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Regionalization of the probability of wet spells and rainfall persistence in the Basque Country (Northern Spain)

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ABSTRACT: The following paper deals with the modelling of a 30-year-long daily rainfall time series (1965–1994) from 39 weather stations in the Basque Country region in Northern Spain. Markov chain models are used to explore the temporal rainfall patterns in the area and to characterize the persistence of daily rain in terms of the order of the discrete Markov process. The Markov models – theoretical probabilities – are fitted to the empirical probability of wet spells lasting one more day than a specific length in the time series under the assumption of three different values (1, 5 and 10 mm) of a minimum threshold. Markovian orders that first fit the empirical distributions are used to map the theoretical persistence of daily rainfall in the Basque Country area through the use of geostatistical interpolators. Markovian orders have been confirmed as remarkable stochastic models for fitting empirical distributions of wet spells in this area, ultimately being shown as a spatial representation of theoretical persistence. Copyright © 2011 Royal Meteorological Society

KEY WORDS Basque Country; rainfall; regionalization; wet spells; Markovian models

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1. Introduction

There are many ways of approaching the climatologic study of precipitation for one region. Some are based on descriptive statistics indicators. Another approach can be based on the idea of classifying statistically physical parameters of air masses or analysing the atmospheric circulation patterns in a specific area. Our approach consists of the adjusting empirical data through the study of probability distributions. This approach is in the inferential statistics field and focused on the study of temporary rainfall structure. In other words, this research has studied in depth the probability of daily rainfall persisting on contiguous days. Changes in these physical patterns impact on many economic activities such as agriculture, transport, tourism, health and so on.

The present research brings together the statistical analysis of daily rainfall datasets (Domínguez, 1937; Caskey, 1963; Martín-Vide, 1996; Mateo González, 1965a,b), the use of different orders of stochastic models (Gabriel and Neumann, 1962; Caskey, 1963; Feyerherm *et al.*, 1967; Lowry and Guthrie, 1968; Gates and Tong, 1976; Martín-Vide, 1981; Raso, 1982; Perez Manrique *et al.*, 1984; Conesa Garcia and Martín-Vide, 1983, 1989, 1993; Young, 1994; Gómez Navarro, 1997) and the employment of geographic information technologies and geostatistical techniques (Franke, 1982; Davis, 1986; Journel, 1989; Cressie, 1990; Powell, 1990; Carlson and Foley, 1991; Cressie, 1991; Martín-Vide and Gómez Navarro, 1999). The region that has been selected for the development and application of the proposed methodology is the Basque Country in Northern of Spain (Figure 1).

The area has an extension of over 7000 square kilometres with a population of over 2 100 000 inhabitants. From a biogeographic point of view, the Basque Country is located on the border between the Eurosiberian and Mediterranean regions. Its location between these two enormous biotic systems makes it a perfect place to study precipitation changes in transition areas. Spanning an area less than 200 km from north to south, it stretches from the Bay of Biscay, which has an Atlantic climate (1.200 mm/year), to the Rioja region (550 mm/year), where traditional Mediterranean crops such as grapes are grown. Located in an area of climatic transition between temperate oceanic mid-latitudes and Mediterranean climates (Ruiz Urrestarazu, 1982), it gives us a perfect opportunity to study spatial variability of rainfall persistence in a small portion of the earth.

2. Data sources and methodological approach

2.1. Data sources

The proposed methodology is based on the study of wet spells and was applied to daily rainfall data registered from 1 January 1965 to 31 December 1994 by different public and private institutions, such as the National Agency of Meteorology (AEMET), the Spanish Air Navigation Association (AENA) and the national electric energy supplier IBERDROLA. Daily rainfall datasets

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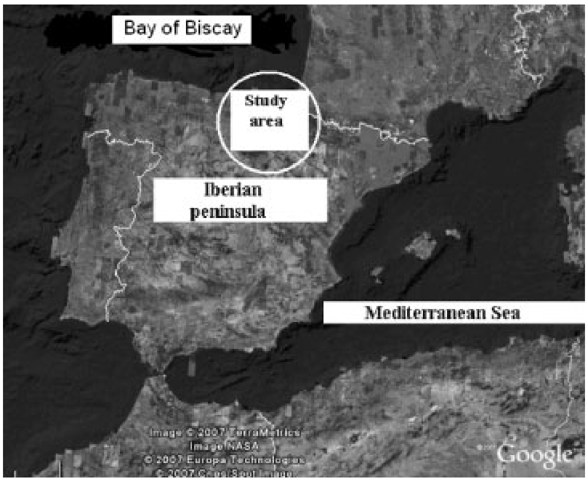

Figure 1. The study area in the Iberian Peninsula by Google Earth.

from 39 weather stations were collected in the Basque Country (Table I). Datasets were collected according to similar observation criteria. Data quality was evaluated through the double-mass curves method and the real precision index. Manual weather stations have progressively been replaced by automatic ones, and new datasets are registered nowadays. Figure 2 shows the spatial distribution of weather stations in the study area.

2.2. Methodological approach

A wet spell is a sequence of wet days that starts and ends with a dry day. A 3-d wet spell can be symbolized as 0-1-1-1-0. A wet day is any day on which the amount of registered rainfall is equal to or exceeds to a specific threshold. The use of the 0.1-mm threshold has been considered by some Spanish researchers studying dry (Conesa Garcia and Martín-Vide, 1993; Martín-Vide et Gómez Navarro, 1999) and wet spells (Mateo González, 1965a,b; Gómez Navarro, 1996). Nevertheless, this threshold has not been considered here because this particular value may have been missed at manual weather stations. The use of this threshold would have implied the use of higher Markovian orders. In this research, a wet day is any day on which the amount of registered rainfall is equal to or exceeds to 1, 5 or 10 mm being they related to evapotranspiration, soil infiltration and runoff episodes, respectively (Berger and Goossens, 1983; Yair and Lavee, 1985; Perzyna, 1994; Martinez-Murillo and Ruiz-Sinoga, 2007). In this sense, three different empirical distributions of wet spells are obtained for each meteorological station. The definition of thresholds plays a key role later on in the outcomes of the research.

First, empirical distributions of wet spells are calculated to frame the research. Basic indicators of their frequency under each threshold are given, and their empirical probabilities are mapped through multi-quadratic radial function interpolators. A Pearson correlation analysis is also developed according to the geographic location and altitude of each meteorological station. Due to the fact that the research is developed in a small area, latitude must be understood as the distance of each station from the Bay of Biscay, to the north, rather than the relative position with respect to the equator.

Table I. List of weather stations at the study area.

Location		UTM[a] 30N – (metres)	
Name	Official code	Longitude	Latitude
Elduayen	1031	581169.0	4776506.6
Ategorrieta	1024	585092.9	4796917.3
Lasarte	1035	579434.4	4791511.1
Igueldo	1024e	577905.2	4795103.1
Etxebarria	1053	542458.5	4788957.7
Eibar	1050	543025.3	4781341.6
Aranzazu (g)	1046	549217.4	4758463.1
Legazpia	1037	554198.6	4767292.5
Carranza	1093	471424.2	4787188.4
Abadiano	1070	531467.6	4776404.3
Ochandiano	9077e	528012.2	4765160.8
Aranzazu (v)	1075e	517121.1	4777124.4
Sondica	1082	506060.7	4794226.0
Fuenterrabía	1014	598033.4	4800918.4
Arcentales	1083	482019.4	4785239.5
Amurrio	1060	499502.3	4766306.4
Arlucea	9095e	537364.9	4730379.5
Albina	9078	530185.3	4759833.5
Archua	9072j	502041.5	4748107.5
Arriola	9074c	549565.5	4751031.3
Anda	9072h	508524.6	4751567.2
Urrunaga	9080	528480.0	4756032.0
Sendadiano	9072i	507394.5	4748327.1
Ullibarri	9076	531848.0	4752869.6
Izarra	9072c	507681.4	4755421.9
Hueto Arriba	9092	516036.0	4748526.9
Lagrán	9175	533986.4	4719041.8
Betolaza	9080c	527197.1	4753867.5
Opacua	9073i	552381.2	4741582.0
Peñacerrada	9103	523432.6	4721095.6
Arcaute	9086	530662.4	4744258.1
Gámiz	9085i	531178.6	4740528.0
Salvatierra	9074	550248.0	4744527.4
Osma de Alava	9063o	494737.8	4748479.3
Salinas de Añana	9064	500976.7	4738606.8
Espejo	9064i	496002.7	4739409.9
Puentelarrá	9065i	496135.3	4732839.8
Armiñón	9094u	510416.4	4729854.6
Zambrana	9103x	509857.6	4722975.4

[a] Universal Transverse Mercator

Second, the number and the relative frequency of wet transitions are calculated for each type of wet spell. The transitions probabilities (p) for each type of wet spell has been estimated based on the following formulae:

$$p\ (1\text{-}1) = (1\text{-}1)/(1) \quad (1)$$

$$p\ (1\text{-}1\text{-}1) = (1\text{-}1\text{-}1)/(1\text{-}1) \quad (2)$$

and so on, with p (1-1) is the probability of having one wet day after another wet day, (1-1) the number

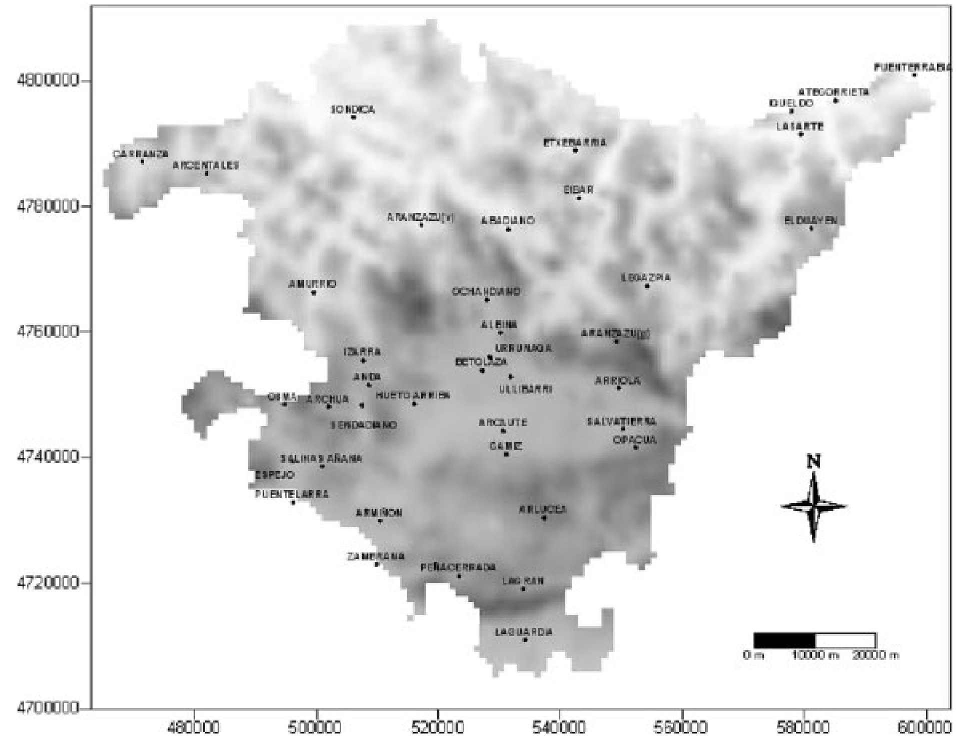

Figure 2. Spatial distribution of meteorological stations.

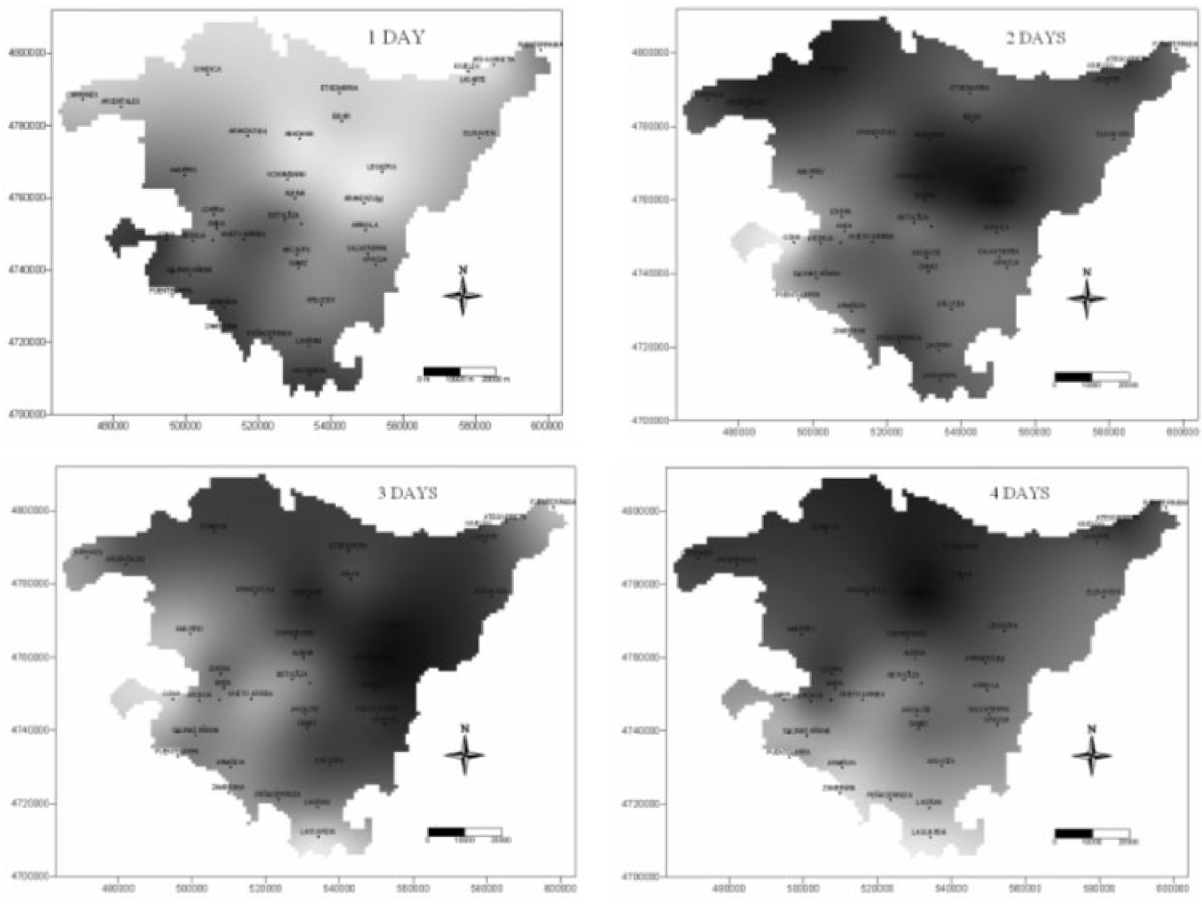

Figure 3. Empirical probabilities of wet spells at 1-mm threshold.

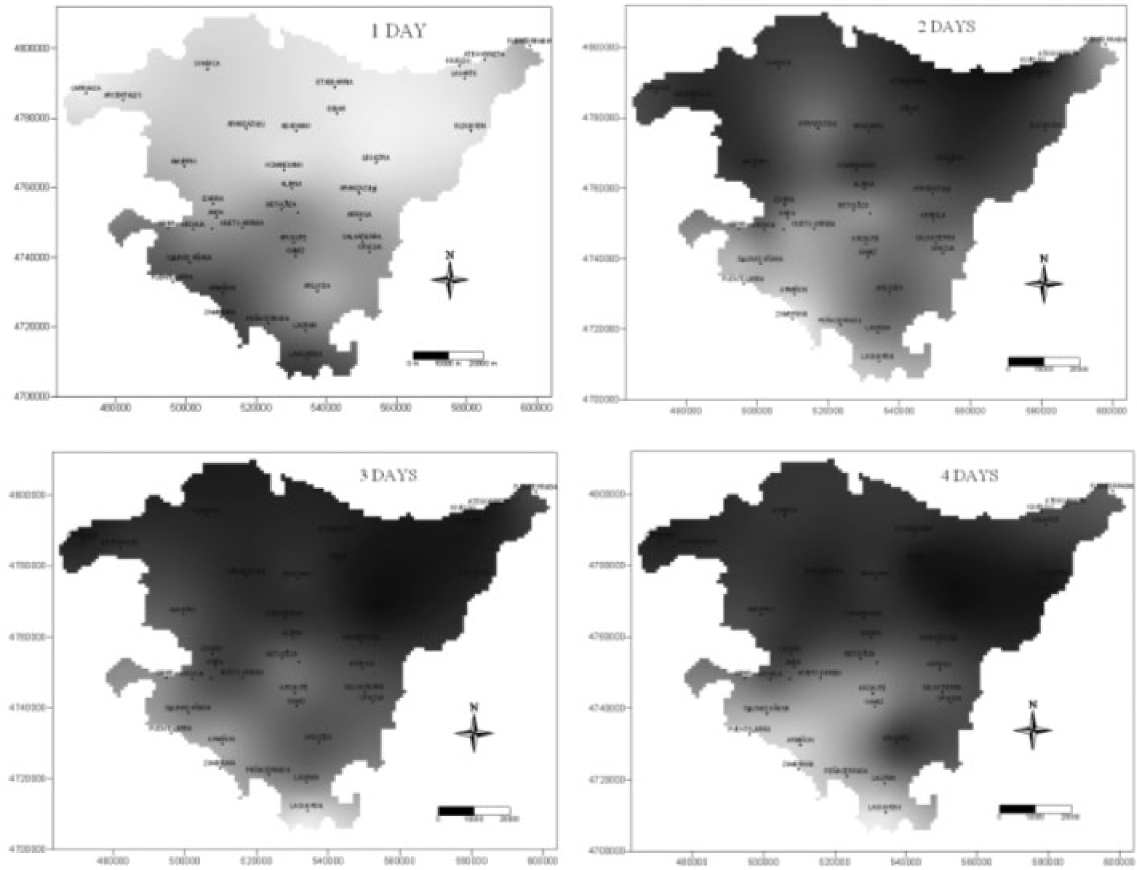

Figure 4. Empirical probability of wet spells at 5-mm threshold.

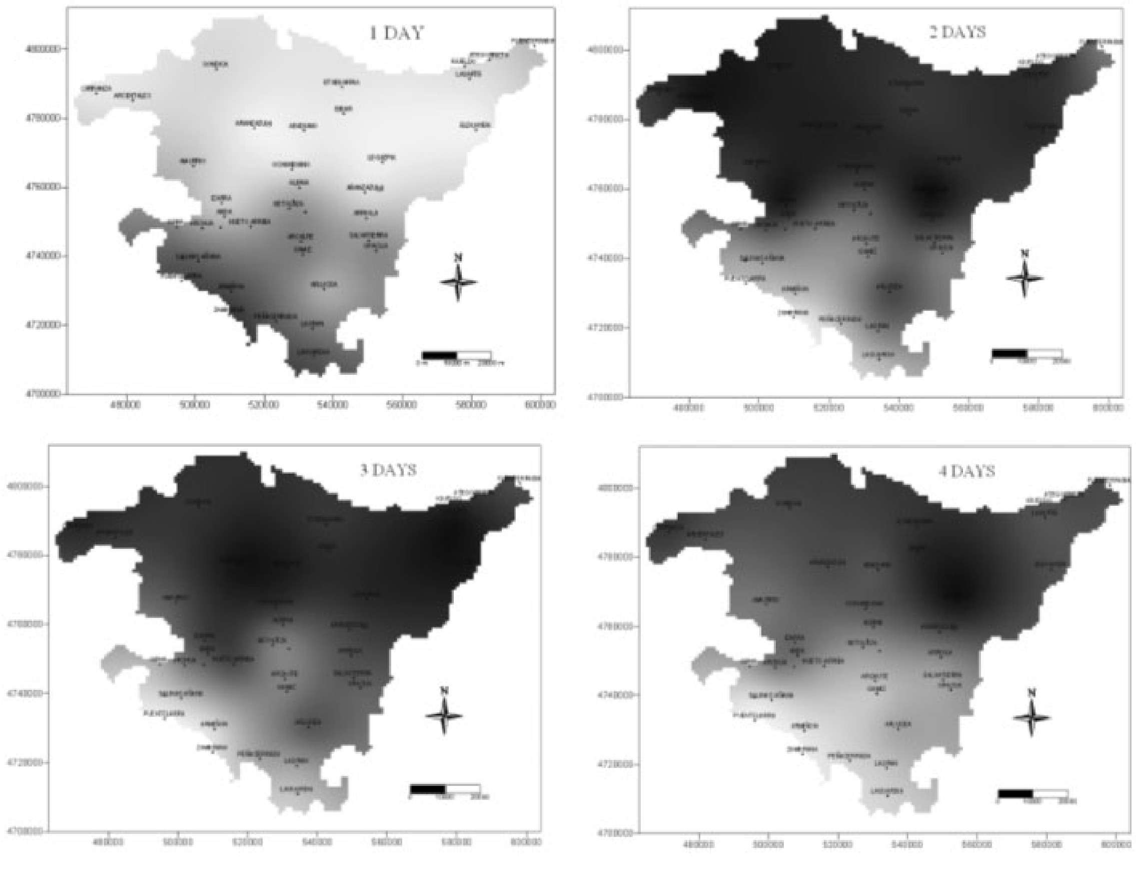

Figure 5. Empirical probabilities of wet spells at 10-mm threshold.

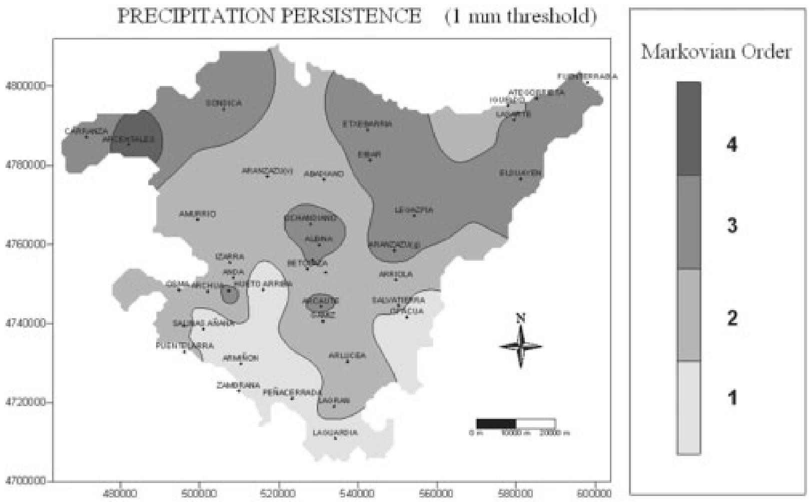

Figure 6. Markovian orders' spatial distribution at 1-mm threshold.

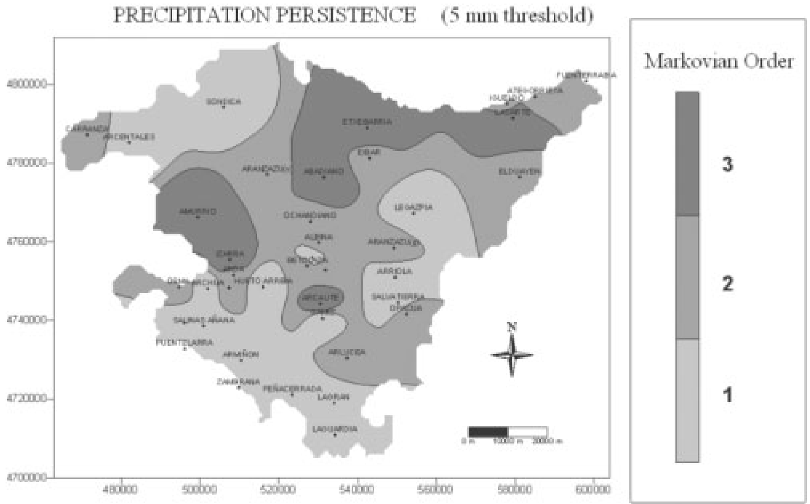

Figure 7. Markovian orders' spatial distribution at 5-mm threshold.

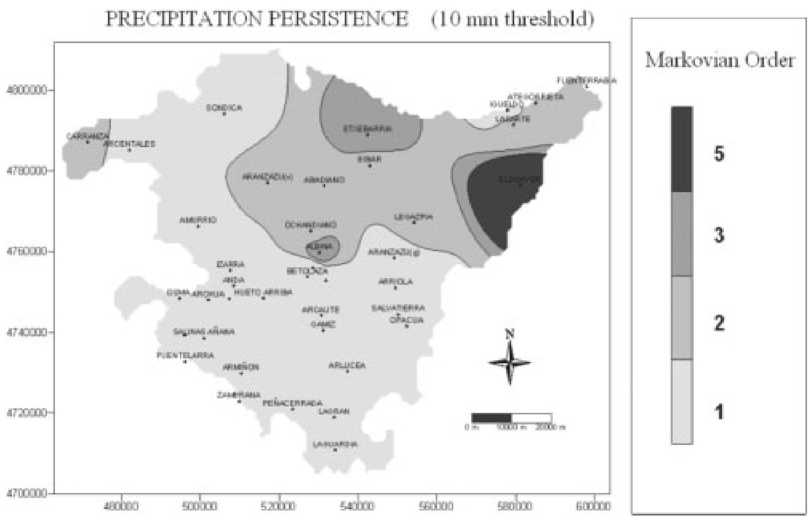

Figure 8. Markovian orders' spatial distribution at 10-mm threshold.

of transitions (rainy day - rainy day), (1) the number of rainy days, p (1-1-1) the probability of having one wet day after two wet days, (1-1-1) the number of transitions (rainy day - rainy day - rainy day).

Therefore, the idea of empirical persistence is based on the conditional probabilities according to the following mathematical statement:

$$p\ (1) < p\ (1\text{-}1) < p\ (1\text{-}1\text{-}1) \quad (3)$$

In this sense, computation of transitions probabilities is essential for calculating Markovian probabilities. Once the persistent behaviour of the dataset has been empirically verified, Markovian models are applied to estimate the theoretical probabilities of having a wet day after n wet days in a wet spell.

Markov chains define mathematically the idea of persistence through the use of conditional probabilities. These models estimate the Markovian probability (Pn) of a wet spell lasting n days. The higher the order, the higher the memory the model uses.

First order Markovian model formula:

$$Pn = p\ (1\text{-}1)^{n-1} \times p\ (1\text{-}0) \text{ for } n \geq 1 \quad (4)$$

with p (1-0) the probability of having a dry day following a rainy one.

Note that the first order only considers the character – rainy or dry – of the previous day. Moreover, formulation does not consider the first factor p (0–1) because, as we are working with wet spells, it always gets a probability value of 1.

The second Markovian order determines the calculation considering the character of preceding 2 d.

$$Pn = p\ (0\text{-}1\text{-}1) \times p\ (1\text{-}1\text{-}1)^{n-2} \times p\ (1\text{-}1\text{-}0) \text{ for } n \geq 2 \quad (5)$$

$$P1 = p\ (0\text{-}1\text{-}0) \quad (6)$$

with p (0-1-0) is the probability of having a wet spell that lasts just one day, p (0-1-1) the probability of having one rainy day following another rainy, following a dry day and so on and p (1-1-0) the probability of having one dry day following two rainy days.

The third Markovian order determines the calculation considering the character of preceding 3 d and so on.

$$Pn = p\ (0\text{-}1\text{-}1\text{-}1) \times p\ (1\text{-}1\text{-}1\text{-}1)^{n-3} \times p\ (1\text{-}1\text{-}1\text{-}0) \text{ for } n \geq 3 \quad (7)$$

Markovian probabilities allow us to estimate the theoretical distribution for each wet spell under the 1-, 5- and 10-mm thresholds. Theoretical probabilities depend on the memory of each model applied. For instance, a third-order Markovian model will not be able to calculate the theoretical probability for wet spells that last 1 or 2 d.

The accuracy of the adjustments between theoretical and empirical distributions has been confirmed by the chi-square test (χ^2) to a level of significance $\alpha = 0.05$ and for ν-1 freedom. Because of the low frequency of wet spells at the end of the empirical distributions, the categories with a frequency of less than five were grouped together. The selected orders to elaborate final maps were those whose χ^2 values were first inferior to the χ^2 values in the distribution table.

By these means, the spatial variability of rainfall persistence is also represented in the studied region. A smooth inverse distance weighted technique has been used as interpolator in this case.

3. Results

3.1. Descriptive indicators

Results confirmed that the total number of wet spells registered by all weather stations decreases according to the increment in the threshold value from 57 073 wet spells for the 1-mm threshold to 42 647 for the 5-mm threshold and to 28 636 for the 10 mm one. The average number goes from 1463.4 (1 mm) to 1093.5 (5 mm) and to 734.2 spells (10 mm). The diversity of wet spell duration also decreases with the elevation of the threshold from 26 different wet spells for the 1-mm threshold to 15 types for the 5 mm one. Only 11 different types of wet spells were registered for the 10-mm threshold. More than 99% of the wet spells lasted less than 10 d, and the percentage of one-day wet spells went up from 49.5% for the lower threshold to 61.5% and to 69.3% for the 5- and 10-mm thresholds, respectively. Table II presents the absolute number of spells, the average spell duration, the number of rainy days and the longest spells registered for each meteorological station.

The average length for the 1-mm threshold wet spell is 2.17 d, while the standard deviation was a quarter of a day. For the second threshold (5 mm), it is 1.69 d the standard deviation being 2.79 d, while for the third one (10 mm), it lasts 2.5 d with a standard deviation of 0.15. When one-day spells are taken out of the analysis, the average length is extended to 3.31, 2.79 and 2.5 d, respectively. The longest wet spell under the 1-mm threshold was 31 d and took place at the Arrigorriaga meteorological station. Most of the longest wet spells at the 1- and 5-mm thresholds took place when the dominant wind component was from north or northwest with the northeast circulation for the 10-mm threshold also being relevant.

3.2. Empirical probabilities of wet spells and cartographic representation

The empirical probability of a one-day wet spell is relatively high. It is important to distinguish between the probability of registering a rainy day (i.e. 28.9% in Fuenterrabía) and the probability for a wet spell lasting 1 d (i.e. 52% in Fuenterrabía). Table III shows the empirical probability of wet spells that differs for the

Table II. Wet spells descriptive indicators at the 1-mm threshold.

Meteorological station	Official code	Annual rainfall	Total spells	Rainy days	Average spell duration	The longest spell
Fuenterrabía	1014	1204	1469	3173	2.16	21
Ategorrieta	1024	1724	1717	4454	2.59	31
Igueldo	1024e	1604	1737	4389	2.53	20
Sondica	1082	1224	1633	3915	2.40	15
Lasarte	1035	1635	1651	3967	2.40	31
Etxebarria	1053	1580	1674	4121	2.46	28
Carranza	1093	1436	1510	3804	2.52	21
Arcentales	1083	1170	1380	3205	2.32	22
Eibar	1050	1526	1602	3845	2.40	18
Aranzazu (v)	1075e	1266	1365	3103	2.27	17
Elduayen	1031	2002	1663	3827	2.30	19
Abadiano	1070	1306	1481	3835	2.59	25
Legazpia	1037	1439	1597	4063	2.54	24
Amurrio	1060	1122	1496	2997	2.00	16
Ochandiano	9077e	1286	1429	3475	2.43	24
Albina	9078	1076	1532	3405	2.22	15
Aranzazu (g)	1046	1457	1490	3850	2.58	24
Urrunaga	9080	965	1569	3324	2.12	16
Izarra	9072c	913	1229	2758	2.24	21
Betolaza	9080c	837	1313	2433	1.85	14
Ullibarri-Gamboa	9076	931	1528	3225	2.11	15
Anda	9072h	972	1467	3038	2.07	15
Arriola	9074c	975	1484	3313	2.23	14
Hueto arriba	9092	911	1312	2378	1.81	14
Osma	9063o	701	1207	2158	1.79	10
Sendadiano	9072i	957	1455	3032	2.08	15
Archua	9072j	1055	1620	3568	2.20	13
Salvatierra	9074	726	1275	2688	2.11	13
Arkaute	9086	771	1402	3082	2.20	15
Opacua	9073i	836	1382	2757	1.99	11
Gamiz	9085i	732	1456	3011	2.07	12
Espejo	9064i	679	1357	2499	1.84	10
Salinas Añana	9064	690	1467	2780	1.90	10
Puentelarrá	9065i	562	1335	2506	1.88	10
Arlucea	9095e	1081	1225	2692	2.20	15
Armiñón	9094u	559	1320	2346	1.78	9
Zambrana	9103x	529	1277	2250	1.76	11
Peñacerrada	9103	772	1409	2766	1.96	11
Lagrán	9175	863	1558	3011	1.93	11

Table III. Range of different-length empirical probabilities of wet spells at the 1-, 5- and 10-mm thresholds.

	Wet spell probability ranges					
Length	1-mm threshold		5-mm threshold		10-mm threshold	
Days	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
1	0.4034	0.6214	0.5438	0.736	0.6253	0.8480
2	0.206	0.252	0.189	0.243	0.141	0.226
3	0.084	0.129	0.035	0.100	0.018	0.079
4	0.040	0.076	0.011	0.052	0.001	0.044
5	0.020	0.056	0.0032	0.037	–	–
6	0.010	0.034	0.0013	0.0204	–	–
7	0.0028	0.0021	–	–	–	–
8	0.002	0.015	–	–	–	–
8	0.001	0.0105	–	–	–	–
10	0.00089	0.0073	–	–	–	–

different thresholds by up to 10 d. They are shown only for the types of wet spells that have been registered at the 39 weather stations.

The spatial distribution of the empirical probabilities for the 1-mm threshold is shown in Figure 3. The first map on the top left-hand side shows the probability for 1-day wet spells and the last map on the bottom right-hand side refers to the probability of having a 4-day wet spell. Figure 4 corresponds to the 5-mm threshold and Figure 5 to the 10-mm threshold. The maps show only data for the different types of wet spell at the 39 weather stations. Cartographic representation has not been produced where there is a weather station in which the frequency of a specific type of wet spell is zero. In these maps, darkness indicates a higher probability of having an n-day wet spell, while the light areas represent a lower one. Maps are not visually comparable with each other because ranges that have been applied are different in each particular case. A first glance at them will confirm that wet spells that last 1 d bear an inverse correlation to the distance from the sea.

Table IV shows the Pearson correlation for the wet spell probabilities and the geographic location of the weather stations for the 1-mm threshold in the Basque Community.

Probability maps of wet spells related to the 5 mm threshold are shown on Figure 5. The map on the top left-hand side represents the probability for 1-d wet spells, while the last figure on the bottom right-hand side refers to the probability of having a 4-d wet spell. For the map on the top left-hand side, the same spatial pattern of probabilities that was shown with the lowest threshold is confirmed. On the other maps, the North and the East of the area have a significantly higher probability of receiving wet spells than the west and the south of the territory.

Table V shows the Pearson correlation for probabilities of wet spells and the geographic location of the weather stations for the 5-mm threshold. At this particular threshold, latitude acquires crucial relevance in explaining the probabilities of wet spells for most types of wet spell.

Finally, maps corresponding to the 10-mm threshold are shown below. Due to the increase of the threshold, the frequency of types of wet spells decreases drastically. The spatial representation confirms the particular behaviour of 1-d wet spells. Table VI shows the same values as Tables IV and V for the 10-mm threshold.

Table IV. Pearson correlations between geographic location of weather stations and empirical probabilities of wet spells at 1-mm threshold.

Length (days)	Correlation	Longitude	Latitude	Altitude
1	Pearson correlation	−0.388[a]	−0.666[b]	0.395[a]
	Sig. (bilateral)	0.015	0.000	0.013
2	Pearson correlation	0.194	0.327[a]	−0.140
	Sig. (bilateral)	0.237	0.042	0.394
3	Pearson correlation	0.307	0.180	0.011
	Sig. (bilateral)	0.058	0.274	0.947
4	Pearson correlation	0.172	0.679[b]	−0.461[b]
	Sig. (bilateral)	0.296	0.000	0.003
5	Pearson correlation	0.499[b]	0.630[b]	−0.364[a]
	Sig. (bilateral)	0.001	0.000	0.023
6	Pearson correlation	0.307	0.683[b]	−0.397[a]
	Sig. (bilateral)	0.057	0.000	0.012
7	Pearson correlation	0.475[b]	0.728[b]	−0.556[b]
	Sig. (bilateral)	0.002	0.000	0.000
8	Pearson correlation	0.203	0.667[b]	−0.415[b]
	Sig. (bilateral)	0.214	0.000	0.009
9	Pearson correlation	0.441[b]	0.585[b]	−0.413[b]
	Sig. (bilateral)	0.005	0.000	0.009
10	Pearson correlation	0.229	515[b]	−0.338[a]
	Sig. (bilateral)	179	001	044

sig., significant.
[a] Correlation is significant at 0.05 (bilateral).
[b] Correlation is significant at 0.01 (bilateral).

Table V. Pearson correlations between geographic location of weather stations and empirical probabilities of wet spells at 5-mm threshold.

Length (days)	Correlations	Longitude	Latitude	Altitude
1	Pearson correlation	−0.340[a]	−0.765[b]	0.474[b]
	Sig. (bilateral)	0.034	0.000	0.002
2	Pearson correlation	0.219	0.547[b]	−0.290
	Sig. (bilateral)	0.180	0.000	0.073
3	Pearson correlation	0.387[a]	0.708[b]	−0.433[b]
	Sig. (bilateral)	0.015	0.000	0.006
4	Pearson correlation	0.224	0.613[b]	−0.301
	Sig. (bilateral)	0.171	0.000	0.063
5	Pearson correlation	0.327[a]	0.805[b]	−0.584[b]
	Sig. (bilateral)	0.042	0.000	0.000
6	Pearson correlation	0.364[a]	0.726[b]	−0.508[b]
	Sig. (bilateral)	0.023	0.000	0.001

sig., significant.
[a] Correlation is significant at 0.05 (bilateral).
[b] Correlation is significant at 0.01 (bilateral).

Table VI. Pearson correlations between geographic location of weather stations and empirical probabilities of wet spells at 10-mm threshold.

Length (days)	Correlations	Longitude	Latitude	Altitude
1	Pearson correlation	−0.307	−0.760[b]	0.448[b]
	Sig. (bilateral)	0.057	0.000	0.004
2	Pearson correlation	0.151	0.591[b]	−0.232
	Sig. (bilateral)	0.360	0.000	0.154
3	Pearson correlation	0.384[a]	0.704[b]	−0.432[b]
	Sig. (bilateral)	0.016	0.000	0.006
4	Pearson correlation	0.313	0.793[b]	−0.504[b]
	Sig. (bilateral)	0.052	0.000	0.001

sig., significant.
[a] Correlation is significant at 0.05 (bilateral).
[b] Correlation is significant at 0.01 (bilateral).

3.3. Empirical persistence of wet spells

The analysis of empirical persistence is developed through the study of wet transitions. One rainy day followed by another rainy day (1-1) is one wet transition. One rainy day followed by another rainy day and in turn by another rainy day (1-1-1) are two wet transitions. The study of wet transitions has been very useful in justifying the uses of superior Markovian orders (Martin-Vide and Gómez Navarro, 1999) due to the difficulties that the lowest orders have in fitting some of the empirical distributions. At the same time, the analysis of wet transitions allows us to identify different levels of empirical persistence at the different thresholds.

In general terms, it can be said that empirical persistence decreases according to the increase of the threshold. At the 1-mm threshold, the empirical probability of having a new wet day after n wet days in many of the weather stations starts to decrease after six wet transitions. Abadiano and Aranzazu (v) stations obtained increments in the probability of wet transitions of up to nine transitions. On the other hand, Ullibarri-Gamboa, Opacua and Puentelarrá did not see an increase in the percentage of the transition probability beyond two wet links.

When we look at the 5-mm threshold, an average limit is found, generally speaking, after four wet transitions on the north side of the study area and after three wet transitions on the south side. According to the 10-mm threshold, the average percentage limit of four wet transitions is established in some places in the north such as Lasarte, Aranzazu (v), Abadiano and Arlucea and at two wet transitions for the locations on the southern side (i.e. Izarra, Betolaza, Arriola, Salvatierra, Arcaute, Gámiz, Espejo, Salinas de Añana, Puentelarrá, Armiñón, Lagrán).

3.4. Markovian probabilities

Markovian models up to the fifth order have been applied in this case to the meteorological data. Results are shown for the Carranza meteorological station at the 1-mm threshold (Table VII).

By means of Markov chains, absolute theoretical numbers of wet spells related to each type and threshold have also been estimated (Table VIII).

Here, a general adjustment validation has been defined to find out the Markovian order that first fits the global empirical distribution according to the chi-square test (χ^2) to a level of significance $\alpha = 0.05$ and for ν-1 freedom. Chi-square values for Carranza meteorological station at the 1-mm threshold are shown in Table IX as an example. Table X shows how often each Markovian order first fits the empirical distributions of wet spells at the weather stations. Results are also shown in the Figures 6–8 for the different thresholds considered in the study.

4. Discussion of results

The definition of thresholds has been adopted in order to frame the properties of precipitation in the Basque Country. The use of three different levels of analysis has allowed us to describe the temporal structure of precipitation in the Basque Country based on wet spells and has made it easier to understand the behaviour of rainfall.

Table VII. Markovian probabilities of wet spells at Carranza at 1-mm threshold.

Spell length (days)	First order	Second order	Third order	Fourth order	Fifth order
1	0.396951	0.445695	–	–	–
2	0.239381	0.202246	0.434886	–	–
3	0.144358	0.128454	0.183458	0.327696	–
4	0.087055	0.081585	0.123900	0.217269	0.330189
5	0.052499	0.051818	0.083677	0.147054	0.214219
6	0.031659	0.032911	0.056512	0.099531	0.145707
7	0.019092	0.020903	0.038166	0.067365	0.099107
8	0.011513	0.013276	0.025776	0.045595	0.067411
9	0.006943	0.008432	0.017408	0.030860	0.045852
10	0.004187	0.005356	0.011757	0.020887	0.031187
11	0.002525	0.003402	0.007940	0.014137	0.021213
12	0.001523	0.002160	0.005362	0.009568	0.014429
13	0.000918	0.001372	0.003622	0.006476	0.009814
14	0.000554	0.000872	0.002446	0.004383	0.006675
15	0.000334	0.000554	0.001652	0.002967	0.004540
16	0.000201	0.000352	0.001116	0.002008	0.003088
17	0.000121	0.000223	0.000753	0.001359	0.002101
18	0.000073	0.000142	0.000509	0.000920	0.001429
19	0.000044	0.000090	0.000344	0.000623	0.000972
20	0.000027	0.000057	0.000232	0.000421	0.000661
21	0.000016	0.000036	0.000157	0.000285	0.000450

Table VIII. Theoretical frequency of wet spells at Carranza station at 1-mm threshold.

Spell length (days)	Number of empirical spells	Total	1510	837	473	318
		First order	Second order	Third order	Fourth order	Fifth order
1	673	599.40	673.00	–	–	–
2	364	361.47	305.39	364.00	–	–
3	155	217.98	193.97	153.55	155.00	–
4	105	131.45	123.19	103.70	102.77	105.00
5	68	79.27	78.24	70.04	69.56	68.12
6	54	47.81	49.70	47.30	47.08	46.33
7	25	28.83	31.56	31.95	31.86	31.52
8	23	17.39	20.05	21.57	21.57	21.44
9	12	10.48	12.73	14.57	14.60	14.58
10	10	6.32	8.09	9.84	9.88	9.92
11	6	3.81	5.14	6.65	6.69	6.75
12	6	2.30	3.26	4.49	4.53	4.59
13	1	1.39	2.07	3.03	3.06	3.12
14	1	0.84	1.32	2.05	2.07	2.12
15	2	0.50	0.84	1.38	1.40	1.44
16	0	0.30	0.53	0.93	0.95	0.98
17	1	0.18	0.34	0.63	0.64	0.67
18	3	0.11	0.21	0.43	0.44	0.45
19	0	0.07	0.14	0.29	0.29	0.31
20	0	0.04	0.09	0.19	0.20	0.21
21	1	0.02	0.05	0.13	0.13	0.14
Total	–	1509.96	1509.90	836.73	472.72	317.70

Table IX. Chi-square test (χ^2) to a level of significance $\alpha = 0.05$ and for ν-1 freedom at Carranza station at 1-mm threshold.

Spell length (days)	First order	Second order	Third order	Fourth order	Fifth order
1	9.0385	0.0000	–	–	–
2	0.0178	11.2475	0.0000	–	–
3	18.1972	7.8276	0.0136	0.0000	–
4	5.3235	2.6870	0.0162	0.0485	0.0000
5	1.6031	1.3414	0.0593	0.0348	0.0002
6	0.8027	0.3727	0.9488	1.0178	1.2680
7	0.5086	1.3649	1.5099	1.4785	1.3472
8	1.8133	0.4349	0.0942	0.0953	0.1140
9	0.2191	0.0422	0.4535	0.4619	0.4568
10	2.1390	0.4525	0.0026	0.0015	0.0007
11	1.2547	0.1452	0.0628	0.0705	0.0824
12	5.9562	2.2975	0.5091	0.4802	0.4343
21	8.8920	2.0909	0.0005	0.0042	0.0218
Total	55.77	30.30	**3.67**	**3.69**	**3.73**

A bold number means a χ^2 lower than the corresponding theoretical χ^2 value in tables.

Several aspects are relevant in relation to the threshold increment. The increase of the threshold is not a limiting factor to the physical relationship between the empirical probabilities of wet spells and the geographic location of meteorological stations. Nevertheless, it affects the way in which these correlations take place for each type of wet spell. Latitude, understood as distance from the Bay of Biscay, is a central factor in explaining how wet spells occur in the territory (Uriarte, 1983). Topographic surface will also play a crucial role in relation to the spatial distribution of wet spells.

One-day-long wet spells behave in a different way to any other type of wet spell at the three thresholds. There is a significant inverse correlation to distance from the sea. The further the station is from the shore line, the higher is the probability of having this type of wet spell. For the rest of the wet spells, the probability increases positively when the station is closer to the sea or to the northeast because of the general atmospheric pattern in this area, where the circulation of westerlies has traditionally been an important issue (Mateo Gonzalez, 1965a,b; Jenkinson and Collison, 1977; Ruiz Urrestarazu, 1982;

Table X. Number of weather station first adjusted by Markovian orders and threshold.

Threshold	Order 1	Order 2	Order 3	Order 4	Order 5
1 mm	5	18	15	1	–
5 mm	16	17	6	–	–
10 mm	27	9	2	–	1

Uriarte, 1983). Most of the types of wet spells over 1 d in length have relevant statistical correlations with the distance from the sea, except those that lasted 2 or 3 d at the 1-mm threshold. The correlation of these two types of wet spells with the geographic location is higher as the threshold increases. This shows that spatial forecasting of these kinds of events is more difficult than those lasting 2 or 3 d at the 5- or 10-mm threshold.

Generally speaking, altitude is inversely related to the probability of wet spells. This leads us to a discussion on weather topographic elevations favour persistence. On one hand, the barrier effect of the mountains can make persistence more likely by making air masses stop at a specific location. On the other hand, the elevation of maritime air masses can produce some precipitation that does not affect the lowland. In this regard, 1-d wet spells become more frequent in the mountains and consequently persistence decreases. Moreover, the wet sequence may be broken when air masses jump the hills because of Foehn effect, and as a result, wet spells become shorter (Uriarte, 1983). The lack of weather stations at high altitudes is also an important issue here.

Longitude is also relevant to explain rainfall in the Basque Country, but it seems to be less important than latitude in determining the probability of having wet spells. Three- and five-day-long wet spells are mainly related to this geographic factor. The western components of most of the types of atmospheric circulation that affect the area explain this correlation (Rasilla, 2003).

The analysis of empirical persistence through the wet transitions in the spells has allowed us to justify the uses of superior Markovian orders (Lowry et Guthrie, 1968) due to the difficulties that the lowest orders have in fitting some of the empirical distributions (Martin-Vide and Gómez Navarro, 1999). At the same time, the analysis of wet transitions enables us to identify different levels of empirical persistence.

5. Conclusions

In general terms, it can be said that the empirical probability of having a new wet day at many of the weather stations at the 1-mm threshold starts to decrease after six wet links. Abadiano and Aranzazu (v) meteorological stations obtained positive increments in the probability of wet transitions of up to nine transitions. At the other extreme, Ullibarri-Gamboa, Opacua and Puentelarrá did not see an increase in the probability of transition further than two wet links. When we look at the 5-mm threshold, an average limit is found, generally speaking, after four wet transitions on the north side of the study area and three wet transitions on the south side. At the 10-mm threshold, the limit is established at four wet transitions in some places in the north and at two wet transitions in the south. In any case, the empirical probability decreases as the threshold increases.

Absolute estimations for each specific order generate remarkable differences. While one particular type of spell is underestimated by the model, another is clearly overestimated. For instance, at Carranza station, the first Markovian model overestimates the number of 5-d wet spells, and at the same time, underestimates the 11-d ones.

In this regard, wet spells with a low frequency (right tails of the distributions) become especially relevant in relation to obtain a good general adjustment of the empirical distributions to the theoretical models being the discrepancy between observed values and the acceptable expected values. Nevertheless, it is also necessary to point out that there are also important relative differences in tails of some distributions. We should make a distinction between the weather stations with a good general adjustment and those with a good general adjustment except in the tails of the distribution.

The spatial distribution of the persistence of precipitation at the 1-mm threshold responds to the first Markovian order in a small area in the south, where the influence of the Mediterranean is felt throughout the Ebro river valley. The second Markovian model covers most of the extension of the study area in a very irregular way, affecting a small part of the coast. The third Markovian order corresponds to the northeast area and to the Northwest, where even the fourth order is registered in one particular case.

The first Markovian order becomes much more relevant when threshold is increased to 5 mm. It affects most of the southern area and also important regions in the east and the northwest. The second Markovian order continues as the predominant order. It spreads its limits mainly towards the northeast. The northeast coast is characterized by a high level of persistence, fitting the third Markovian order.

At the 10-mm threshold, the persistence map becomes much more simplified. The first Markovian order covers almost three quarters of the study area. It is on the northeast side of the map, where the second, third and fifth orders occur, the highest order corresponding to an area where maximum rainfall is registered in the Basque Community.

According to the wet spell analysis in the Basque Country, it can be said that the rainfall landscape varies dramatically over a very small area to the extent that this is a reduced region in which the Euro Siberian and the Mediterranean biota are joined.

In this transition from Atlantic to Mediterranean climate, there is a wide variation of the spatial distribution of wet spell frequency due to the interaction of climatic, geographic and topographic factors. Generally speaking, the highest frequencies occur on the north side of the study area, while the lowest are located to the south, and there is coherence in the length of the average spell and the amount of precipitation that is registered.

The geostatistical techniques that have been applied to elaborate on the probability maps and the persistence maps reflect the general trends of precipitation behaviour in the area, given that the interpolation techniques have been applied over isotropic surfaces. Daily rainfall structure can be considered Markovian in the study area under the 1-, 5- and 10-mm thresholds.

Finally, one of the main outcomes of this research is that Markovian models can also be very useful to study the impact of climate change on temporal rainfall structure in areas where persistence is one of its key characteristics, such as in the Basque Country.

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