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Future variability of droughts in three Mediterranean catchments

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Abstract In the present study, we analyze the magnitude and frequency of long-term droughts throughout the present century in Catalonia in the north-eastern Iberian Peninsula (Spain). In fact, this western Mediterranean region has recently suffered one of the most extreme dry episodes (2006–2008) in the last decades. This calls for further study of future perspectives of drought variability at the local scale. We selected three medium-sized catchments on the Catalan littoral: Fluvià, Tordera and Siurana. We employed both instrumental and simulated temperature and rainfall data to calculate two multi-scalar drought indices: the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI). Instrumental data consisted of several weather stations for a recent period: 1984–2008. Future projections covering the 2001–2100 period were extracted from a dynamical downscaling procedure at a 15-km horizontal grid resolution, nesting the mesoscale model MM5 into the atmosphere–ocean coupled model ECHAM5/MPI-OM, performed by the Meteorological Service of Catalonia. We calculated 24-month SPI and SPEI values for the instrumental and simulated periods, and no changes were found in drought variability for the early twenty-first century. For the mid-century, high climatic variability was detected, as extremely dry and wet periods might alternate according to the SPI values. At the end of the present century, we generally detected, particularly in the dry catchment of southern Catalonia, Siurana, more severe and longer droughts than the last extreme drought (2006–2008). There is a need to implement appropriate and specific adaptation strategies for water management of each catchment over the next decades to reduce the risk of the forecasted drought conditions.

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1 Introduction

Drought constitutes one of the most serious natural hazards in many regions of the Earth (Mishra and Singh 2010) and causes big socioeconomic losses and environmental impacts (Hewitt 1997; Wilhite 2000). Thus, agriculture is strongly affected by droughts (Earl and Davis 2003; Wu and Wilhite 2004), and huge efforts are required to achieve a stable yield during these episodes (Parry et al. 2005). Moreover, under drought conditions, forests are often damaged (Allen et al. 2010; García-Haro et al. 2010; Pasho et al. 2011) or burned (Flannigan and Harrington 1988; Dimitrakopoulos et al. 2011) and big changes occur in vegetation (e.g., Lloret et al. 2005; Peñuelas et al. 2012; Vicente-Serrano et al. 2013). It is a complex task to define this climatic phenomenon (Wilhite and Glantz 1985), but many authors consider drought to be a long period without rainfall, that is, with water deficit (Havens 1954; Redmond 2002). Drought is a gradual process, and it is quite difficult to determine when it starts and ends, or even the geographical area it affects (Briffa et al. 1994; Gómez-Navarro 2002; Vicente-Serrano et al. 2010). This hydric deficit can alternate with heavy rainfall events, a fact that can even enhance its detrimental impact (Estrela et al. 2000).

Drought is usually defined in terms of its links to meteorology (i.e., meteorological drought, based on less precipitation during a specific period of time), hydrology (i.e., hydrological drought, based on lower stream flows and reservoir content), to agriculture (i.e., agricultural drought, corresponding to the overall effect of a decrease in rainfall and increased temperature which in turn increases evapotranspiration and affects plant physiology) and to society (i.e., socioeconomic drought, related to mass media alarm, urban water supply shortages and profound economic impacts) (Wilhite and Glantz 1985; Martín-Vide and Olcina-Cantos 2001; Mishra and Singh 2010; NDMC 2012). Some authors also refer to hydrogeological drought when the level of groundwater aquifers drops drastically (Machlica et al. 2010; Sapriza et al. 2011). It is a well-known fact that the direct cause of meteorological droughts is air subsidence under an anticyclone, which inhibits cloudiness (Martín-Vide and Olcina-Cantos 2001). Hydrological droughts are not only dependent on rainfall, but also upon the volume of water from rivers and dams. Equally, the agricultural droughts depend on significant changes in potential evapotranspiration (PET) under dry conditions. Finally, socioeconomic drought can be associated with agriculture and urban demand, whereas precipitation does not necessarily have to be below normal values. Socioeconomic drought is therefore not only dependent on rainfall deficits, and water demand and management can be more connected with social water scarcity (Morales et al. 2000; Iglesias et al. 2009), with social perception of the severity of a drought being strongly influenced by the mass media (Yun et al. 2012; Ruiz-Sinoga and León-Gross 2013).

Predicting droughts is a challenging task, as they result from multiple causes such as precipitation, temperature, orography, changes in land uses, air–sea interaction, soil moisture and others (NDMC 2012). The long-range forecast of drought variability is crucial for policy makers to develop suitable strategies for adapting to climate change. Any serious efforts to assess the magnitude and duration of future droughts under climate change scenarios will be very limited due to the lack of knowledge of how the variables of the hydrological cycle will respond to a new climate scenario (Boroneanţ et al. 2011). Regional climate models (RCMs) and downscaling methods can help to improve the prediction of drought behavior and, overall, climate variability in local regions (Dobler et al. 2013).

In the case of the Mediterranean region, droughts are recognized as one of the most frequent and severe natural hazards (Morales et al. 2000; Olcina-Cantos 2001; Pausas 2004; Giannakopoulos et al. 2009). Moreover, the Mediterranean area will be seriously affected by climate change because most climate models and scenarios coincide in predicting less precipitation in all seasons, particularly in summer (Christensen et al. 2007; Dai 2011). The general circulation models (GCMs) used in the last Intergovernmental Panel on Climate Change (IPCC) assessment report show increased aridity in the Mediterranean region throughout the twenty-first century (Meehl et al. 2007). A future increase in droughts in Southern Europe will be mainly caused by a decrease in precipitation (Houghton et al. 2001; Lionello et al. 2002), but also by increased PET resulting from a rise in temperature (Gibelin and Déqué 2003). Climate change in the Mediterranean region might be partially caused by a gradual northward shifting of the subtropical anticyclone belt (Gillett and Stott 2009). Heinrich and Gobiet (2012) showed how climate might evolve in Europe at the regional scale by means of several RCMs, which they were developed within the European Union project ENSEMBLES (van der Linden and Mitchell 2009) and observed drier conditions in the Mediterranean region.

Drought variability in the Iberian Peninsula has been studied since 1500 with the use of historical documentary sources (rogation ceremonies) (Martin-Vide and Barriendos 1995; Barriendos 2005). The most intense droughts were detected at the end of the eighteenth century during a period of high climatic variability (Barriendos and Llasat 2003; Vicente-Serrano and Cuadrat 2007a; Domínguez-Castro et al. 2012). Vicente-Serrano (2006) analyzed the temporal pattern of droughts on the Iberian Peninsula over the twentieth century, and the most intense episodes were recorded in the 1940s, 1950s, 1980s and 1990s. Furthermore, a significant increase in the drought severity in the middle Ebro valley (NE Spain) was identified during the second half of the last century (Vicente-Serrano and Cuadrat-Prats 2007b). The Iberian regional climates also determine drought magnitude and duration and consequently, three types of drought in the peninsula are defined: Cantabrian drought (isolated dry years), Iberian drought (2–4 dry years) and south-eastern drought (humid years are rare) (Olcina-Cantos 2001).

2 Objective and study areas

Our overall objective is to analyze the magnitude and frequency of long-term droughts during the end of the twentieth century and the whole twenty-first century at the local scale in a Mediterranean region, Catalonia, located in the north-eastern (NE) Iberian Peninsula (Spain). This is a region of particular interest because Heinrich and Gobiet (2012) predicted drier conditions for the whole Iberian Peninsula by the mid-twenty-first century, and several studies specifically predict a decrease in mean annual precipitation over NE Iberian Peninsula along the twenty-first century, with the summer season becoming even drier (Sumner et al. 2003; Altava-Ortiz 2010; Ribas et al. 2010; Barrera-Escoda and Cunillera 2011). We used instrumental data, climate projections and drought indices to analyze recent last and future droughts in three medium-sized catchments along the Catalan coast. It is well known that droughts are a geographically widespread phenomenon, but they are not spatially uniform at local scale (Briffa et al. 1994; van der Schrier et al. 2006); thus, we used the results of a dynamic downscaling performed by the Meteorological Service of Catalonia (SMC) for Catalonia. That downscaling enabled us to calculate drought indices for a future period at local scale.

The three catchments selected are located in Catalonia and are representative of the Mediterranean coastal region: Fluvià, Tordera and Siurana (Fig. 1). They are quite similar in area and present a wide range of topographic, climatic and environmental conditions, land uses and water demands and have almost no regulation in channel runoffs. The Fluvià catchment is characterized by a humid climate, especially in the headwater, which has an annual mean precipitation greater than 1,000 mm. According to the Land Cover Map of Catalonia of 2005 (LCMC 2005), this catchment is mostly occupied by forestland (77 %) and agricultural lands (19 %), mainly concentrated in the low watercourse. The Tordera catchment has an annual mean precipitation somewhat lower than the Fluvià catchment (700–800 mm). It presents high forest diversity, with forestlands occupying 81 % of the catchment, while agricultural lands (10 %) are concentrated in the medium and low watercourse. Finally, the Siurana catchment, a tributary of the Ebro River, is representative of southern arid Catalonia, where precipitation is approximately 500–600 mm. In this catchment, forestlands occupy 76 % of the area and there is a greater predominance of croplands (22 % of the total catchment area). The Siurana catchment is characterized by a small population which has undergone an intense rural exodus during the last few decades, while the Fluvià and Tordera catchments show a noteworthy increase in population in the last decade (Idescat 2012). In the latter two catchments, the coastal areas are subjected to great demographic pressure in summer due to a large influx of tourists, which significantly increases water demand. This phenomenon coincides with the driest season and can give rise to water scarcity (Rico-Amoros et al. 2009).

3 Data and methods

3.1 Climatic data processing

We used a 25-year instrumental period (1984–2008) to evaluate and compare the most recent droughts with several weather stations in each catchment. This 25-year period was chosen because it was the longest time slice in which daily climatic data were available for almost all stations. For this period, daily climate data were obtained from weather stations belonging to the Spanish State Meteorological Agency (AEMET) and the SMC. Daily climatic series included precipitation and minimum and maximum temperatures from seven to eight weather stations per catchment (Fig. 2). We selected stations according to their location within or close to each catchment, considering climatic heterogeneity within each watershed and continuity in the data series. Measured series gaps were filled with the weather generator model included in the Soil and Water Assessment Tool (SWAT) (Sharpley and Williams 1990).

SWAT is a physical semidistributed and continuous hydrological model that estimates surface and subsurface flow, erosion and sediment deposition and nutrient movement within the basin at a daily temporal resolution (Gassman et al. 2007). Moreover, SWAT corrects climate temporal series according to the effects of orography using GIS techniques. The relationship between climate and orography was derived from the digital elevation model (DEM) of Catalonia (ICC 2012) and the Digital Climatic Atlas of Catalonia (Ninyerola et al. 2000). Both processes, filling and correction, were made at the subbasin level, which considers units smaller than a catchment with similar orographic

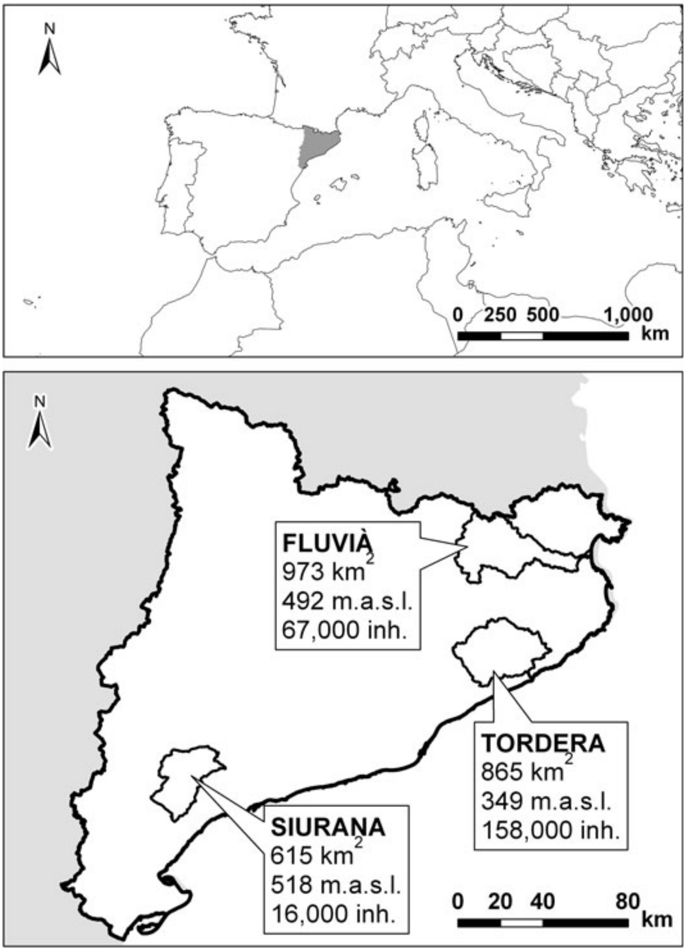

Fig. 1 Location of the three Mediterranean catchments selected in Catalonia, north-eastern (NE) Spain, and their surface area (km^2), mean elevation (m.a.s.l.) and population in 2008 (number of inhabitants)

characteristics. SWAT performs a spatial interpolation of climate series at subbasin level in order to obtain daily data homogeneously distributed throughout the catchment. We identified 16 subbasins in the Fluvià catchment, 17 in the Tordera catchment and 15 in the Siurana catchment (Fig. 2). We derived monthly series from the daily series of each subbasin and standardized and averaged them for each catchment following the recommendations described in Jones and Hulme (1996). Finally, we obtained overall monthly precipitation and mean temperature series for each catchment for the 1984–2008 period. SWAT is a useful model to obtain an overall climatic series from catchments as the physical geographical conditions are corrected at subbasin level.

3.2 Climate modeling and downscaling

Climate projections were based on the atmosphere–ocean coupled model ECHAM5/MPI-OM (Marsland et al. 2003; Roeckner et al. 2003). This GCM was jointly developed by the

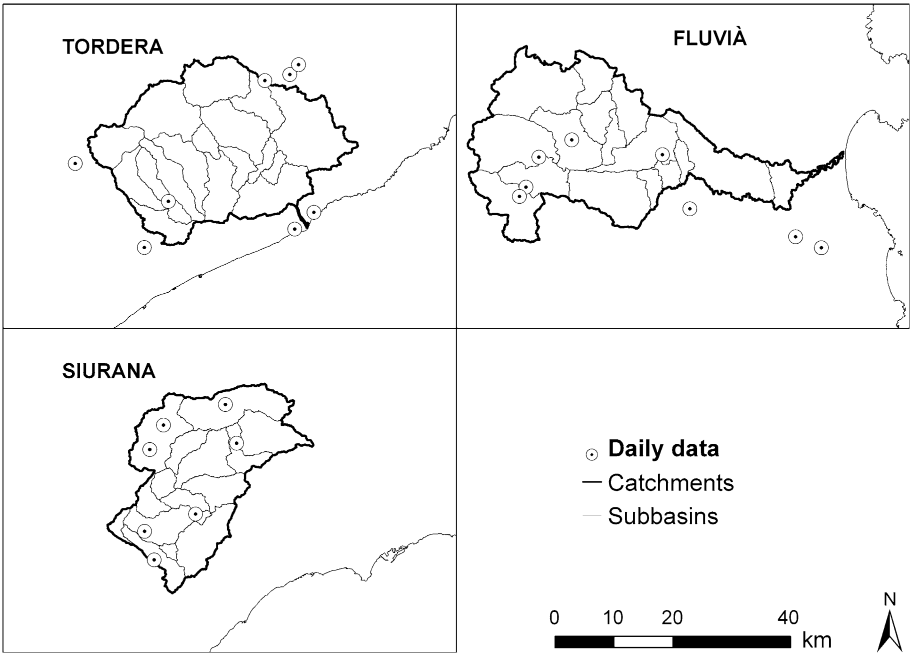

Fig. 2 Weather stations selected to obtain historical data of precipitation and temperature and the subbasins identified from the soil and water assessment tool (SWAT) in the three catchments

European Centre for Medium-Range Weather Forecasts (ECMWF) and the Max-Planck Institut für Meteorologie in Hamburg, and it provides a horizontal resolution of 1.875° (Roeckner et al. 2006a, b). In the present study, the A2 and B1 scenarios defined by the IPCC (2007) were considered. The A2 scenario implies a high anthropogenic emissions level in a context of greater economic and regional development, whereas B1 scenario represents a low emissions level in a context of greater environmental and global development. Climate projections by the ECHAM5/MPI-OM present low spatial resolution and are not useful for analyzing climate changes at regional or local scale. For this reason, we used the results of a dynamic downscaling performed by the SMC for Catalonia (Barrera-Escoda and Cunillera 2010, 2011). Those authors used three one-way nested domains with 135-, 45- and 15-km horizontal grid resolution and 23 vertical levels. The SMC for Catalonia forced the simulation nesting the mesoscale meteorological model MM5 (Dudhia et al. 2005) into boundary conditions from the ECHAM5/MPI-OM. They also simulated the current climate nesting the MM5 into the boundary conditions of the ERA-40 reanalysis data (Kållberg et al. 2004) for the 1971–2000 period. This last downscaling procedure was performed to evaluate the MM5, and it proved to be very satisfactory because it showed a climatologically reliable distribution of the spatial patterns of simulated annual and seasonal precipitation and temperature compared with those obtained from real observed data (Barrera-Escoda and Cunillera 2011); moreover, the climatic series generated also reproduced well the evolution of annual mean anomalies of precipitation and temperature for Catalonia. Thus, the simulated series used for our study provided high temporal (6-h) and spatial resolution (15-km), nesting the MM5 into the ECHAM5/MPI-OM, for the reference period (1971–2000) and for the projected period (2001–2100).

We applied a direct scale factor at daily resolution to these simulated series, having transformed 6-hourly simulated data into daily data, to correct the divergence between real and modeled data (Lenderink et al. 2007). The values of the direct scale factor were obtained from the 1984–2000 common period of the daily registered data (1984–2008) in the weather stations of Fig. 2 and the simulated data of the reference period (1971–2000). We then introduced these scaled series into the SWAT program to obtain daily continuous series for each subbasin for the common period (1984–2000) and the future period (2001–2100). The simulation of the 1984–2000 time slice is obviously the same for scenarios A2 and B1. For the 1984–2100 period, overall monthly precipitation and mean temperature series for each catchment and scenario were calculated with the use of the same standardization procedure used for the instrumental period (1984–2008).

3.3 Drought indices

There are many drought indices to assess and quantify the magnitude and duration of droughts (Palmer 1965; Gibbs and Maher 1967; Bhalme and Mooley 1980; McKee et al. 1995; Wells et al. 2004; Vicente-Serrano et al. 2010). Among them, we only used the Standardized Precipitation Index (SPI) (McKee et al. 1995) and the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010). The SPI is mathematically based on fitting precipitation series to a gamma distribution (Edwards 1997) and is fully accepted worldwide because its values are easily comparable in time and in different locations simultaneously (Guttman 1999). The SPEI is based on the original SPI calculation procedure, but with some modifications in order to include PET. Hence, the SPEI detects changes in PET related to mean temperature variability. The SPEI allows us to consider increases in PET resulting from the effect of global warming, which was a crucial point for our study, as the three catchments selected were predominantly occupied by forests. By using both indices, the SPI and the SPEI, we were able to detect the effect of temperature rise under current climate change upon drought characteristics in different locations.

The SPI and the SPEI must be associated with a time scale in order to be able to monitor multi-scalar properties of drought. Some typical time scales for calculating the SPI and the SPEI are from 1 to 48 months (Xoplaki et al. 2012). In this case, we selected a 24-month time scale because we analyzed variability of long-term droughts. We did so because we previously found that the 24-month time scale was more suitable than 12 months for the study of long-term droughts (not shown), whereas time scales greater than 24 months may be unreliable (Guttman 1999). An SPI calculator (http://digital.csic.es/handle/10261/10006; Vicente-Serrano and Cuadrat 2002) and an SPEI calculator (http://digital.csic.es/handle/10261/10002; Vicente-Serrano et al. 2010) were downloaded from the Spanish National Research Council (CSIC) Web site to calculate the SPI and the SPEI values for our series. The first value of the SPI and the SPEI was shifted forward 24 months because the time scale selected obviously implied an accumulated index of 24 months. The most common classification for the SPI values, based on many authors (McKee et al. 1995; Hayes et al. 1999; Komuscu 1999), is: $\geq$2.00 (extremely wet), 1.50–1.99 (very wet), 1.00–1.49 (moderately wet), −0.99–0.99 (near normal), −1.00 to −1.49 (moderately dry), −1.50 to −1.99 (severely dry) and $\leq$−2.00 (extremely dry). The SPI drought classification can be used to assess the SPEI values too, as it is based on the SPI calculation procedure (Vicente-Serrano et al. 2010).

4 Results

4.1 Recent past droughts

Figure 3 shows the 24-month SPI and SPEI values from the series generated by SWAT following the input of daily historical data for the three catchments from 1984 to 2008. According to the SPI, an extreme drought episode was observed during the final years (2006–2008) of the study period in the three catchments. Moderate droughts and humid periods alternated in all catchments in the same periods, with a better correspondence between the Fluvià and Tordera catchments. In general terms, four moderate droughts were detected: at the end of the 1980s, the start of the 1990s, in the mid-1990s and around 2000. A very wet period was registered in 1992–1993 in the Fluvià and Tordera catchments and in 1997 and 2004 in the Siurana catchment. According to the SPEI, a common extreme drought was detected in the three catchments at the end of the period (2006–2008), and an additional extreme drought was observed in the Siurana catchment at the beginning of the 1990s. The results were quite similar to those explained by the SPI, and only the very wet ($2.0 > \text{SPI} \geq 1.5$) period of the first half of the 1990s in the Fluvià catchment was then observed with the SPEI as being extremely wet ($\text{SPEI} \geq 2.0$).

4.2 Future droughts

Figure 4 shows the 24-month SPI and SPEI values for the three catchments throughout the 1984–2100 period using the series generated by SWAT in A2 scenario. According to the SPI, several extremely wet periods are to be expected, especially in the Fluvià and Tordera catchments, during the first half of the twenty-first century. There will probably be high climate variability in the middle of the century, as an extremely wet period was seen to be closely followed by an extremely dry one. Humid periods will be scarce in the second half of the twenty-first century, and there will be a clear predominance of moderate droughts, which will be extreme and continuous during the last decade of the century. There was a clear similarity in the SPI values between the Fluvià and Tordera catchments; the Siurana catchment showed its own particularities, as the humid periods will not be as significant as in the other two catchments during the first half of the twenty-first century and the dry periods will be more intense throughout the second half. We found a similar temporal pattern of the SPEI compared to the SPI, but with less intense and longer episodes. With this index, severity and variability of the episodes were smoothed and there was an enhanced correspondence between the Fluvià and Tordera catchments. The SPEI predicted a more evident predominance of wet periods in the first half of the twenty-first century and long droughts in the second half in all three catchments. It is important to highlight a very likely and continuous drought during the last four decades of this century in the Siurana catchment, since no positive SPEI values were seen after 2060.

Figure 5 shows the 24-month SPI and SPEI values for the three catchments along the 1984–2100 period in B1 scenario. According to the SPI, an alternation of moderately wet and dry periods will likely occur throughout the first half of the twenty-first century and an extreme drought was detected in the 2000s in all catchments, similar to the drought of the 2006–2008 period recorded by the instrumental data (Fig. 3). The mid-century will be characterized by a noteworthy variability, as extremely wet and dry periods were closely visualized. During the second half of the twenty-first century, we detected a major occurrence of rather moderate droughts, which were longer and more severe in the Siurana catchment than in the other two catchments. According to the SPEI, no extreme drought

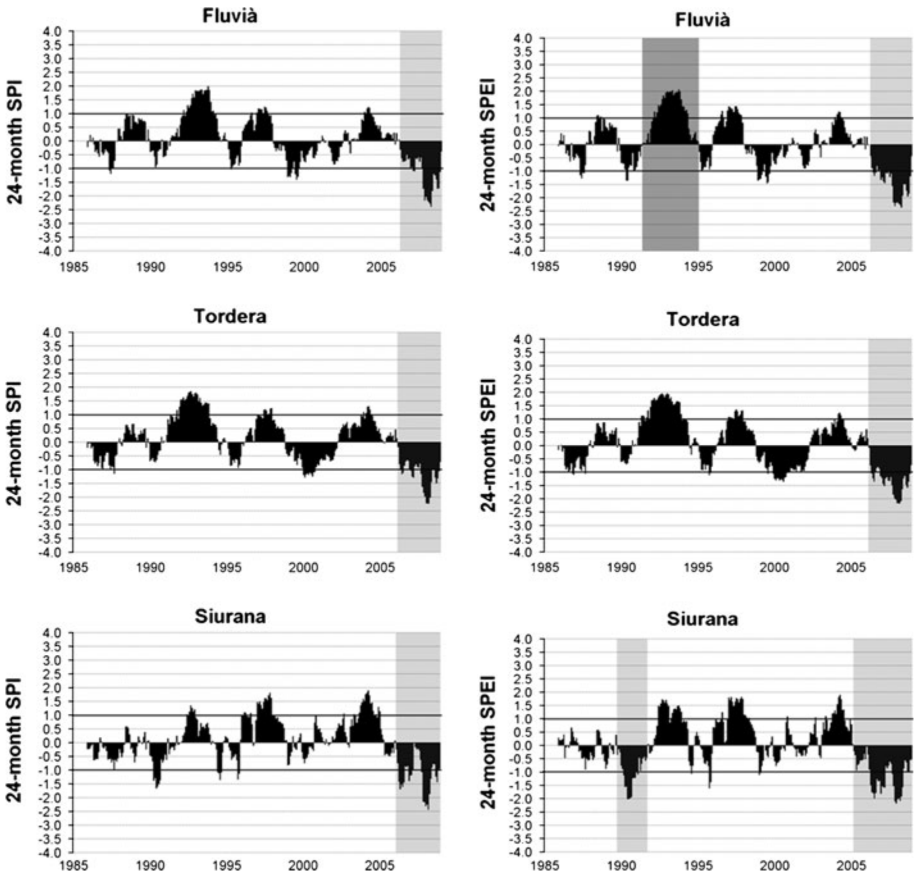

Fig. 3 24-Month standardized precipitation index (SPI; graphs on the *left*) and standardized precipitation evapotranspiration index (SPEI; graphs on the *right*) at Fluvià, Tordera and Siurana catchments for the 1984–2008 period using the data generated by SWAT from the daily instrumental observations. Extremely wet/drought episodes with a value of the index *higher/lower* than 1.99/−1.99 are *shaded* in *dark/light gray*. *Bold lines* show thresholds of moderate wet episodes (*above* 0.99) and moderate droughts (*below* −0.99), respectively

periods were detected in the first half of the twenty-first century, whereas extreme and moderate humid periods were frequently observed in the three catchments during this period. In addition, Tordera catchment showed no extreme drought periods throughout the whole twenty-first century. On the other hand, moderate droughts might be frequent and long-lasting in all catchments during the last four decades of the century, and particularly severe and continuous in the Siurana catchment.

5 Discussion

According to the instrumental climate data, the droughts observed in the three catchments can be said to belong to the Iberian type (2–4 dry years) of the Olcina-Cantos (2001) classification. This kind of drought in NE Iberia is rather moderate as it is described in

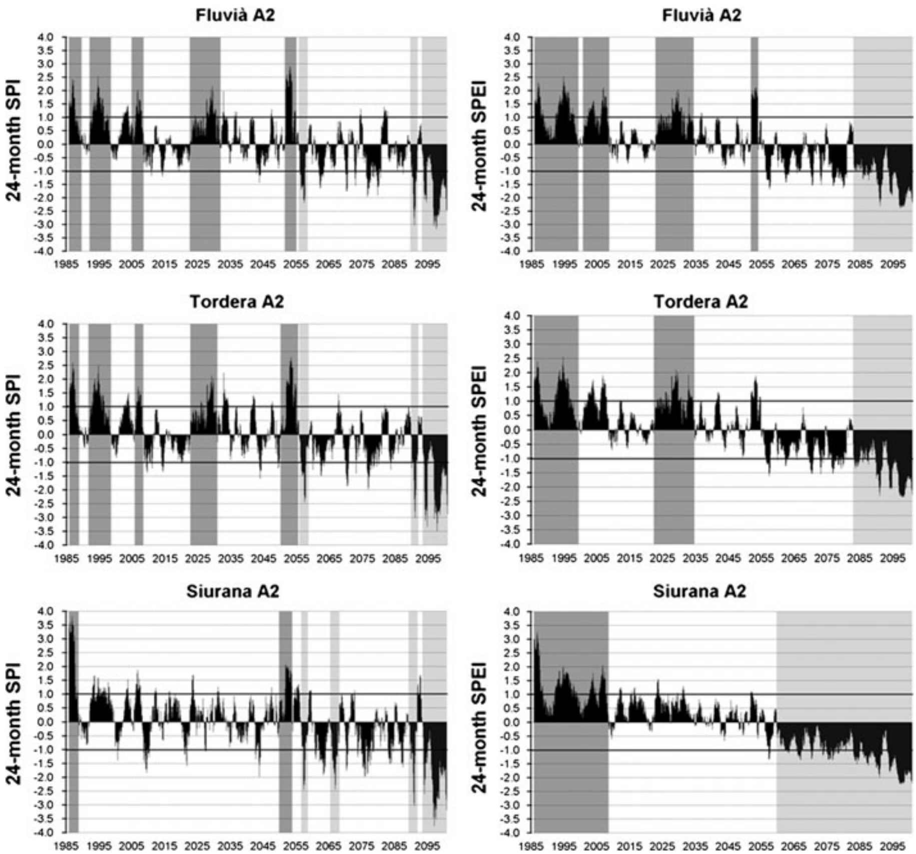

Fig. 4 As Fig. 3 but for the 1984–2100 period using the data generated by SWAT from the model simulations in the A2 scenario

Lana et al. (2008). The Fluvià and Tordera catchments are geographically close to each other and have similar topographic conditions, thus the overall climatic series for each catchment, generated by SWAT, tended to have similar characteristics. In general, a physical geographical influence was observed between the Fluvià and Tordera catchments and the Siurana catchment as this latter one, located within a drier part of the Catalan region, tended to suffer more frequent and severe droughts than the other two catchments.

Our drought indices projections showed an unexpected lack of severe droughts during the first half of the present century in Catalonia in the two scenarios, A2 and B1, while extremely wet (index value $\geq$ 2.0) and very wet (2.0 $>$ index value $\geq$ 1.5) episodes were observed during this period. The simulated 1984–2000 period only showed wet periods, and these wet periods can occasionally occur with the same magnitude and length until 2060. Calbó et al. (2012) did not infer a significant rainfall reduction over Catalonia along the first half of the present century, either. For the mid-twenty-first century, an overall high variability of climate was detected by the SPI values in the A2 and B1 scenarios; this increased variability in the Mediterranean climate has already been described in many studies of climate change (Sumner et al. 2003; Christensen and Christensen 2004; Christensen 2005).

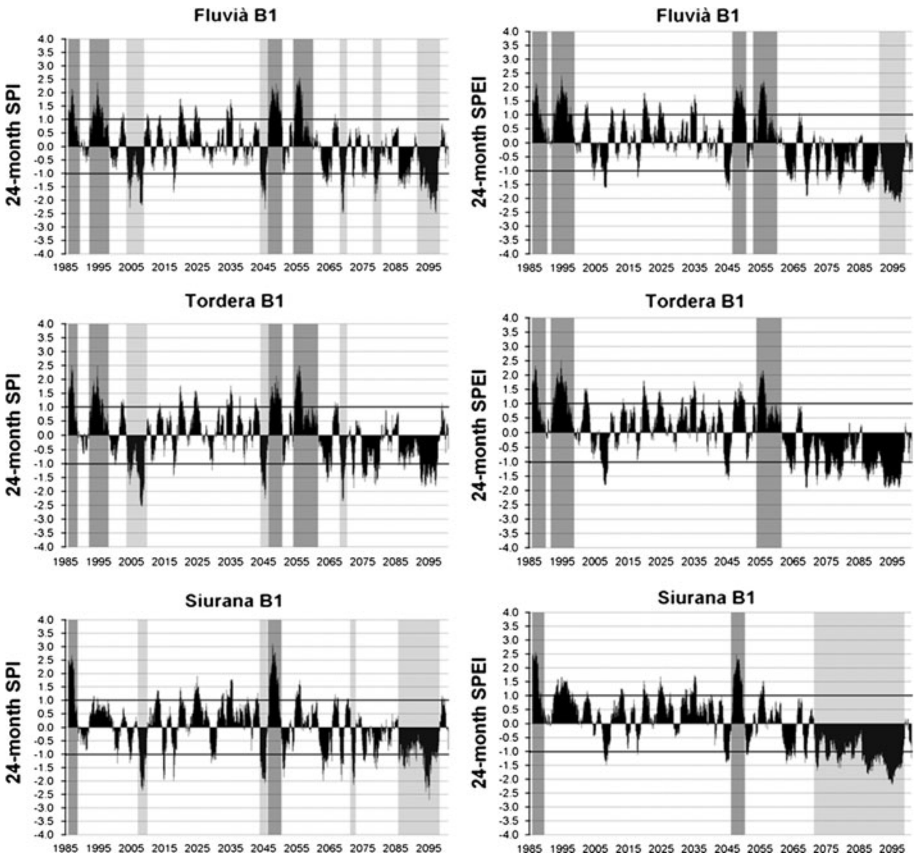

Fig. 5 As Fig. 4 but for the B1 scenario

Overall, drought indices showed that the second half of the present century might be characterized by severe and long droughts, mainly in southern Catalonia. This result is in line with several recent studies and reports on climate change: increased solar radiation over Catalonia (Ribas et al. 2010), greater frequency of heat waves over the Mediterranean Basin (Sánchez et al. 2004; Beniston et al. 2007) and drier conditions for Southern Europe (Blenkinsop and Fowler 2007; Christensen et al. 2007; Dai 2011; Heinrich and Gobiet 2012). Despite the relevant uncertainty and the big differences in emission levels between the A2 and B1 scenarios for the end of the present century, they both pointed out an overall increase in the severity and duration of droughts. Droughts of major severity and duration can be expected for the end of the present century, above all with the SPEI and in the A2 scenario; these would be even more intense and longer than the last extreme drought (2006–2008) recorded in Catalonia (Fig. 3).

We suggest that when both the 24-month SPI and the SPEI coincide with low values (<-1.0) for a long period (2–3 years), an intense drought is highly likely to occur in Catalonia, with evident social consequences (i.e., a socioeconomic drought). Nevertheless, the relative precipitation values reveal that the humid regions like the Fluvià and Tordera catchments could suffer a dry year with a moderate decrease in mean precipitation, whereas the semiarid regions like the Siurana catchment could tolerate a greater decrease in rainfall (Martín-Vide and Olcina-Cantos 2001). Both indices satisfactorily detect those periods with decreases in rainfall, but the role of evapotranspiration is only taken into account with the SPEI. In our results, we observed temporal and spatial differences between the SPI and the SPEI in the detection of moderate and extreme droughts. Temperature exhibits more homogeneous temporal and spatial variability than precipitation (Barrera-Escoda and Cunillera 2011); thus, we detected extreme episodes in the same periods in all catchments using the SPEI, and we found an overall lower variability and less extreme values with the SPEI than with the SPI. Furthermore, the SPI did not clearly record some extreme droughts in both the instrumental and the projected data.

There is no doubt about the important role of temperature and its implications on PET with regard to assessing future water resource availability in climatic conditions (Gibelin and Déqué 2003; Wang 2005). As suggested by Vicente-Serrano et al. (2010), the SPI describes well water deficits in a not warming or cooling climate, but in a changing climate, as it is occurring now, the use of the SPEI seems more reasonable. Moreover, we agree with Oladipo (1985) that the SPI is more appropriate for detecting meteorological droughts. On the other hand, the SPEI is more useful for detecting hydrological droughts, based on the losses of large areas of surface water in dams caused by evaporation (Snoussi et al. 2002) or by changes in land uses (Pla et al. 2010; Dai 2011) and agricultural droughts, based on the soil and vegetation water content (Hu and Willson 2000; Narasimhan and Srinivasan 2005). Therefore, we inferred that the current global change (including different drivers of change, not only climate) may have influence on drought occurrence and severity at local scale, and this would be well detected by the SPEI. Nevertheless, further research is required, and it should involve the calculation of hydrological drought indices using the stream flows derived from SWAT.

In the Mediterranean Basin, extreme droughts tend to disappear gradually but this can occur suddenly following torrential rainfall (Gómez-Navarro 2002). This was well registered in our SPI values, as it recently occurred in the last extreme drought in Catalonia in 2006–2008 (Fig. 3), but water scarcity can continue because the intense rainfall in the Mediterranean climate is difficult to retain and make use of (Estrela et al. 2000). Before the 2006–2008 extreme drought, Catalonia also suffered other extreme droughts in the 1920s and in the second half of the 1940s (ACA 2007; Altava-Ortiz 2010). These past droughts might have been more harmful than the recent 2006–2008 drought because water management plans and strategies were poorly developed at that moment in the region (ACA 2007). In the second half of the present century, the vulnerability of society will mainly depend on the effectiveness of the adaptation strategies, since there will be major exposure of society to severe dry episodes if climate models are accurate in their projections of drought characteristics in the Mediterranean Basin. Serious impacts are to be expected on tourist activities on the Catalan coast and intense droughts could make this littoral less attractive to tourists due to water shortages (Ribas et al. 2010). We ought not to underestimate these impacts on the agricultural sector, since it is the economic activity most dependent on water availability and is the main consumer of water resources in eastern Iberia. Risk management of water scarcity constitutes the objective of future studies, and the key to this could lie in local strategies for medium-sized catchments (Iglesias et al. 2007), such as the three analyzed in our study.

Furthermore, under severe dry conditions, serious disturbance of vegetation could occur throughout vast areas, as occurred during the growing season across Spain in 2005 (García-Haro et al. 2010), and semiarid Mediterranean regions, as the Siurana catchment, might be affected by desertification processes (Vicente-Serrano et al. 2012). On the other hand, in the early twenty-first century, climate will be warmer and wet periods are expected to occur; this consequently implies increased forest growth and major water retention by vegetation. There is a need for appropriate forest management to prevent the risk of big fires (Loepfe et al. 2010). In short, this is only a brief account of possible consequences for the Catalan littoral of the future behavior of droughts in the present century.

6 Conclusions

We calculated two drought indices, the SPI and the SPEI, to assess recent past and future variability of moderate and extreme droughts in three Mediterranean catchments. These indices enabled us to study variability of long-term droughts on a 24-month time scale. The use of future downscaled climate projections at a high-spatial resolution is a strong point in this study to analyze future drought variability at local scale. The use of the SPEI is preferable to the SPI to assess future water resource availability in the present global warming due to the important role of temperature in PET.

The main results showed no changes in drought variability for the early twenty-first century in the Catalan littoral. For the mid-century, high climatic variability was detected, as extremely dry and wet periods might closely alternate according to the SPI values. At the end of the present century, we generally detected, particularly in the dry catchment of southern Catalonia, Siurana, more severe and longer droughts than in the last extreme dry episode in 2006–2008.

After 2060 results could lead to a significant decrease in water availability in these Mediterranean catchments, above all, with A2 scenario. It is likely that by the end of the century, overall water resource availability in Catalonia will not be guaranteed for many uses without full implementation of suitable hydrological plans based on water saving, efficiency and reuse.

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