Assessing drought hazard under non-stationary conditions on southeast of Spain

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Abstract The vulnerability of semi-arid basins such as the Segura River basin (southeast Spain), to rainfall variability, implies uncertainties in agricultural activities. Increasing the knowledge about plausible trends of drought events will improve the adaptation and mitigation measures. The non-stationary character of hydrometeorological series, based on climate and anthropogenic changes, is the main criticism of traditional frequency analysis. An innovative methodology for non-stationary analysis of droughts events, applying GAMLSS (Generalized Additive Models for Location, Scale and Shape) is presented. The analyses were based on observed data and selected regional climate models (RCMs). The series of maximum length of dry spells (MDSL) from observed data show an intensification of drought events in headwater catchments from the 1980s onwards. From various RCMs, plausible trends of MDSL are identified. By adjusting pdf to series of observed MDSL, applying GAMLSS and bootstrapping techniques, the assessment of regional trends associated to return period, from hazard maps is possible.

Key words drought; non-stationary probabilistic models; GAMLSS; Segura River Basin; Spain

INTRODUCTION

The analysis of time series is a main tool in hydrology and water resources management. However, the most used methods assume stationarity of hydrological processes. But, today, it is no longer possible to consider the hydrological systems as stationary, since these are affected by several drivers such as land-use change, groundwater development, dam building, climate variability and change (Milly *et al.*, 2008). This is the case of the basins of southeast Spain, such as the Segura River Basin (SRB), where a sharp decrease of runoff was observed in headwater basins from the late 1970s. These decreases were attributed to changes in land uses (intensive reforestation to halt desertification and erosion), as well as climate change and variability.

The hydroclimatic variability implies probability density functions (pdf) whose parameters vary with time. The pdfs are used for the evaluation and management of water supply risks, to estimate the design flood for hydraulic structures and for flood hazard/risk mitigation programmes. The assessment of floods and droughts are focused on the tails of the pdf, but the ability to predict or detect change is most effective on the central tendency (Hirsch, 2010). In this sense, the modelling tool GAMLSS, proposed by Rigby & Stasinopoulos (2005), provides a framework for the non-stationary modelling of time series.

The regional climate models (RCMs) provide information, with adequate spatial-temporal resolution that allows impact studies at basin scale of frequency and severity of dry spells, as well as to forecast plausible trends. The maximum dry spells (MDS), or the maximum number of consecutive days without rainfall, or days with rainfall below a threshold, are partial duration series. The MDS have major impacts on agriculture due to their influence on soil moisture content. Studies of non-stationary conditions will contribute to improve the drought contingency preparedness and recovery operations, at basin scale. Several authors have studied the variability of rainfall and dry spells in the Iberian Peninsula, applying pdfs in some cases, but without considering non-stationary parameters (Vicente-Serrano & Beguería-Portugués, 2003; Paredes *et al.*, 2006).

In the following section, the basin study, its zoning, and the databases to be used, are presented. Then, the GAMLSS tool is described, and subsequently applied to observed series of

MDS lengths (MDSL) for each zone of the basin after subdividing it. The ability of RCMs to represent the cdfs (cumulative distribution functions) of observed MDSL is evaluated. Based on bias analysis, results from selected RCMs in zones of interest are presented. Finally, spatial patterns of observed MDSL are identified by means of maps associated with several return periods and the time frame defined.

BASIN STUDY AND DATABASES

The Segura River Basin (SRB) located in southeast Spain (Fig. 1), with an area of 18 870 km^2, presents a semi-arid climate. Highly regulated, its main water demand corresponds to agriculture. Due to water scarcity, which the basin suffers in a recurrent form, it regularly receives water transfer from the Tagus River Basin and water from desalinization. The SRB was selected as a Spanish Pilot River Basin under the *European Group of Experts of Water Scarcity and Droughts.*

For the purposes of regional analysis, the SRB has been subdivided into six zones: Z1, headwater of Segura River, including Taibilla River Basin; Z2, Mundo River Basin; Z3, Guadalentín River Basin; Z4, basins of northeast, some of them endorheic; Z5, medium basin, including several basins with irrigation agriculture; and Z6, lower basin and coast zone, considering coast basins and agriculture areas. Zones 1, 2, and 3, correspond to headwater basins with important water contributions, vital for the region. For the analyses, 81 sites were identified in the SRB and surrounding areas (Fig. 1).

Working with grids of daily rainfall (cell size 25 km), from the European Climate Assessment (ECA) observational database (Haylock *et al.*, 2008) for the 1950–2009 time period, and results provided by RCMs from the European ENSEMBLES Project (Christensen *et al.*, 2009), for the time period 1950–2050. The RCMS considered, driven by GCMs (global climate models), are: HIRHAM-ARPEGE (DMI), RegCM-ECHAM5-r3 (ICTP), REMO-ECHAM5-r3 (MPI), RCA-ECHAM5-r3 (SMHI), RCA3-HADCM3(C4I), and HIRHAM- HADCM3Q0 (METNO).

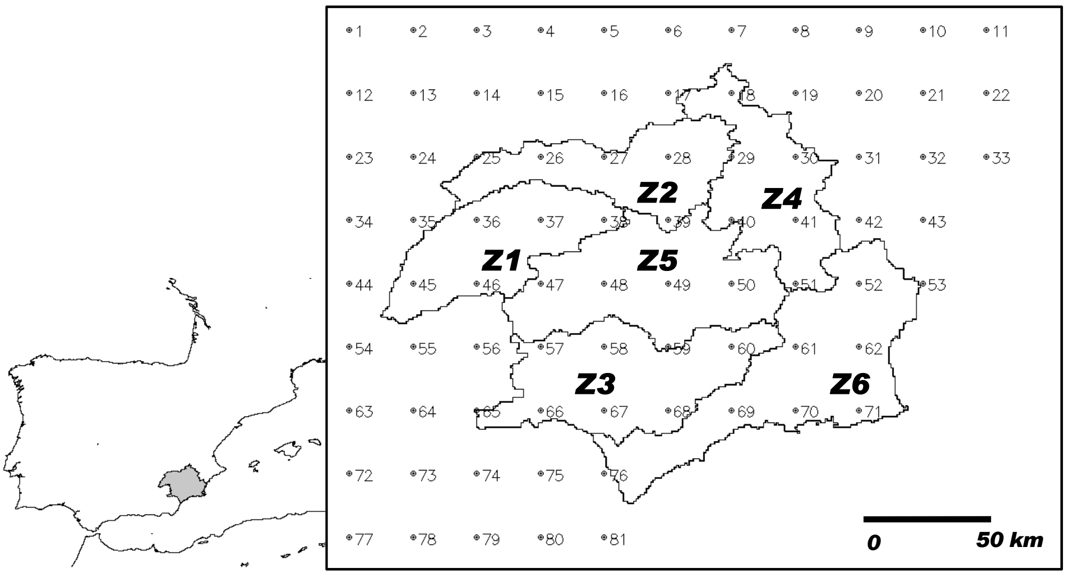

Fig. 1 Location of Segura River basin, definition of zones (Z1–Z6), and sites for analyses.

NON-STATIONARY METHODOLOGY OF TIME SERIES ANALYSIS: GAMLSS APPROACH

In the analysis of trends of MDSL series in the SRB, GAMLSS has been used. This tool consists of semi-parametric regression models, since they allow relating of the parameters of a pdf as a function of an explanatory variable through non-parametric smoothing functions (Stasinopoulos & Rigby, 2007). Several authors have applied GAMLSS for non-stationary modelling of hydrometeorological series (Villarini *et al*., 2009, 2010; Karambiri *et al*., 2010). In the present work, four pdfs of two parameters are considered when applying GAMLSS: Gumbel (GU), Gamma (GA), Lognormal (LN) and Weibull (WEI).

ANALYSIS OF MAXIMUM DRY SPELL LENGTH (MDSL) AT REGIONAL SCALE

GAMLSS application to MDSL series from ECA database

GAMLSS has been applied to series of MDSL identified from the ECA database (for the time period 1950–2009), for the study zones defined. The centile curves (5–95%) are shown by dashes, and the pdf fitted, in the corresponding figures.

Considering thresholds of daily rainfall of 1 mm, 5 mm, and 10 mm, MDSL were identified from the ECA database. The results of analysis of MDSL series for the threshold of 1 mm/d (Fig. 2), show a clear increase of MDSL from the 1980s for Z1, Z2, and Z5 (Fig. 2), and a long dry spell in the 1950s. Several authors have assessed the severity of this drought event (of the 1950s), in several parts of the Iberian Peninsula (López Bustos, 1958; Estrela *et al*., 2000). It is convenient to analyse the spatial distribution of MDSL.

MDLS hazard maps for several return periods, from ECA database

The MDSL series for all sites identified (Fig. 1) from the ECA database (time period 1950–2009), were modelled by GAMLSS. Therefore, the building of spatial distributions of MDSL associated with defined return periods (*Tr*) – hazard maps – for a particular year or time frame selected, is possible (Fig. 3). The procedure applied to construct the MDSL hazard maps, is the following: 1, to select the year and the exceedence probability of interest; 2, from the fitted pdf for each site, the length of dry spell associated to year and probability selected, is estimated; and 3, finally, these values are interpolated (using universal kriging in this case).

Figure 3 represents the MDSL hazard maps considering the threshold of 1 mm/d and *Tr* = 10 years, for 1950 (Fig. 3(a)), 1980 (Fig. 3(b)) and 2009 (Fig. 3(c)), exhibiting a great spatial and temporal variability. The map of 1950 represents estimates of severe MDSL, due to the long dry

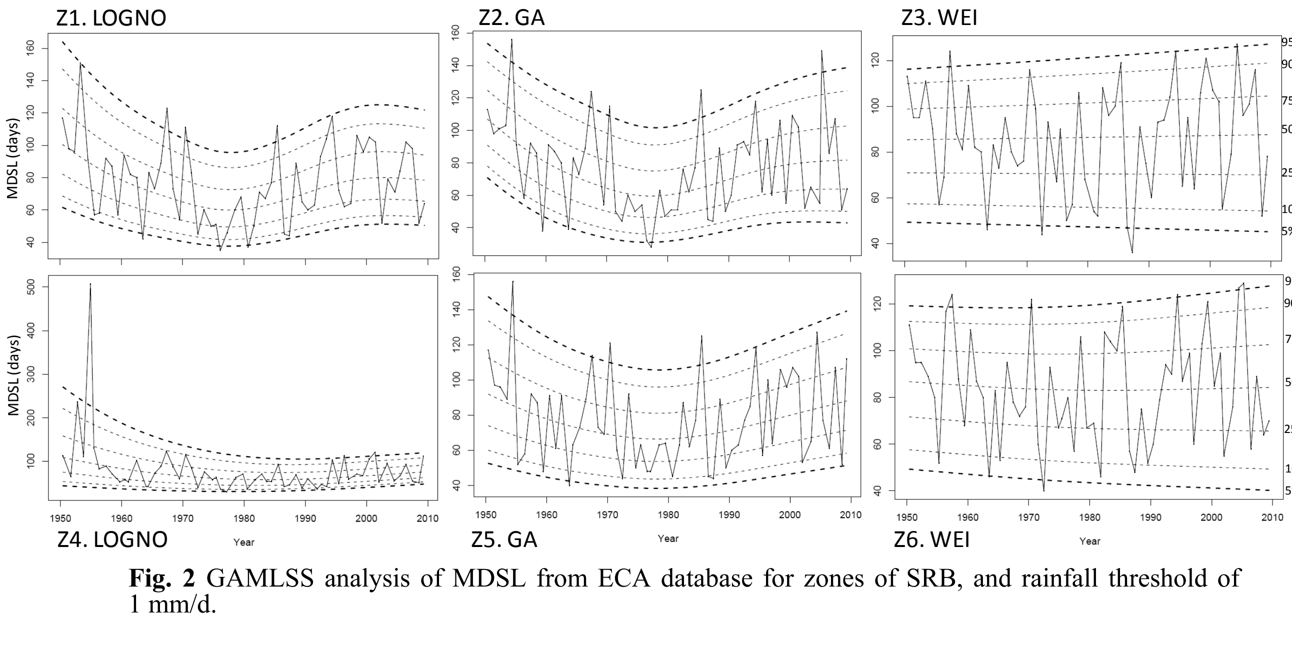

Fig. 2 GAMLSS analysis of MDSL from ECA database for zones of SRB, and rainfall threshold of 1 mm/d.

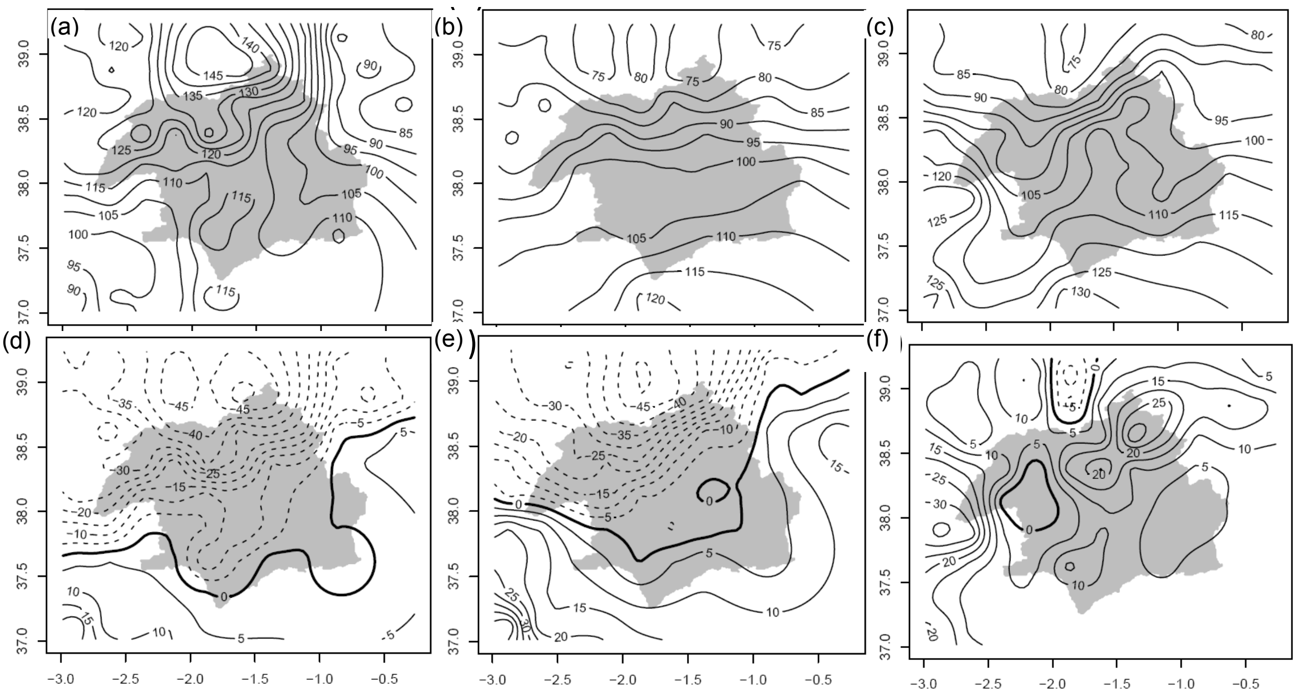

Fig. 3 MDSL (days) associated to *Tr* = 10 years and rainfall threshold 1 mm/d, from ECA database: (a) 1950; (b) 1980; (c) 2009; (d) percentage difference between 1980 and 1950; (e) percentage difference between 2009 and 1950; and (f) percentage difference between 2009 and 1980. Dashed lines represent negatives values.

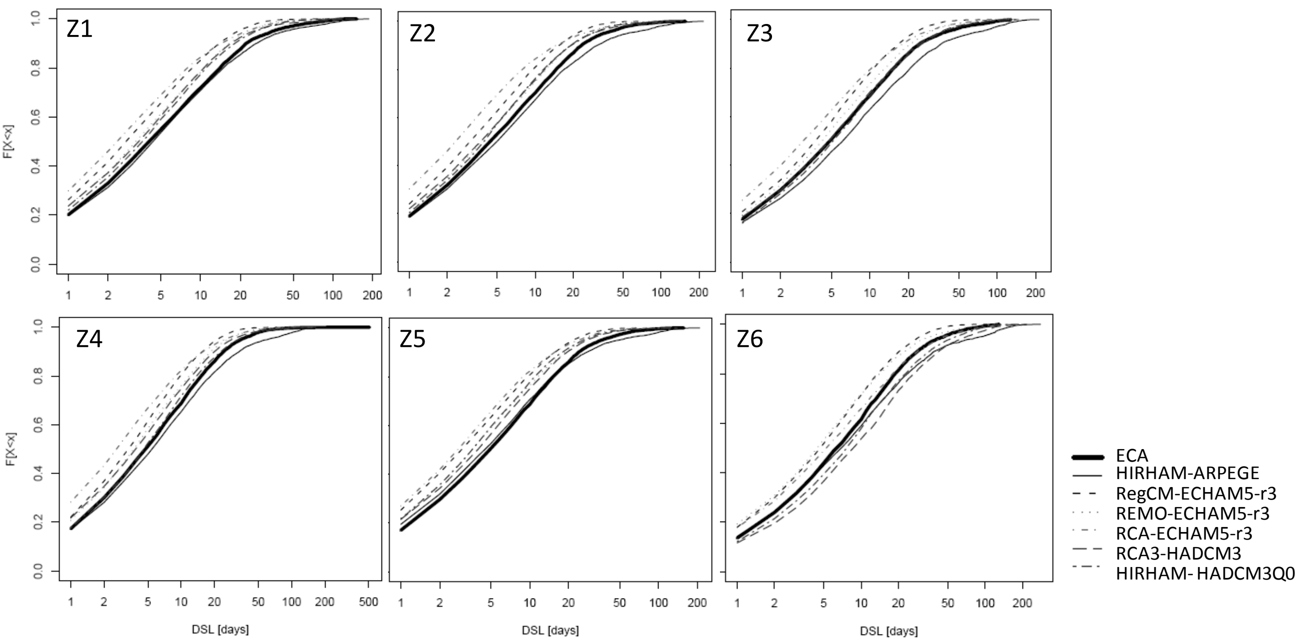

Fig. 4 CDFs of MDSL series obtained for each zone, from ECA and RCM databases.

period detected. Then, the map of 1980 exhibits shorter dry spells within the period of analysis, and there is a clear north–south gradient intensified by increasing the *Tr* (not shown). Finally, the map for 2009 reveals a growing trend of MDSL in some areas, stepping in headwater catchments. Then, the percentage differences between the maps of 1950 and 1980 (Fig. 3(d)), 2009 and 1950 (Fig. 3(e)) and 2009 and 1980 (Fig. 3(f)), were estimated. The negative percentage differences observed in Fig 3(d) and Fig. 3(e), are justified in the very severe drought episode registered in 50 years. In general, there is a northward movement of the isolines of MDSL in recent decades (since the 1980s), resulting in longer and more severe droughts for headwater basins, with an increase of over 20% (Fig. 3(f)). Therefore, the analysis of plausible trends from RCMs is considered important.

Bias analysis

Considering the MDSL series for the rainfall threshold 1 mm/d, extracted for each zone and site according to Fig. 1, for time period 1950–2009 from ECA and RCMs databases, the CDFs were obtained (Fig. 4). This type of analysis was applied in other regions, such as the Senegal River Basin, to evaluate the ability of RCMs to represent MDSL (García Galiano & Giraldo Osorio, 2010). Based on p-value of the two-sample Kolmogorov-Smirnov (K-S) goodness of fit test, the RCMs with the best skill for each zone are identified: for Z1, Z2, and Z5 the HIRHAM-ARPEGE; for Z4 and Z6 the HIRHAM-HADCM3Q0; and for Z3 the RCA3-HADCM3 presented the best skill (Fig. 4).

GAMLSS application to MDSL series from RCM databases

GAMLSS tools were applied to selected RCM databases. Considering the results obtained from the bias analysis of CDFs (Fig. 4), the results for HIRHAM-ARPEGE, HIRHAM-HACM3Q0, and RCA3-HADCM3 RCMs, are presented comparatively for Z2 (Mundo River Basin) and Z6 (Lower basin and coast zone) in Fig. 5. Divergences between the results are observed (Fig. 5), therefore it is not possible to conclude about the “ideal model” for all zones. According to the opinion of Sánchez *et al*. (2009), an ensemble of models could be considered a more accurate description of the limitations, uncertainties and a probabilistic approach for future climate projections.

MDSL hazard maps for several return periods, from RCMs

With the objective of analysing plausible trends in MDSL, an ensemble model was built from the pdfs fitted to MDSL identified from RCMs for each site. The skill score applied to each RCM was defined according to the performance in the bias analysis, using bootstrapping techniques (Efron & Tibshirani, 1993). From Fig. 6, a plausible increase in the MDSL is detected for year 2050

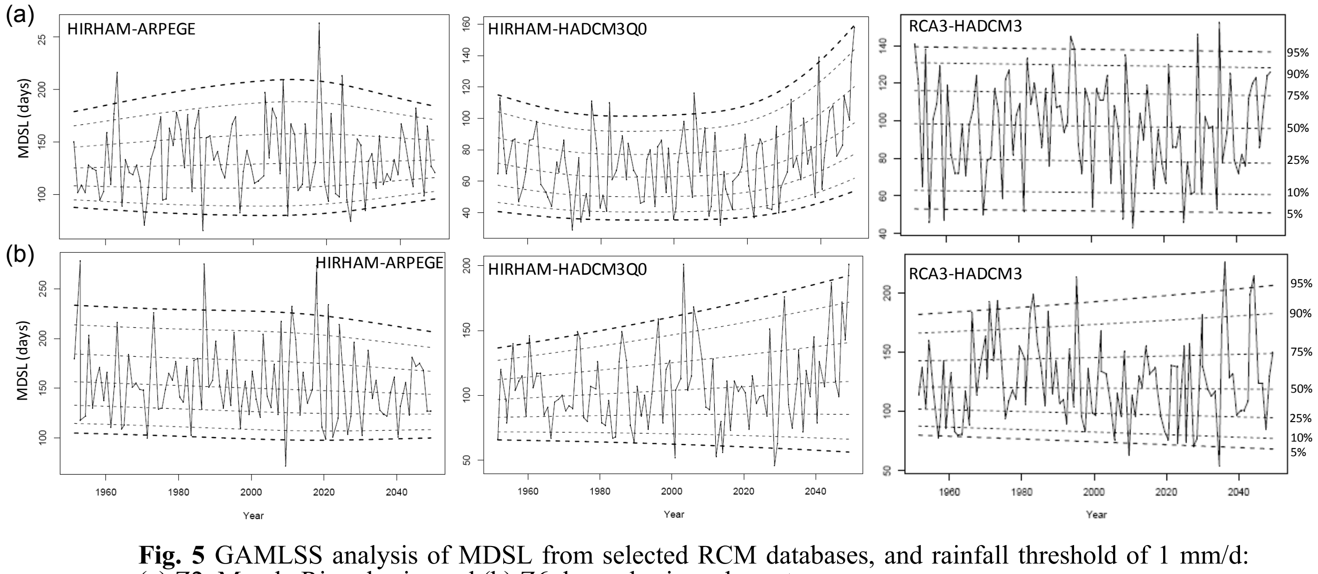

Fig. 5 GAMLSS analysis of MDSL from selected RCM databases, and rainfall threshold of 1 mm/d: (a) Z2, Mundo River basin, and (b) Z6, lower basin and coast zone.

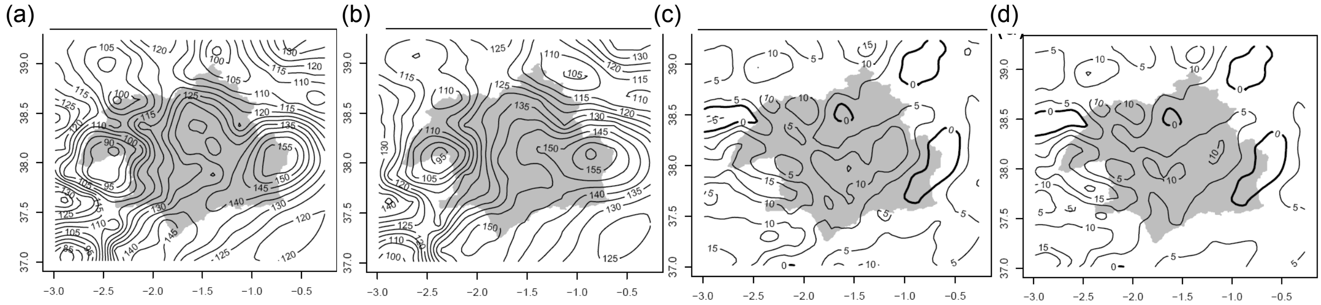

Fig. 6 Ensemble MDSL (days) associated with *Tr* = 10 years and rainfall threshold 1 mm/d, from RCMs: (a) year 1990; (b) year 2050; (c) difference between MDLS (days) for 2050 and 1990; and (d) percentage difference.

(Fig. 6(b)) in contrast to year 1990 (Fig. 6(a)). The maximum percentage difference is about 15% in the head basin of Segura River Basin (Z1) and headwater of Guadalentín River (Z3), for 2050 (Fig. 6(d)).

DISCUSSION AND CONCLUSIONS

This study describes the variability and discontinuities detected in the spatial patterns of dry spells in a Mediterranean basin of southeast Spain (SRB), by non-stationary modelling. Improving the knowledge regarding expected trends of MDSL is important for the management of water resources, especially for agricultural needs (which constitutes 80% of water use in the basin), and to develop contingency plans, which are the leading edge of adaptive management strategy. To take into account the variability over time in drought hazard, time-dependent parameters of the pdfs are employed. The main findings of the study are summarized, as follows.

The GAMLSS analysis provides dispiriting results about the evolution of drought events in most of the SRB, especially in the headwater basins of water resources providers. From the MDSL maps associated with different *Tr*, built from GAMLSS analysis, changes in the spatial pattern are appreciated. Considering the time horizons 1980 and 2009 comparatively, and the rainfall threshold of 1 mm/d, there is a clear shift of the observed MDSL isolines to the north. While trends in precipitation may not translate directly into changes in streamflows, the intensification of droughts obviously has an impact on the various components of the water cycle.

Taking into account an ensemble pdf from RCMs, a general increase of MDSL is expected for 2050 (with a maximum of about 15% in headwater basins), with the consequent negative impact on water reserves of the Segura River. The maintenance of external water inputs such as the Tagus–Segura River water transfer, and even the increase in the generation of resources from desalination, and the intensification of efficient water-use techniques in agriculture, are emerging as vital options in water deficit basins of southeast Spain. In conclusion, we have presented a methodology for assessing trends in hydrometeorological series and a novel approach to address the hazards associated with a continuously changing MDSL frequency distribution. In order to exploit all the information provided by the RCMs available, an ensemble pdf should be constructed for each site based on the bias analysis. Future research will be addressed in this direction, with the aim to compare robust, reproducible and consistent methodologies for definition of skill scores for ensemble model building of application to hydrometeorological extremes, monthly precipitation and other quantities (such as temperature).

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