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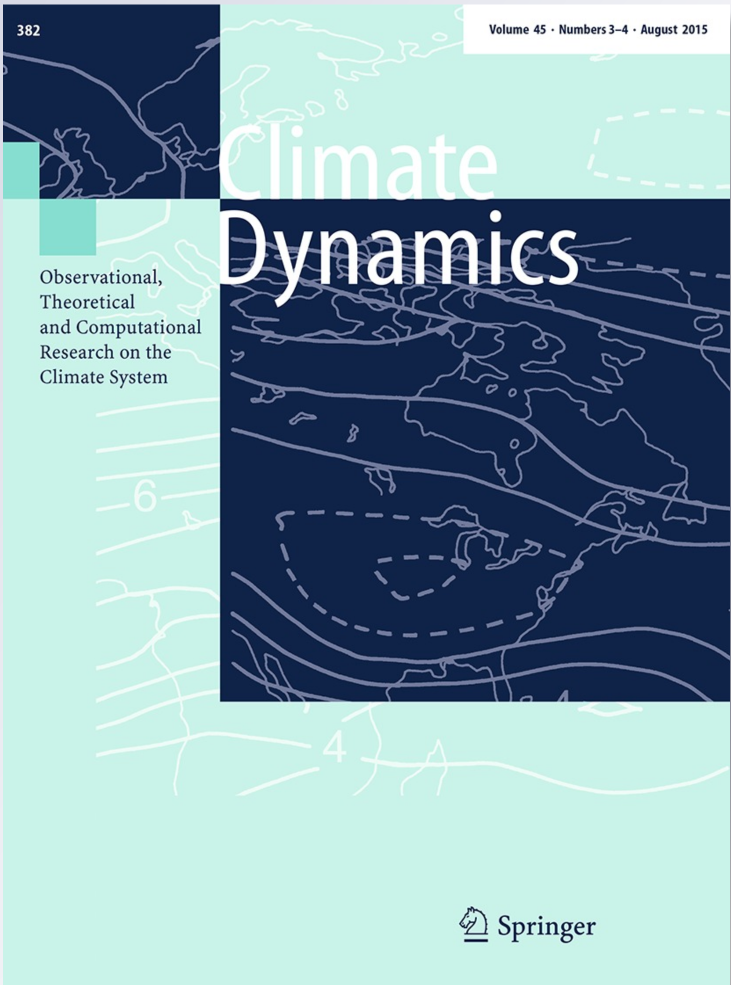

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Markovian characteristics of dry spells over the Iberian Peninsula under present and future conditions using ESCENA ensemble of regional climate models

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Abstract The study analyses the annual structure of dry spells over the Iberian Peninsula through a second markov chain model based on the persistence concept under present and future conditions. The persistence of dryness can be considered as an indicator of drought, being useful for early warning drought systems. It can be studied as an isolated factor, here we focus the analysis on the probability of dry spells occurrence at each grid point of the domain by means of a two-state second order of Markov Chain model. Previous studies using this model along twentieth century observational data obtained successful results in the dry spells characterisation over several regions. First, the application of this theoretical model on three observational datasets over the domain, confirms the second order of markov chain characteristics of the observed dry spells. Then, the observational climate (1989–2007) EraInterim-forced regional climate model simulations from Spanish ESCENA project are successfully compared with those observational datasets results. Then, the study of climate change projections on the markovian behaviour is studied through the ECHAM5r2 global climate model and the regional models under present (1970–2000) and future (2021–2050) climate conditions. They indicate that the markovian characteristics of dry spells are kept in the future over the domain except some points in the South East coast. A decrease of the probability of occurrence of short dry spells (1–7 days) is obtained, while the longest dry spells (>12 days) are increased. These results are coherent with the analysis of the annual average of dry spells length.

Keywords Dry spells · Markov chain · Regional climate models · ESCENA project · Iberian Peninsula

1 Introduction

Drought is one of the most costly natural disasters from economic and environmental points of view around many areas of the world. It occurs in all climatic zones affecting specially to economic climate sensitive sectors as agriculture, livestock (Mishra and Singh 2010) or health systems (García-Pando et al. 2014; Thomson et al. 2014). The fifth IPCC report (Hartmann et al. 2013) underlines the analysis of drought as a target process in climate change studies. In general terms, the drought is defined as a prolonged absence of precipitation, such as a season or a year, that results in water shortage for some activity or for some group (Solomon et al. 2007). As the drought is a mixture of complex processes, different definitions are found according to different perspectives. Wilhite and Glantz (1985) classify the drought in four categories: meteorological, agricultural, hydrological, and socio-economic. They differ

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in the considered processes, for example, while the agricultural definition takes into account the evapotranspiration and soil moisture, the socio-economic contemplates the demand of water of the society. However, the lack of precipitation during a long time or dryness is the common factor in all of them, being considered as an essential process of the drought. Thus, expected regions to suffer dryness in the future due to changes in the spatial-temporal precipitation distribution are identified as vulnerable related to climate change drought impacts (Sheffield and Wood 2008).

Furthermore, the perception of drought differs among regions and time periods (Vicente-Serrano 2006). Wilhite and Svoboda (2000) illustrate it with the next example: 2 months without rainfall during the growing season may result in serious drought conditions in sub-humid climates. This period can be considered normal for semiarid climates, where water reservoirs may be used for crops adapted to that region. This aspect points to the need of local drought indicators that help water management in the planning and response to droughts (Wilhite and Svoboda 2000; Robertson et al. 2014). Duration, frequency and persistence of dryness are considered as the main indicators. All of them have the advantage that can be quantified through the definition of a threshold, that distinguishes a drought category, and determines when drought response actions should begin or end (Steinemann 2003). The study of these indicators are an essential tool in the drought early warning systems needed to plan adaptation and mitigation strategies in the water managing policies (Wilhite and Svoboda 2000). The definition of a dry spell as the number of consecutive dry days is a very useful magnitude to know the behaviour of dryness of a region. General features of dry spells focused on their duration and frequency have been widely studied (Llano and Penalba 2011; Sarhadi and Heydarizadeh 2013; Serra et al. 2013). However, some authors (Singh et al. 1981; Anagnostopoulou et al. 2003; Cindrić et al. 2010) remark that a deeper analysis of the dry spells including the persistence, is needed to take into account also the temporal structure of the drought.

The persistence of an event is related to the maintenance of a state of the climatic system throughout the time. From a statistical point of view, persistence can be measured as the probability of the system to stay in a given state, that should be greater than the probabilities to change (Wilks 2005). The binary perception of the precipitation allows the analysis of the persistence of both dry and wet events. Thus, the persistence of dryness can be computed as an isolated factor or can be consider into the study of probabilities of occurrence of dry spells. The probabilities of occurrence allow to know what dry spells length is characteristic of a region. Studies on month or seasonal basis could help to identify the driest month and seasons of a region (Douguedroit 1987; Srinisareddy et al. 2010; Penalba and Llano 2008; Agnese et al. 2014). But spells longer than these periods then could not be detected (Anagnostopoulou et al. 2003), and this is the case of many parts of the Iberian Peninsula, specially over the southern part of the region.

Several probability models are used to compute the probability of occurrence of dry (wet) spells during *n* days, based on the concept of persistence of dryness (wetness) using different statistical approaches (Deni et al. 2008). Among them, the Markov Chains models (MC) is one of the most employed (Deni and Jemain 2009). This model considers the persistence as the conditional probabilities of the dry (wet) days, that is, the dryness (wetness) of the present day depends on the state of the previous days (Wilks 2005). It can be used for different orders, corresponding with the number of preceding days that determine the present day system state. For example, a second-order Markov chain considers the states of the two preceding days and the third-order, of the three preceding days. Gabriel and Neumann (1962) found that the occurrence of daily precipitation has a double-state first order Markov Chain characteristics. Different orders of model have been used to describe the phenomenon or tendency of dry (wet) periods to persist (Ochola and Kerkides 2003; Tolika and Maheras 2005; Schoof and Pryor 2008; Khoshghalb et al. 2010; Mahmud and Deni 2011). However, different studies along twentieth century suggested a second order in the study of dry spells (Singh et al. 1981; Lana and Burgueño 1998; Dastidar et al. 2010). The translation of these studies into the future would allow to estimate how the dry spells characterization of a region would change as a response to climate change conditions. This could be useful to the water managers to plan long term strategies, specially in areas where a larger precipitation variability regimes affects seriously water resources, and thus impacting over economic sectors as agriculture or tourism, as well as, health system (Wilhite 2005; Cook et al. 2008).

The Iberian Peninsula region (IB), including the Balearic Islands, is an excellent example of areas located between temperate and subtropical climates, where hydrological stresses, with large periods of precipitation absence, are very relevant (Font Tullot 2000). This transitional climatic situation characteristic causes the precipitation and its variability to be determined by different atmospheric patterns, that cause significant spatial differences in the dry spells behaviour (Martin-Vide 2004; Vicente-Serrano 2006; Lionello 2012; Zolina et al. 2013). Previous studies have analysed the temporal structure of dry/wet spells in specific areas of the domain using meteorological station data (Lana and Burgueño 1998; Ceballos et al. 2004; Fernandez-Arroyabe Hernáez and Martin-Vide 2012). These studies are in agreement with the markovian behaviour of dry spells in the IB. Different markovian behaviours are found between the North, with low persistence of dry days and

Table 1 Description of the (a) Observational gridded datasets (b) Regional Climate Models and (c) Global Climate Model employed along the present study

	Reference	Horizontal resolution	Baseline period 1989–2007	Present period 1971–2000 (SRES 20C3M)	Future period 2021–2050 (SRES A1B)
(a)					
Spain02	Herrera et al. (2012)	0.2°	X	X	–
E-OBSv6	Haylock et al. (2008)	0.25°	X	–	–
CPC	Chen et al. (2008)	0.5°	X	–	–
(b)					
PROMES					
REMO	ESCENA Project		EraInterim	ECHAM5r2	ECHAM5r2
WRF-A	Jiménez-Guerrero et al. (2013)	0.25°	Forcing	Forcing	Forcing
WRF-B					
MM5					
(c)					
ECHAM5r2	Jungclaus et al. (2006)	1.875°	-	X	X

Their use in the different time periods is marked with X

the South, with a subtropical character of the precipitation, with a large persistence of dry days. This clear distinction was pointed by Martín-Vide and Gomez (1999).

Regional climate models (RCMs) have demonstrated to be an adequate tool in the study of dry spells characteristics in the future (May 2008; Giorgi and Lionello 2008; Sushama et al. 2010; Bouagila and Sushama 2013; Sánchez et al. 2011; Giraldo Osorio and García Galiano 2012). Projections at the end of twenty first century indicated the South of the IB as one the areas with the largest increases of the length of the dry spells over the Mediterranean region (Beniston et al. 2007; Gao and Giorgi 2008; López-Franca et al. 2013). Due to their high spatial resolution information, sharing the physically-based description of the atmospheric evolution equations of the smaller resolution Global Climate Models (GCMs), they can be very useful in the analysis at local scales, for example in regions with complex orography as the IB (Sánchez et al. 2011; Giraldo Osorio and García Galiano 2012; Domínguez et al. 2013).

The main target of this work is the study of the markovian behaviour of dry spells over the Iberian Peninsula as described by the regional climate models under present and future conditions. A background of dry spells lengths analysis over the domain and their projected changes in the future is needed to understand the markovian processes features. Thus, the first aim is to apply a double-state second order of Markov chain model over gridded observational datasets to check if the markovian process is a characteristic of dry spells over the domain of study. Once this analysis is performed, the second aim is to evaluate the ability of the RCMs to reproduce the spatial pattern of the observational results in the observational period (1989–2007). Finally, the last aim is to inspect the projected changes in the markovian characteristics of dry spells from the RCM-GCM forced simulations at the middle of twenty first century (2021–2050) under A1B SRES emission scenarios with respect to present climate conditions (1971–2000). The work is structured as following: in the Sect. 2 the data and methods employed are explained. The results obtained are described in the Sect. 3. The discussion of the principal findings are exposed in the Sect. 4.

2 Datasets and methods

2.1 Datasets

Daily precipitation amounts over the IB is the variable used as the basis in the analysis. Observational datasets, regional and global climate model outputs are the results employed along this study. A summary of the main characteristics is shown in Table 1.

Three observational gridded datasets (Spain02, E-OBSv6 and CPC) are used to first describe markovian characteristics over the domain in the observational period (1989–2007). Spain02 dataset (Herrera et al. 2012) is obtained from the most dense network of observational stations available over the region of study. E-OBS version 6 (Haylock et al. 2008) and CPC (Unified Gauge-Based Analysis of Global Daily Precipitation) (Chen et al. 2008) datasets are also employed because their large domains allow to reproduce the proposed methods in other regions of the world.

The analysis of markovian characteristics of the dry spells for present (1971–2000) and future (2021–2050) periods are computed from five RCM-forced simulations provided by ESCENA Spanish project (2008–2012) (Jiménez-Guerrero et al. 2013): PROMES, REMO, WRF-A, WRF-B and MM5. The two configurations of WRF model, A and B, differ in the planetary boundary layer (PBL) scheme (Jiménez-Guerrero et al. 2013). Most of these RCMs were also included in the ENSEMBLES European project (2004–2009) (Van der Linden and Mitchell 2009) with the same horizontal resolution. Simulations at ESCENA ensemble include new versions of the RCMs, more emissions scenarios and other GCMs forcings. Moreover the domain is centred over the IB rather than over the centre of Europe (Domínguez et al. 2013), and therefore covering more Atlantic area and northern Africa. Thus, they can be considered as a valuable complement over ENSEMBLES when focusing on impact studies over the IB.

The ESCENA RCMs used in this study are first forced by ERA-Interim reanalysis (Dee et al. 2011) in the observational period. The length of observational period is mainly limited by the availability of that perfect boundary conditions reanalysis at the time the project was developed, together with the longest common time periods of the observational databases.

Moreover the RCMs employed in this study also are forced by the ECHAM5r2 GCM (Jungclaus et al. 2006) for present period under 20C3M SRES and future under A1B SRES emissions scenario (Solomon et al. 2007). The analysis of the ECHAM5r2 GCM also is computed for present and future climate conditions. The choice of these periods follows two main conditions that allows to inspect the potential changes due to greenhouse gases emission changes. The first one is that present and future periods were separated enough in the time line, while the second one is that the time period lengths were equal, in this case, they cover the classical length of a climatology (30 years).

2.2 Methods

Different rainfall thresholds can be chosen to define a dry day. In this work a 1 mm/day is used, commonly applied when RCMs are applied (Heinrich and Gobiet 2012; Giraldo Osorio and García Galiano 2012; Domínguez et al. 2013). Hence, a dry spell is consider as a number of consecutive dry days.

A first overview to focus the present study can be obtained with the annual average of dry spells length (AADSL), computed for Spain02 for present climate period. Only this observational dataset is considered because it is one with the most dense observational data over the domain. Then, the AADSL spatial pattern under present climate conditions and its change in the future under SRES A1B scenario is computed from each RCM ECHAM5r2-forced simulation. The adequate reproduction of the present-day (observational period) dry spells characteristics from ESCENA RCMs has been already shown in (Domínguez et al. 2013).

Secondly, a double-state second order of Markov chain model (MC2) is chosen as the theoretical model to study the markovian behaviour of the dry spells over the IB. The suitability of the MC2 theoretical process as a characteristic of the dryness in the domain is tested for the observational datasets in observational period. Then, the ability of each RCM to reproduce these observational spatial behaviour of MC2 is checked. For this aim, the observational results are compared with those obtained by ERAinterim reanalysis-forced RCMs in the same period (observational period). In this step, the study of each RCM simulation is a usual procedure to inspect uncertainties and individual model biases due to the parametrizations used to describe climatic processes. This individual information could also be very valuable in further studies where these climate models could be employed to analyse another dry spells characteristics over the IB.

Finally, to inspect how climate change will affect to the markovian process features in the future, RCM ECHAM5-forced simulations are studied for present and future 30-year periods. The change signal is computed in percentage as: $((Future - Present)/Present) * 100$. The comparison between RCMs and GCM simulations allows to check if the higher horizontal resolution is able to give more regional features, specially in orographically complex areas.

The computations of mean length and frequency of dry spells are under an annual base at each model grid point. The annual mean frequency of dry spells is computed by dividing the total number of dry spell (TNDS) for each length to the number of years of each period (Anagnostopoulou et al. 2003; Tolika and Maheras 2005). In the analysis of the markovian characteristics of the dry spells, the empirical and theoretical dry spells frequencies are first estimated for the observational gridded dataset and climate models. By empirical frequencies we mean those computed from the dataset outputs directly, while the theoretical frequencies are those resulting after applying the MC2 model. The theoretical frequencies, covering all dry spells lengths are determined as the probability of occurrence (Q_n) multiplied by the empirical sample size, N. The probability of occurrence of a dry spell lasting n days (Q_n) from MC2 model is computed through the following analytical expression (Wilks 2005):

$$\begin{aligned} Q_n &= p_{100} \cdot (p_{000})^{(n-2)} \cdot p_{001}, \quad for \quad n \geq 2 \\ Q_1 &= p_{101} \end{aligned} \qquad (1)$$

where 0 represents a dry day and 1 a wet day. p (conditional probabilities) means that the transition probabilities depend on the states (values of the time series) at lags of both one and two time periods. p_{100} is the prior probability of the dry spell. They are obtained from the conditional relative frequencies of the transition counts (n_{hij}) and the marginal totals ($n_{hi\bullet}$), hence:

$$p_{hij} = \frac{n_{hij}}{n_{hi\bullet}} \tag{2}$$

where h denotes the state at time $(t-2)$, i denotes the state in time $(t-1)$, and j specifies the state at time (t). The notation can be defined as:

$$p_{hij} = \{X_t = j \mid X_{t-1} = i, X_{t-2} = h\} \tag{3}$$

That is, given that the value of the time series at time $(t-2)$ was X_{t-2} and the value of the time series at time $(t-1)$ was X_{t-1}, the probability that the present (t) value of the time series $X_t = j$ is p_{hij}. As a result of it, the four combinations of the conditional probabilities for the indices h, i and j, are:

$$p_{100} = \frac{n_{100}}{n_{10\bullet}};\ p_{000} = \frac{n_{000}}{n_{00\bullet}};\ p_{001} = \frac{n_{001}}{n_{00\bullet}};\ p_{101} = \frac{n_{101}}{n_{10\bullet}} \tag{4}$$

where, the marginal totals correspond to:

$$\begin{aligned} n_{10\bullet} &= n_{101} + n_{100} \\ n_{00\bullet} &= n_{001} + n_{000} \end{aligned} \tag{5}$$

- p_{100} is the probability of a dry day following a dry day when the day before is a wet one.
- p_{000} is the probability of a dry day after two consequently dry days.
- p_{001} is the probability of a rainy day after two dry days.
- p_{101} is the probability of rainy day following a dry day when the day before is a wet one.

- The goodness-of-fit of the empirical frequency distribution to the theoretical model is computed by the χ^2 test (Wilks 2005) for all the datasets. This test is recommended to compare a data histogram with the probability distribution for discrete variables. It actually operates more naturally for discrete random variables, since to implement it the range of the data must be divided into discrete classes (Wilks 2005).

To establish the classes, the observational Spain02 dataset has been selected. The choice of this dataset as the reference for this computation is because this study considers it as the best available observations gridded dataset of the domain because as it involves the largest number of meteorological stations. The number and definition of the classes presents a somewhat arbitrary criteria (Anagnostopoulou et al. 2003; Tolika and Maheras 2005). Here, they have been chosen taking into account at least five theoretical counts per class, to avoid classes with very small number of events (Wilks 2005). Hence, three dry spell length classes are defined. They are grouped for adjacent spells, resulting in:

- Short dry spells length (SDSL): 1–6 days
- Medium dry spells length (MDSL): 7–12 days
- Long dry spells length (LDSL): >12 days

- Thus, the null hypothesis H_0 considers that the empirical distribution fits to MC2 process, while the alternative H_1 does not consider it. To contrast the null hypothesis H_0 against the alternative H_1, the Pearson statistic (λ) is computed with a significance level of $\alpha = 0.05$. For each class the empirical and theoretical frequencies are the result of the sum of the different dry spells length frequencies. Therefore, the sum of the probabilities of the three dry spell classes is equal to 1.

$$\lambda = \sum_{classes} \frac{(Empirical\ TNDS - Theoretical\ TNDS)^2}{Theoretical\ TNDS)} \tag{6}$$

H_0 is accepted if $\lambda < \chi^2_{k-1;\alpha}$, being k the number of valid classes to be consider into the test at each point. Dry spell classes with a theoretical frequency less than five counts are not considered.

The measure of fitting quality of the empirical frequency dry spells distribution to MC2 theoretical model at each grid point is made through the H_0 and k criteria. A fitted grid point means that the H_0 is accepted and $k \geq 2$, hence the probability of occurrence is computed applying MC2 model. However if a grid point does not follow these two conditions, it is considered as unfitted and the probability of occurrence is not computed. Both, the fitting of the empirical distribution to MC2 process and the probability of occurrence by the established dry spells length classes are showed in the next section.

3 Results

3.1 Dry spells length spatial distribution for present and future conditions

The Fig. 1 shows the spatial pattern of AADSL over IB for present climate conditions (1971–2000) from Spain02 observational dataset and from the five RCM ECHAM5r2-forced simulations under SRES 20C3M for the same period, as well as its projected changes for 2021–2050 under SRES A1B emissions scenario. The results of the ECHAM5r2 GCM are also presented.

The observational gridded dataset Spain02 presents a North to South gradient of the AADSL along the IB. In

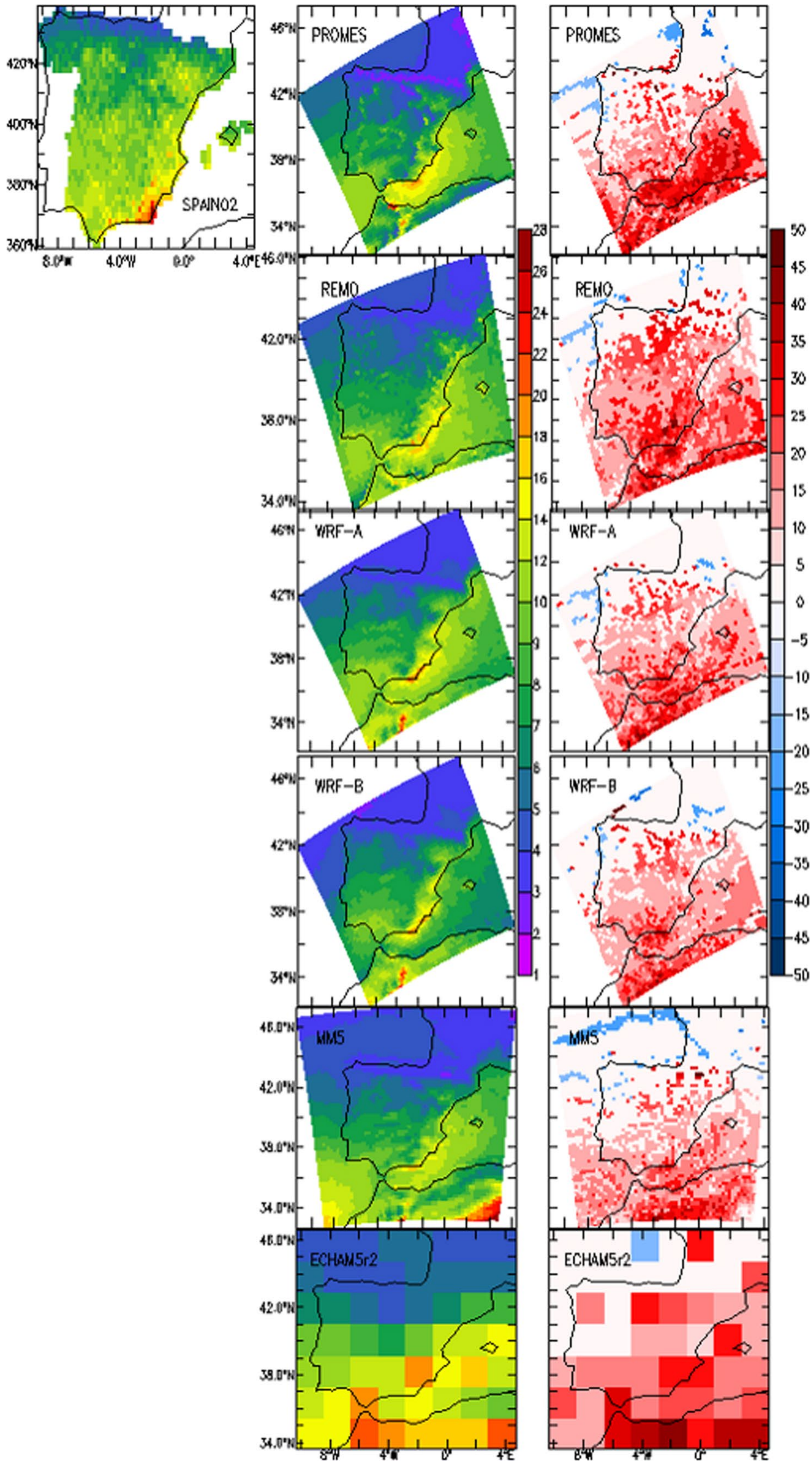


Fig. 1 Spatial pattern of the annual average of dry spells length over the Iberian Peninsula. The first column represents the Spain02 observational gridded dataset and the second one corresponds to ESCENA ECHAM5r2-RCM forced simulations. Both are computed in present period (1971–2000). The third column shows the climate change signal for future (2021–2050) as percentage respect to the present period (1971–2000). The leftmost color bar are related with the average of dry spells length in days, while the rightmost one corresponds to % of probability differences

the Cantabrian coast and Pyrenees, the dry spells length around 3–5 days. From here, the values are increased to the South with values of around 6–14 over the South Subplateau. The maximum values (between 20 and 28 days) are obtained in the South East region. Effects of orography on the AADSL spatial pattern are obtained in the Iberian and Central mountain ranges (around 6 days, slightly slower than their surrounding values) and at the Ebro river basin (around 15 days). Balearic Islands (BA) seems to show a latitudinal pattern, with values around 9 days. Similar spatial patterns are found by Domínguez et al. (2013) in their study of the CDD (Consecutive Dry Days) ETCCDI index (Zhang et al. 2011) over the IB from the ESCENA RCM-EraInterim forced simulations.

For this present climate 30-year period, the regional climate model simulations reproduce the same AADSL pattern described by Spain02. The RCM simulations exhibit perhaps a more homogeneous pattern than the observations, with the areas of maximum (around 20 days in the South East) and minimum (around 2–5, in the North) values. The RCMs show a close concordance among them and with the ECHAM5r2 GCM. These results are coherent with those found by Herrera et al. (2010) in their study of consecutive dry days using Spain02 and ENSEMBLES RCM present climate simulations. This global climate model clearly overestimates the Strait of Gibraltar values (20 days) with respect to the RCMs and Spain02 (around 12 days), probably related to the difficulties of the GCM to properly describe the land-ocean features. This strait is likely not be considered as an oceanic point for the GCM. Not all the RCMs show the same orographic detail, being PROMES model the one that exhibits more details.

With respect to the change (in percentage terms) of AADSL projected for future conditions, all of the simulations coincide in the same spatial pattern gradient. The North of IB does not present noticeable changes, while the South East areas show the largest increases, reaching +50 % in some points. BA projects increases around +15–25 %. Again ECHAM5r2 GCM overestimates the Strait of Gibraltar values (by +30 %) respect the RCMs (by +20 %). These climate change projections are in agreement with those found by Sánchez et al. (2011) and Giraldo Osorio and García Galiano (2012) using PRUDENCE and ENSEMBLES RCM datasets, respectively.

3.2 Markovian behaviour of gridded observational dry spells (1989–2007)

The Fig. 2 depicts the empirical dry spells distribution fitting to MC2 process over the whole domain, describing the probability of occurrence of each of the three dry spell length classes for the three observational datasets available for the observational period (1989–2007). The points where the null hypothesis (H_0) is rejected are marked as black, hence in these points the fitting to MC2 does not occur.

All the observational datasets successfully fit the empirical dry spells distribution to MC2 model in almost all over the domain, confirming the markovian characteristics of the dry spells over the IB. Moreover, the three describe a very similar spatial pattern for each dry spell length class. The small differences among them are related to the horizontal resolution they use, the number of observational data used in their construction, and the numerical methods employed in their interpolation procedure.

Spain02 dataset (first row of Fig. 2) shows a latitudinal gradient of the probability of occurrence in all of the classes, with the maximum values in the North and the minimum in the South for the SDSL (dry spells length between 1 and 6 days), while MDSL (between 6 and 12 days) and LDSL (more than 12 days) present the inverse spatial pattern. The differences between the maximum and minimum values are higher in the SDSL (around 0.35) and LDSL (around 0.5) than in the MDSL (around 0.15), that presents a more homogeneous spatial pattern along the domain. The SDSL reach 0.85 of occurrence probability in the North, decreasing to the South with the lowest values in the South East (around 0.40). The Central System and Iberian mountain ranges present values around 0.60, slightly larger than its surroundings, and BA exhibit values of 0.50 of probability. The MDSL present lower values than the SDSL. Moreover, its spatial pattern is different from the other two classes. This medium length class seems to be influenced by both the Cantabrian and Mediterranean seas. The maximum probabilities of occurrence (around 0.25) are located in the Ebro river basin and most of the North of the Mediterranean IB coast, while the minimum ones (around 0.13) are in the northern coast and some points of the South East. BA show values around 0.24 following a slightly latitudinal gradient. The LDSL describe a very similar spatial pattern to the SDSL one, but reversed in relation with the probability values. The maximum probabilities of occurrence are located in the South East region (around 0.50) and the minimum in the North (between 0.05 and 0.10). As it occurs in the SDSL, the Central System and Iberian mountain ranges present a relative maximum, with values around 0.20. The BA ranges from 0.20 to 0.30.

E-OBSv6 and CPC datasets identify the same areas with maximum and minimum values of probability of occurrence in all of the classes, but with lower spatial grid resolution and detail with respect to Spain02. The orographic effects on the SDSL are observed in the Central and Iberian mountains ranges, with 0.50 of probability of occurrence, and CPC dataset extends this values also over the northern half of Portugal. Both datasets have the minimum values of probability (around 0.35) in the South East. For the MDSL these observational datasets extend their minimum

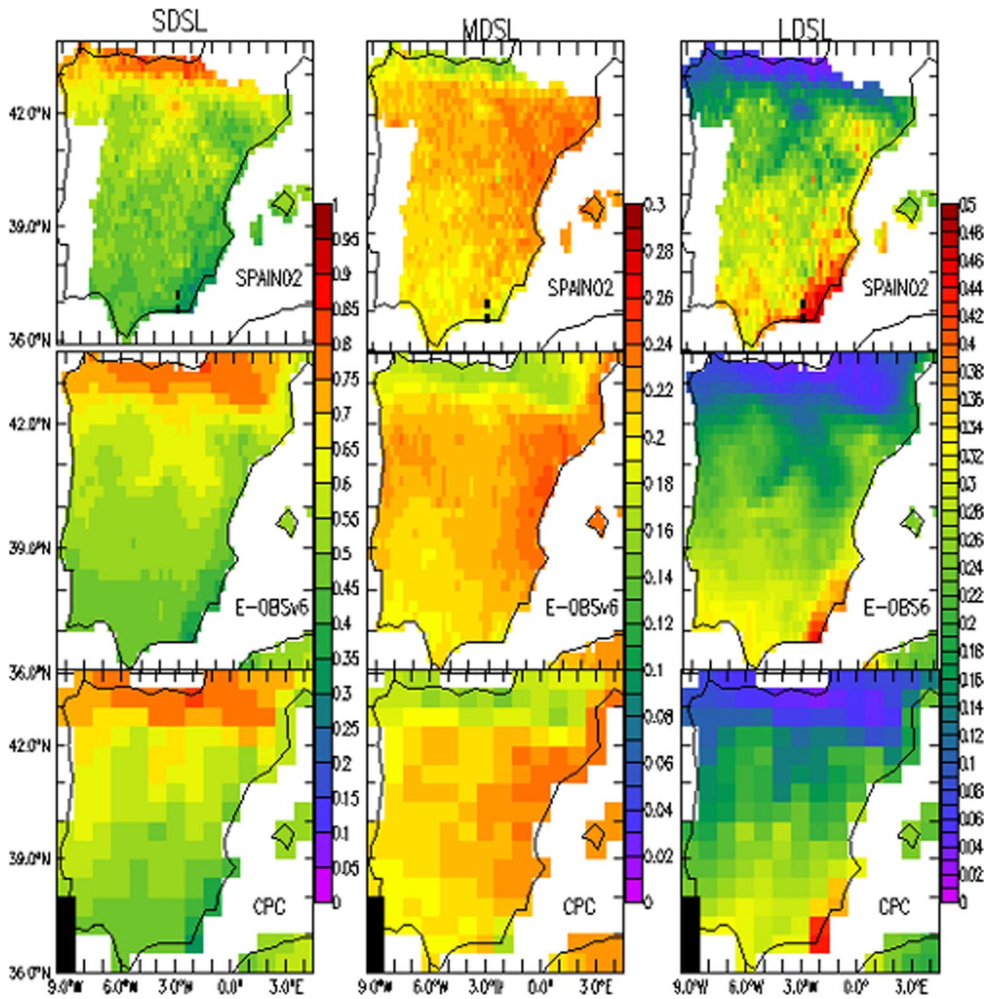


Fig. 2 Probabilites of occurrence of dry spell length classes over the Iberian Peninsula by Spain02, E-OBSv6 and CPC observational datasets in observational period (1989–2007). The dry spell length classes are organized by columns, being from left to right: short (SDSL), medium (MDSL) and long dry spells length (LDSL). The unffited grid points to markov chain model are marked on black

probability of occurrence (around 0.15) all over the North coast and Pyrenees range, showing also minimum values in some point of the South East of IB, specially in CPC. The LDSL present a more smoothed spatial behaviour than in Spain02, but identifying the same minimum values (between 0.02 and 0.1) in the Central and Iberian ranges and the maximum (around 0.45) in the South East as in the Spain02 results.

Therefore, the main result found in this subsection is that, despite the observational dataset it is analyzed, the same spatial pattern is observed for each dry spell length class.

3.3 Markovian behaviour of dry spells as modelled by the RCMs (1989–2007)

The Fig. 3 displays the performance of RCMs to reproduce the markovian characteristics obtained by the observational datasets for the same time period. Thus, the ERA-Interim reanalysis-forced RCM simulations are compared with observational results (Sect. 3.2) in the observational period (1989–2007).

The annual dry spells empirical distribution fits with the MC2 model almost all over the domain, only just a few unfitted isolated points appear in the simulations, located in the North (PROMES) and in the South East of the IB (WRF-A, WRF-B and MM5). The RCMs simulations reproduce the spatial pattern of the three dry spell length classes given by the observational datasets (Fig. 2), perhaps with a more marked orographic detail. A close overall agreement among all the RCMs is seen. In general terms, PROMES regional model presents a more patchy pattern, while MM5 has more smoothed values along the domain. REMO is the closest simulation to Spain02 dataset results, and both WRF configurations present similar results.

In the northern half of the IB, the simulations enlarge the SDSL maximum probability (around 1) of Spain02 results to the peak points of Central and Iberian mountains ranges. The eastern coast and Ebro river basin are distinguishable with values between 0.4 (South East) to 0.50 (Ebro river

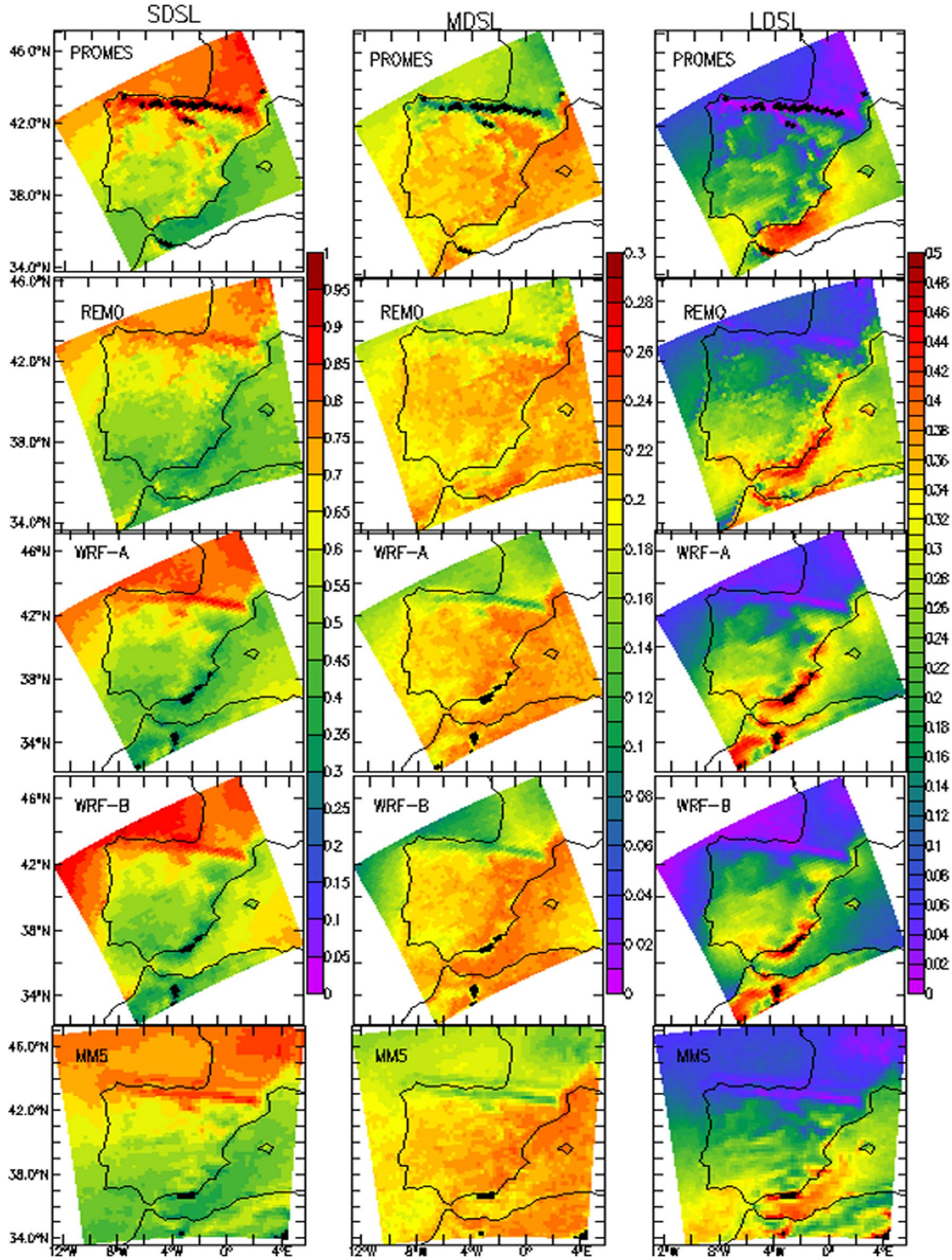


Fig. 3 As Fig. 2 but for ESCENA RCMs forced by EraInterim reanalysis on observational period (1989-2007)

basin). BA is successfully represented by all of the simulations when compared with observations.

With respect to the MDSL class, all the simulations exhibit values of probability around 0.12 at some northern points of IB, being then slightly lower than in the observational datasets (around 0.15). The eastern coast of IB, including the Ebro river basin present similar values to observations (around 0.25).

As in the MDSL case, the simulations present lower values of LDSL occurrence probability in the northern half part of the domain (near to 0 probability), and higher in the eastern coast and Ebro basin (around 30) than observations (around 0.1 and 0.2 respectively). The orographic features effect on the markovian behaviour of dry spells is clear for this class. While the Central system and Iberian mountain range exhibit the minimum values (0 to 0.10), the maximum (0.5) is located in some local areas of the South East of IB in all of the simulations except PROMES model displaces these maximum values to the Mediterranean sea. The Ebro basin present values around 0.3 for almost all the simulations, except PROMES and MM5 (0.25).

Overall, these results indicate the ability of RCMs to reproduce the markovian character of dry spells for each of the classes in the IB found by the observational datasets in the observational period.

3.4 Changes in the markovian characteristics of dry spells at the middle of twenty first century

This subsection analyses the results of the dry spells markovian behaviour from the ECHAM5r2-forced RCMs and ECHAM5r2 GCM simulations. It analysis is divided in two parts. First, the empirical frequency distribution fitting to MC2 model and the probability of occurrence by classes are analysed for present climate conditions (1971–2000). Then, their projected changes under SRES A1B emissions scenario conditions (2021–2050) are presented.

3.4.1 Present climate conditions (1971–2000)

The analysis of present period under SRES 20C3M greenhouse gases concentrations is described in the Fig. 4. All the climate models obtain an empirical dry spells frequency distribution that fits to MC2 theoretical model in all the study domain. Just some unfitted points are located in the North in PROMES and MM5 simulations.

In general terms, the dry spell classes simulated by the climate models show the same spatial pattern than the obtained results in observational period (Fig. 2). PROMES stands out for their more local details, while the rest of RCMs present a smoother pattern. ECHAM5r2 GCM exhibits globally the same spatial pattern as the RCMs, but with relevant local differences in shape and value, due its lower spatial resolution.

Following the N–S gradient displayed by ERA-Interim forcing (Fig. 2), the maximum probabilities of occurrence of SDSL are located in the North, Central system and Iberian mountain ranges, between 0.75 to around 1 for the highest orographic points. Lower values (between 0.35 and 0.5) are obtained in the eastern coast and Ebro basin, locating the minimum in the South East (around 0.35) for all the RCMs simulations. The GCM obtains the same spatial pattern as the RCMs, despite the regional details. Its maximum values are between 0.7 and 0.75, located in Central system and Iberian mountain ranges and the lowest (between 0.35 and 0.5) are shown in the Gibraltar strait and in the eastern coast of the IB.

The probability of occurrence of the MDSL, as in the observational period (Fig. 2) presents a more homogeneous structure. The highest values (between 0.20 and 0.25) are located in the East, with the maximum in the Ebro river basin for almost all the RCM simulations. ECHAM5r2 GCM presents similar values in Catalonia and the Center-East of the IB. In the RCM simulations, the lowest values are obtained in the North, Central system and Iberian mountain range (between 0.10 and 0.15), while ECHAM5r2 locates them in the Strait of Gibraltar (0.10). Low values are also exhibited in some points of the Iberian south-eastern coast (around 0.18) by the RCMs, while ECHAM5r2 extends them to the South. In BA, RCM simulations are similar to values (around 0.25) in observational period results (Fig. 2). However, ECHAM5r2 seems to underestimate it with values around 0.20, very probably related to the fact that these islands are considered as ocean points on this GCM.

The LDSL exhibit, as for the other classes, a similar spatial pattern than in the results shown in Sect. 3.3. The maximum values of probability of occurrence (around 0.5) are observed in the southeastern coast of IB for almost all the simulations. ECHAM5r2 presents their maximum values of LDSL probability over the Strait of Gibraltar. The lowest probabilities (between 0 and 0.05) are located in the North, increasing to South. Intermediate values are seen in the Ebro river basin and South subplateau (around 0.20) by all simulations. BA have around 0.3 of probability in the RCM simulations, while in the ECHAM5r2 reach the 0.45. Cantabrian and Mediterranean seas follow the latitudinal behaviour exhibited by IB in all the dry spell classes for the RCMs as well as for ECHAM5r2 GCM. It must be taken into account that over the ocean, the regional climate models are forced by the same oceanic temperatures coming from the GCM, and use probably very similar and simple atmosphere-ocean interchange schemes. Meanwhile, over land each model uses their own land surface scheme and therefore more different parameterization of fluxes and energy and mass interchanges.

A close agreement between the GCM and RCMs simulations, despite the resolution limitations, is then obtained. The GCM simulation identifies then the overall features of the markovian characteristics of dry spells over IB, being the fine scale of the RCMs the tool improve and give the local detail on the climate features of these processes.

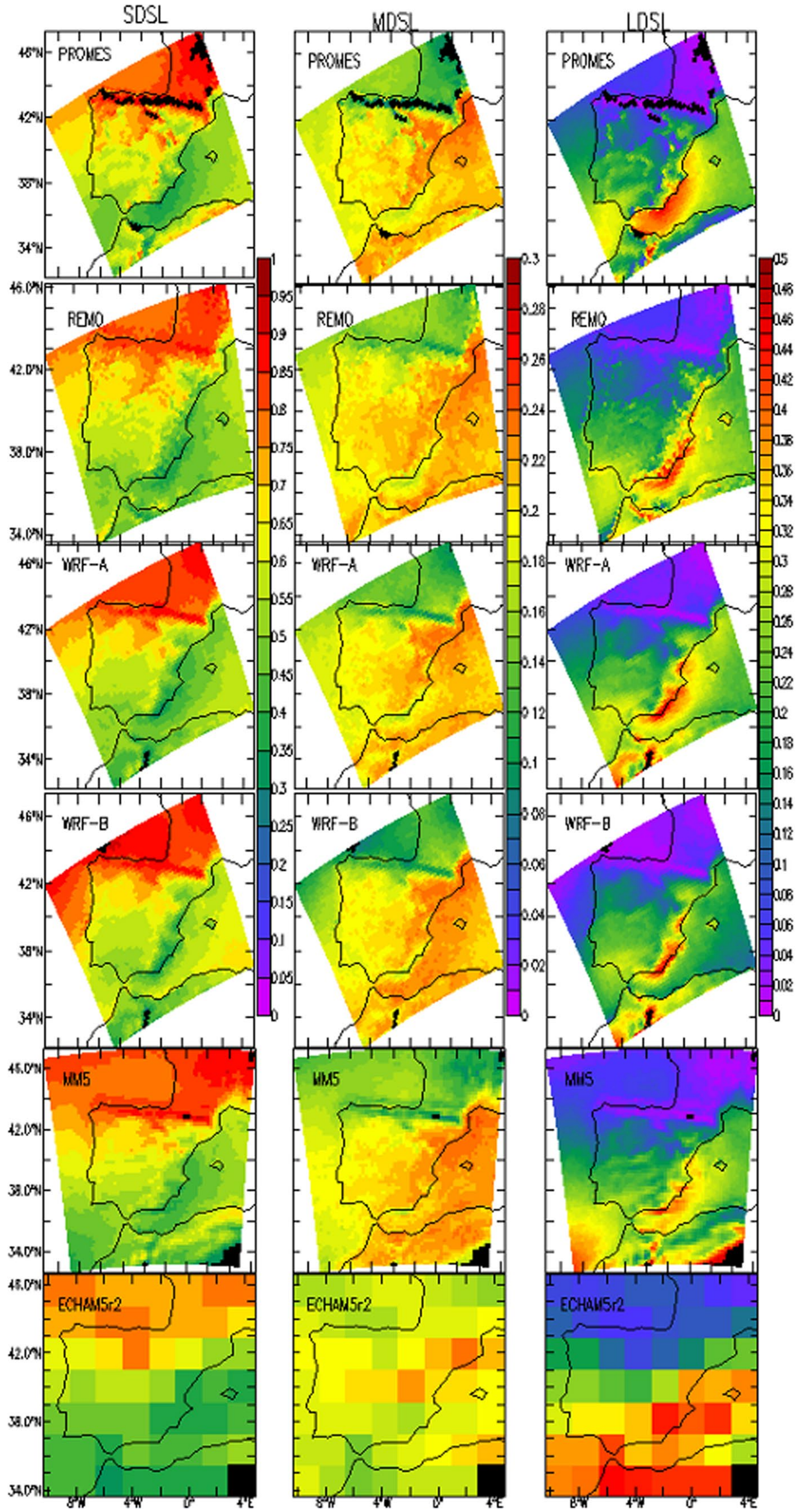


Fig. 4 As Fig. 3 but for ECHAM5r2-RCM forced simulations and GCM ECHAM5r2 in present period (1971–2000) under SRES 20C3M. The first five rows correspond with the RCMs and the last one with the GCM

3.4.2 Climate change signal under SRES A1B scenario

Figure 5 describes the changes of the fitting to MC2 and probability of occurrence of dry spells in the future (2021–2050) under SRES A1B emissions scenarios with respect to the present period (1971–2000) (Fig. 4).

According to these results, for future conditions, the successful of the empirical distribution fitting to MC2 process obtained for present conditions is kept all over the study domain. Just some points are then unfitted in the Iberian south-eastern coast, being obtained by all the simulations. ECHAM5r2 GCM displays, on its coarser resolution, the same behaviour over the Gibraltar strait. On the contrary, some isolated unfitted points become fitted in the Galician Massif, Pyrenees and Iberian mountain range by PROMES and in the Pyrenees by MM5 simulations. A close agreement of the projected changes for each dry spell length class is obtained among the regional climate simulations. As for the previous results, PROMES stands out for its more patchy pattern and MM5 for its more homogeneous pattern with also the lowest change values.

A general decrease of the SDSL probability of occurrence is obtained for all the simulations, keeping the N-S gradient showed for the present period (Fig. 4). The maximum decreases (around −18 %) are located in the South East of IB and any noticeable change is shown in the Atlantic areas and Galician Massif. BA presents decreases around −6 to −9 %.

The simulations coincide in the same regions that show relevant changes for MDSL, although more differences among simulations are found with respect to the SDSL and LDSL classes. PROMES and MM5 exhibit a general increases around by +10 % and decreases (−10 % by PROMES and −5 % by MM5) in some points of the North West and South. REMO, and the WRF simulations display increases (between +10 and 15 %) in the mountain ranges of the North, while the southern half present low decreases, reaching the maximum (−15 %) in the South East by REMO. All the simulations show small decreases or increases (between −5 and +5 %) in BA.

In the case of LDSL, the change in the probability of occurrence depicts a general increase over the domain, with a high agreement among all the simulations. The effect of the orographic features showed in the previous results of LDSL is kept or even increased in the change under future conditions, as the climate change signal also presents such structure. The mountain ranges of the North, specially the Central, Iberian and Pyrenees ranges, and the South East of IB show the maximum increases in all of the simulations (from +20 % in MM5 to +65 % in REMO). The Galician Massif shows decreases around by −20 %, while BA presents increases around +20 %.

The Cantabrian and Mediterranean seas follow a latitudinal spatial pattern of changes for all the dry spell length classes.

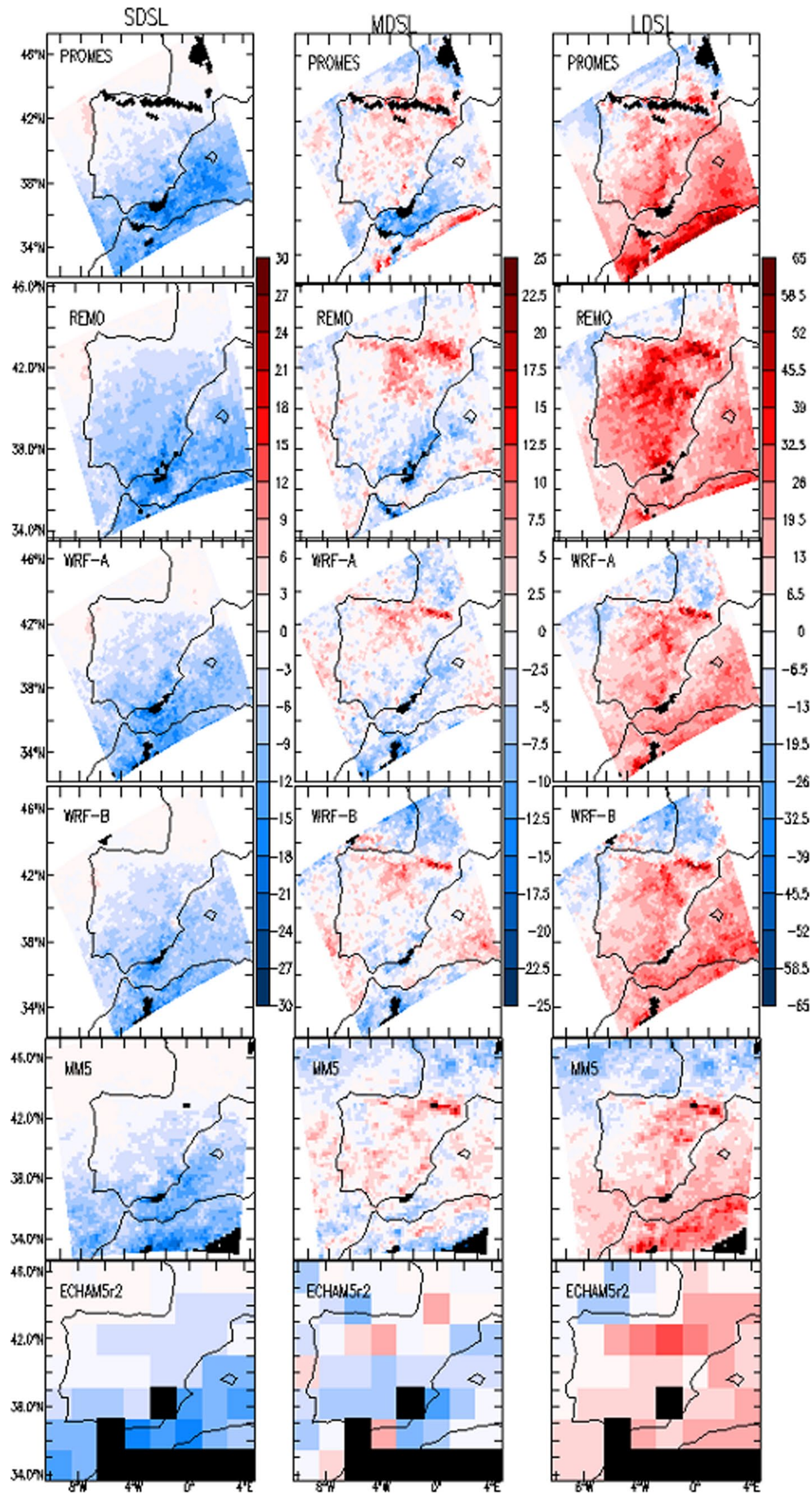
The results of this analysis show how the markovian character of the dry spells is kept in the future for almost all the domain, with only just some points of the southeaster losing this characteristic. In general terms, the probability of occurrence of SDSL decreases in the future, while an increase of the probability of LDSL is projected.

4 Discussion and conclusions

The present study analyses the characterisation of dry spells through a second order markovian process over the Iberian Peninsula. A goodness-of-fit of empirical frequency distribution to the theoretical model is made by the χ^2 test at the significance level of 0.05, obtaining successful results. From this theoretical model the probability of occurrence of three dry spell length classes (short (SDSL), medium (MDSL) and long (LDSL)) is computed at each grid point of IB. First, a background analysis about the annual average dry spells length on present (1971–2000) and future (2021–2050), has been done using Spain02 observational gridded dataset and ESCENA regional climate models. From this analysis, an increased North to South pattern of the dry spells length in the present and a general increase of the lengthening in the future under SRES A1B are obtained, as already seen in Sánchez et al. (2011). Three observational gridded datasets (Spain02, ECAv6 and CPC) have been used to analyse the markovian characteristics in the observational period (1989–2007). The North of Iberian Peninsula is characterised by SDSL, while the South, specially the South–East by LDSL. A strong effect of the main orography over the markovian process is shown specially in the short and long dry spells lengths. The good results of the RCMs to reproduce the markovian characteristics in all the models, demonstrate their adequateness to study temporal dependence relationships between dry days in the IB. Finally this RCMs are employed to project changes in the second order markovian chain behaviour of dry spells in the future under SRES A1B with respect to present. Here the RCMs project the same markovian behaviour in the future over the domain except in the South East, where this characteristic is lost. Short dry spells project a N–S decrease in their probability, while the long lengths increase over all the IB. Medium dry spell lengths show some discrepancies among RCMs. These results are in concordance with the background analysis of AADSL.

The results show that the observed dry spells over IB can be adjusted to a second order markovian process characteristics. This means that the occurrence of a dry day depends on that the two preceding days had also been dry, implying

Fig. 5 As Fig. 4 but for the percentage of change in the future (2021–2050) under SRES A1B respect to present climate conditions (1971–2000)



at the same time persistence of the dryness. This first main result is in agreement with previous studies over different areas of the globe, such as India (Singh et al. 1981) or a subregion of IB as Catalonia (Lana and Burgueño 1998), but it contrasts with those obtained by Martín-Vide and Gomez (1999) for the whole Spain. There, they conclude that the dry spells do not present a markovian behaviour in the South of Spain and the northern fringe needs a third-order to fit their empirical distribution to a Markov chain model. This disagreement with the results present here can be related to the differences in the used observational datasets, the dry day definition and/or the time periods employed in both works. We have also inspected the empirical distribution fitting to a MC2 process defining dry days as in Martín-Vide and Gomez (1999) ($0.1 mm/day$), and the adjustment is still successful in all the points of the domain from Spain02 gridded observational dataset and 1989–2007 as study period (results not shown). Hence, we consider that the possible main cause of this disagreement could be related to the type of observational datasets employed. Here gridded databases are used, and the interpolation procedure to each grid will probably obtain smoother values than the direct value of climatic variables from meteorological stations. Furthermore, Spain02 considers a very dense network of 2756 quality-controlled stations Herrera et al. (2012), and Martín-Vide and Gomez (1999) consider only 35 along Spain, using 10 of them to study the South part of the IB.

The analysis of the observational gridded datasets reveals that the decreasing N–S gradient of the probability of occurrence obtained in the SDSL is reversed from dry spells longer than 6 days (MDSL and LDSL). Thus, important differences between the North (including Central and Iberian systems ranges) and the South East of the IB are observed. The North of IB is characterised by short dry spells length adjustment (between 1 and 6 days), while the South, and especially the South East is characterised by long dry spells (lasting more than 12 days) with probabilities near to 1. The Central-South of IB, Ebro river basin and BA obtain a highest probability of occurrence of 0.55, related to the short lengths. Besides this obtained latitudinal pattern, a strong effect of the main orographic features of the IB over the markovian process of dry spells is also clearly seen. Features as the Pyrenees, Cantabrian coast, Central and Iberian mountain ranges, Ebro river basin, or South East of IB are easily distinguishable in the analysis of the three dry spell length classes, specially in the SDSL and LDSL. These spatial markovian characteristics of dry spells can be easily related to the spatial pattern of the annual dry spell mean (Fig. 1). Precipitation and its absence is locally modified from a larger scale features due to the presence of orographic structures. Respect to the latitudinal pattern, the AADSL in the North of IB presents values around 2–6 days of length, the eastern coast and South East present values higher than 10 days, while the Centre and South are around 7–12 days, corresponding, more or less, with SDSL, LDSL and MDSL classes respectively. The orographic features also are found in the AADSL analysis. All of these results are in agreement with other previous studies (Martín-Vide and Gomez 1999; López-Franca et al. 2013; Domínguez et al. 2013), reflecting the Atlantic, Mediterranean and orographic effects over the precipitation regime are the main factors that determine the dry spells characteristics over the domain (Font Tullot 2000; Herrera et al. 2010).

When comparing the three observational datasets, despite the similar results obtained by them, it can be seen that Spain02 reproduces more regional and orographic details of the domain than E-OBSv6 and CPC. This is probably due to the number of observational stations employed and its higher spatial resolution, being therefore the reference observational dataset chosen of this study. The limitation of this database is that its domain covers only Spain and BA, but not Portugal, to inspect the whole Iberian Peninsula. This good agreement among Spain02, E-OBSv6 and CPC observations let us suggest that over regions that use these last two datasets as gridded observations the methodology used here could be also successfully applied. Thus, the markovian dry spells characteristics obtained in IB and BA by E-OBSv6 and CPC could be compared with similar results over other areas of the world with comparable climate features related to dry spells characteristics.

The second main results obtained here is that all the RCM simulations reproduce successfully the spatial patterns of the MC2 dry spells behaviour given by the observational datasets in observational period. Thus, they can be considered as an useful tool to analyse projected changes in the markovian characteristics under different SRES emissions scenarios for future conditions.

Both the regional (RCM) and global (GCM) climate simulations for present climate conditions also present a similar and coherent spatial patterns between the markovian process and the AADSL over the domain. However, the RCM results provide an added value respect to the ECHAM5r2 results due to its higher resolution, and therefore, their capacity to reproduce regional features. As an example, the Gibraltar strait always exhibits very different values in the ECHAM5r2 with respect to RCMs and gridded observations. This is because of the fact that the GCM grid point there encompasses land from Spain and Morocco and the oceanic area of the strait, and therefore not correctly representing the processes involved on that area.

Despite the overall agreement among all the RCM simulations, some minor differences are also found. PROMES model always exhibits more local details, specially in the Mediterranean areas. Moreover it shows unfitted grid points in the northern mountain ranges at any studied period. This can be due that PROMES presents a wet bias with respect to the observed datasets (Jiménez-Guerrero et al. 2013). If the models overestimates the frequency of wet days, due probably to its convection scheme, then dry spells events features description are also likely to be affected. REMO seems to obtain the highest concordance with the observations. No large differences are found between the two configurations of WRF due their differences in the PBL description, as their effects on the precipitation are probably negligible (Jiménez-Guerrero et al. 2013). MM5 always present lower values than the rest of RCM simulations and the most homogeneous spatial pattern.

Finally, the third main result obtained is the good agreement among the regional climate model simulations observed in the climate change projections related to the markovian characteristics of dry spells. Although, the future conditions are not known, the convergence among simulations is considered as a reliability measure (Giorgi and Mearns 2002; Torres and Marengo 2013). Thus, the similar results obtained among the RCMs imply, from a qualitative point of view, a higher reliability of the projected changes in the MC2 dry spells behaviour in the IB. The whole domain maintains the MC2 characteristics of the present climate (1971–2000) dry spells in the future period (2021–2050), under SRES A1B emissions scenario, except just at some points of the South East of IB, where the adjustment is not then obtained. This last result can be due to large increases in the length of the dry spells as they can be observed in the results of the AADSL change in the future (Sect. 3.1) and previous studies over the IB (Sánchez et al. 2011; Giraldo Osorio and García Galiano 2012; López-Franca et al. 2013). With respect to the change in the probability of occurrence of the dry spell length classes, the SDSL project a latitudinal decrease of their probability of occurrence from North to South over the domain including Cantabrian and Mediterranean seas. In contrast, a increase of long length classes is showed over the whole domain, specially in the orographic points with highest altitudes, except in the North West, where low decreases or even without significant changes are seen. The Cantabrian sea shows increases and the Mediterranean sea (including BA) decreases. Medium dry spells durations exhibit some discrepancies between the simulations. While REMO, WRF-A and WRF-B project slight increases in the North and decreases in the South of IB, PROMES and MM5 display a general increase all over the domain.

In conclusion, this study presents the markovian characterisation of the dry spells over the Iberian Peninsula and the ability and capability of the RCMs as an adequate tool to analyse them, due to their regional characteristics, for present and future climate conditions. The obtained results can be useful to take them into account as indicators of drought in the planning of an drought early warning system over the Iberian Peninsula. Health system, agriculture and tourism are very sensitive sectors to drought impacts and the results presented in this study could be used in adaptation studies, and to understand and design mitigation strategies facing climate change. This study can also be performed over regions with similar precipitation regimes to inspect the applicability and to know to what extent the obtained results are similar over other regions. Several studies can be formulated after the obtained results from different points of view. For example, the results obtained by the ESCENA RCM simulations can be as reference in further studies about dry spells in the IB that use these models. Further analysis on a seasonal basis can help to explain the annual pattern of the dry spells distribution. Studies related with the persistence parameters for present conditions and their changes in future climate periods, could add more knowledge about the markovian behaviour of the dry spells taking into account that the best Markov order can be also a relevant factor when dealing with climate or impact studies. Although successful results has been obtained from a second order Markov chain process, we want to remark that it is not universal. Future works inspecting the best Markov order or the application of different theoretical models are important to complement the analysis presented here, and to find which one describe with more accuracy the temporal dependence between dry days into dry spell over the Iberian Peninsula.

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