Almeria. The adjustment of the general distribution of dry spells according to their length using Markov chains of orders 1 to 10 have to be rejected for the observatories in the southern one third of Spain. On the contrary, along a northern fringe the Markov chain of third-order is enough to obtain an acceptable adjustment. In this area the usefulness and simplicity of Markov models for the study of the dry spells is clear.

In accordance with the adjustment of the distribution of dry spells and the estimates of the number of longest spells, Peninsular Spain can be regionalized in three areas: a northern fringe, where the adjustment and estimates are good, so that drought can be considered a Markovian phenomenon; a central area, where the adjustment is acceptable, but estimates of the model give values clearly inferior to the empirical ones; and the south, where neither adjustments nor estimates are acceptable, so that drought does not present Markovian behaviour.

In general, the lower the latitude, the greater is the influence of the synoptic subtropical patterns in Spain, especially in summer. In the south, the predomination of the subtropical anticyclone in the middle and upper layers of the troposphere in summer cause great atmospheric stability, which expresses itself in very long droughts. In this case, the Markov models are incapable of giving acceptable estimates.

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