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Trends in surface air temperatures, precipitation and combined indices in the southeastern Iberian Peninsula (1970–2007)

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ABSTRACT: This work evaluates recent (1970–2007) climatic changes in the southeastern Iberian Peninsula, a semi-arid region with important human pressure. The high-resolution dataset Spain02 (~20 km) was used. This allowed us to discover local/regional signals, most of them not previously reported because of the use of coarse data or interpolation techniques. Annual precipitation has not experienced long-term changes in most of the region (80%) but showed some negative trends in the wettest mountainous NW area and slight recovery in the most arid S/SE region, mainly due to changes during winter. However, an increase in long-term droughts, examined at 4 locations, was found, which seems highly connected to a temperature increase. Both maximum and minimum temperatures (Tmax, Tmin) have increased in most of the region (in 70 and 88% of the area, respectively) at high rates (average 0.5 and 0.52°C decade^{-1} for Tmax and Tmin, respectively), with steepest trends in spring and summer and distinct subregional differences. Thus, the diurnal temperature range decreased in the most populated areas in the NE and the S/SW (25% of the region), whereas it mainly increased in natural and mountainous areas (15%). Combined indices showed increasing frequency of warm–dry and warm–wet days and less cold days, especially in the central W and NE. Precipitation intensity increased within warm–wet days in the transition seasons (40% of the region), suggesting enhanced convective events, even where total precipitation did not change. Besides large-scale factors, we discuss precipitation–temperature feedbacks and land cover changes in the analyzed period (i.e. increase in mountainous forested areas, urban and agricultural intensification in coastal flatlands), possibly affecting the observed signals. Given the relatively low density of long-term records from which the Spain02 was built, caution is needed in the interpretation of results, especially for temperature in altitude gradients.

KEY WORDS: SE Spain · Precipitation · Maximum temperatures · Minimum temperatures · Spain02 · SPEI · Joint temperature–precipitation modes · Subregional trends · Land cover changes

1. INTRODUCTION

Although climate change is a global issue, many of its impacts, as well as adaptation and mitigation strategies, develop at local and regional levels, where interaction among the natural environment, human living and policymakers is at the highest intensity (Gimeno et al. 2011).

The Iberian southeast is one of the most arid regions in the Mediterranean area. A set of geographical factors (relief, latitude) determine its semiarid climate and landscape, sharing biophysical features with neighbouring regions of northern Africa. Shrubs and perennial grasses are the dominant species (Armas et al. 2011), with forests (mainly pine trees and holm oaks) and dense vegetation being restricted to mountainous areas. Nonetheless, semiarid regions of southeastern Spain are very rich in biological diversity, and there are several endemic plant species which deserve conservation policies

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(e.g. Mendoza-Fernández et al. 2014). Mountainous ranges of the Baetic System, such as the Sierra Nevada (with the highest Iberian mountain, Mulhacen, at 3478 m above sea level), Cazorla and Segura mountains, shelter the region from the influence of Atlantic fronts and determine a west-to-east gradient in the precipitation regime, with the lowest annual means (<200 mm yr^{-1}) recorded in the SE extreme (Cabo de Gata). Winters are cool and moderately wet, whereas summers are quite hot and dry. The Atlantic influence is more notable in winter and spring because of more frequent transient cyclones, which affect mostly higher and western areas. Thus, orography makes southeasternmost Iberia a rain shadow region characterized by few rainy days and large inter-annual precipitation variability (de Luis et al. 2009, Machado et al. 2011). In addition, the proximity of the Mediterranean Sea, the abrupt relief and the high radiation and temperature favour the development of typical autumn and summer convective storms. In semiarid regions like southeastern Iberia, water supply from mountains contributes 50 to 90% to total runoff (López-Moreno et al. 2011). Moreover, mountains exhibit responses to climate change which are often more readily identifiable than in other geographical entities; thus, their inclusion in this study is crucial.

A review of the history of the human fingerprint on the environment in southeastern Spain was presented by Sánchez-Picón et al. (2011). A strong deforestation took place in the mountains in the 19th century due to the mining industry. Afforestation (or 'coniferation') measures started in the 1950s to 1960s (Cortina et al. 2011), coinciding with a strong rural exodus. Thus, a huge change in land use from inland low-yield agriculture and pastures in the mountains towards coastal intensive irrigation horticulture and urbanization has taken place in the last decades, together with a large increase in population (Sánchez-Picón et al. 2011 and references therein). On the one hand, urbanization and intensive agricultural development have had major environmental consequences, such as species extinction (Mota et al. 1996), unsustainable use of subterranean water (Quintas-Soriano et al. 2014) and huge amounts of waste products. On the other hand, the abandonment of agriculture in inland areas has made possible natural revegetation on the mountain slopes which, together with an increase in forested area due to afforestation (IFN 2014), have likely led to several distinct environmental changes. For example, vegetation land cover change in southern Spain has given rise to slightly increasing carbon sequestration over the last 5 decades (Muñoz-Rojas et al. 2011). Also, enhanced fire risk can probably be associated with this increase in fuel (Pausas & Fernández-Muñoz 2012). Land use and land cover changes also induce regional climate changes. For example, it is very likely that the great spatial growth of greenhouse farming in the coastal southwestern Almería province (Campo de Dalías), with a current extension of about 27 000 ha (see Fig. 2 and Sánchez-Picón et al. 2011 supplemental material), has led to a drop in temperature in the area, when compared to neighbouring 'non-greenhouse' areas, because of the highly reflective roofs (Campra et al. 2008, Campra & Millstein 2013). Similarly, the above-mentioned increase in forested area has probably influenced biogeophysical processes (albedo and evapotranspiration), driving changes in temperature and in the hydrological cycle (Bonan 2008).

In the Iberian Peninsula, estimated mean trends in temperature since the mid-1970s to mid-2000s are ca. 0.5°C $decade^{-1}$ (Brunet et al. 2007), considerably higher than estimated rates obtained for global land-only temperature trends described in the IPCC fourth assessment report (Solomon et al. 2007). Beyond regional/local factors, a fraction of both temperature and precipitation variability in Spain is primarily related to large-scale atmospheric circulation (e.g. López-Moreno et al. 2011, Fernández-Montes et al. 2012, 2013, 2014). Predominant anticyclonic conditions in 1980 to the mid-2000s were to some degree responsible for drier and warmer periods, especially in spring (López-Moreno et al. 2011, Fernández-Montes et al. 2012, 2013, 2014). Furthermore, air temperature and precipitation are usually connected by several mechanisms. For example, wetter periods are associated with more cloudiness that damps maximum temperatures. By contrast, very dry soil conditions enhance maximum air temperatures because of increased sensible heat (e.g. Jerez et al. 2010). In turn, higher evaporative demand of a (warmer) atmosphere reinforces soil dryness, defining a positive feedback. In this way, resulting from the temperature rise, drought severity has probably increased in Spain in last 5 decades (Vicente-Serrano et al. 2014). Climate variability and events on shorter timescales also have a huge impact on the environment and society. For example, cold–dry events are harmful for agriculture, and extreme warm days can exert a negative impact on human health and ecosystems, while intense precipitation events in southeastern Iberia often cause damage like floods. Some changes in precipitation can go along with temperature increases (Trenberth 2011), as the atmosphere can hold more water vapour before saturation. Thus, the joint study of both precipitation and temperature data can yield a more complete picture of climate changes and their drivers in southeastern Spain.

The analysis of climate variability in this region of the Iberian Peninsula has been limited by the absence of quality data covering long periods. Previous works are mainly confined to the Alicante and Murcia stations (e.g. Machado et al. 2011, Fernández-Montes et al. 2012, Acero et al. 2014, Vicente-Serrano et al. 2014). Monthly series have been used to study trends in precipitation (e.g. de Luis et al. 2009, del Río et al. 2011) and temperature for the whole of Spain (del Río et al. 2012), including the southeastern region, from the 1960s onwards, although with insufficient subregional detail. Therefore, the objective of this paper is to evaluate and improve the understanding of recent climate changes in southeastern Spain by using high spatial resolution and daily data and focussing jointly on temperature and precipitation. To that end, the gridded dataset Spain02 (Herrera et al. 2012) is used for the most homogeneous period 1970–2007. We analyze trends in annual and seasonal values of 3 variables: maximum and minimum temperature (Tmax, Tmin) and precipitation (Precip). Additionally, we look for changes in the standardized precipitation–evapotranspiration index (SPEI) drought index (Vicente-Serrano et al. 2010) and in the frequency and intensity of combined temperature–precipitation modes (dry–cold, dry–warm, wet–cold and wet–warm days).

2. DATA AND METHODS

We employed climatic data from the recently developed Spain02 database (Herrera 2011, Herrera et al. 2012), which consists of regular 0.2 × 0.2° grids (approximately 20 × 20 km). The version is Spain02 v2.1 (March 2012), downloaded from www.meteo.unican.es/en/datasets/spain02. The database provides continuous daily values of Tmax, Tmin and Precip in the period 1950–2007. All station series used to build the Spain02 dataset underwent quality control and homogeneity tests (Herrera 2011, Herrera et al. 2012). The interpolation methodologies used to build the grids were ordinary kriging (OK) for precipitation and 3D thin-plate splines for monthly means followed by OK for the daily residuals for temperature (Herrera 2011, Herrera et al. 2012). Altitude was considered as variable in the interpolation procedure for temperature but not for precipitation, as the dense precipitation network appropriately represents the orography (Herrera 2011, Herrera et al. 2012).

The selected area in SE Spain encompasses not only dry regions but also wetter mountainous areas such as the Sierra Cazorla and Segura and the Sierra Nevada (Fig. 1). The whole region is divided into 5 sub-regions (NW, N, NE, SW, SE; Fig. 1) which are often referred to in the text. The selected area contains 113 grid points of the Spain02 data (Fig. 2). Because of the varying number of stations used to

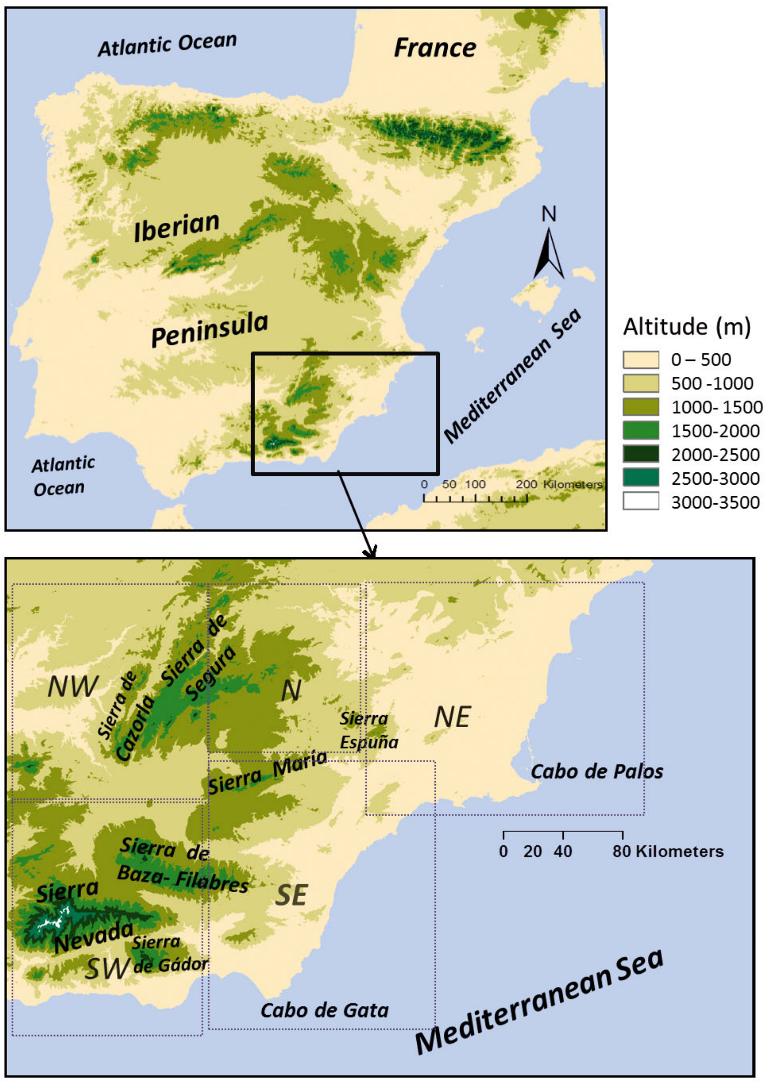

Fig. 1. Study area in the southeastern Iberian Peninsula showing altitude and main mountain ranges. The whole domain is divided into subregions

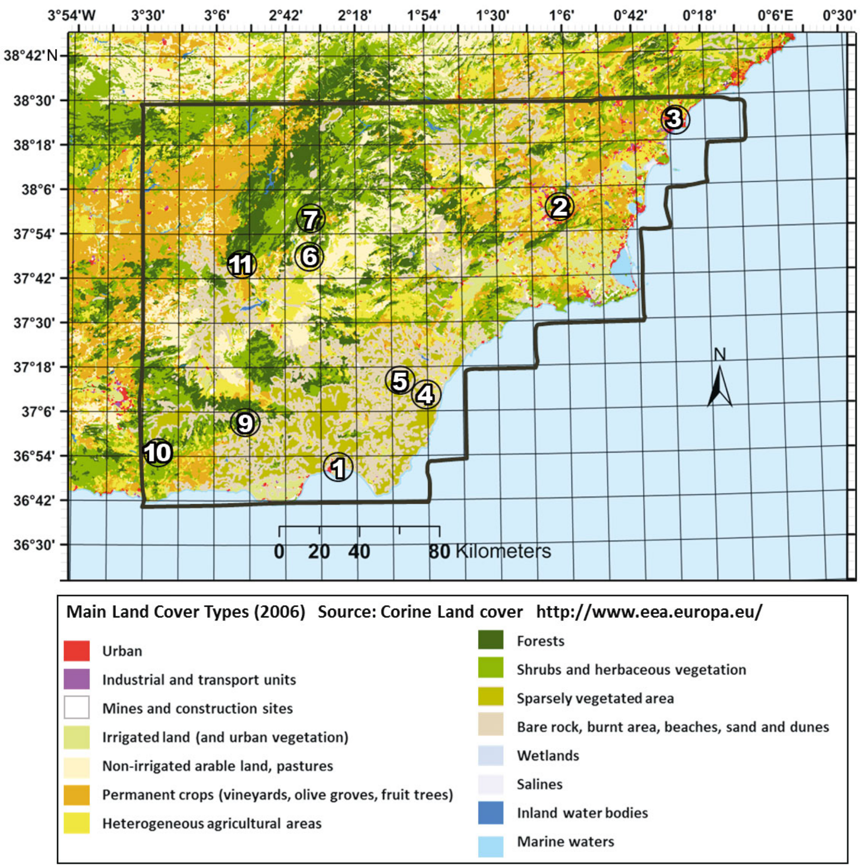

Fig. 2. Spatial resolution of the gridded dataset Spain02 with specification of our domain (113 grids of ca. 20 × 20 km) and geographical position (ID number, circled) of the stations used for validation (see Table 1 for description of station series, ID 8 is coincident with ID 9 location). Main current land cover types are displayed. Source: Corine Land Cover 2006, downloaded from the European Environmental Agency (www.eea.europa.eu/). The original dataset with 44 land cover classes is translated into 15 main types

originally build the Spain02 gridded dataset (Herrera 2011, Herrera et al. 2012), we restricted the study to the period 1970–2007. The number of available stations grows from 1950 until the early 1970s, when it remains approximately constant, although it decreases in the last years (Herrera 2011, Herrera et al. 2012). Hence, the period 1970–2007 can be taken as a more homogenous period from 1950 onwards to assess trends for both precipitation and temperature data, as also considered by Morán-Tejeda et al. (2013). The suitability of the Spain02 data for assessing long-term trends in our domain is probably superior for the N and NE areas of the study region, as the density of complete long-term records is larger than that for the southernmost area (see Fig. 2c in Herrera 2011). Regardless, the spatial coverage of all precipitation and temperature station series (both complete and intermittent) used to construct the interpolated gridded dataset is much higher in southeastern Spain than in other Spanish regions (Herrera 2011); hence, we are quite confident about the representativeness of the data. To approximately validate Spain02 gridded data for our domain (see section 3.1), we made use of station series of the highest quality possible (<8% missing data) from the Spanish State Meteorological Agency AEMET (www.aemet.com) and Junta de Andalucía (www.juntadeandalucia.es/medioambiente/site/rediam), compiled in the framework of the Global Change in Arid Zones (GLOCHARID) project (Fig. 2, Table 1). As a validation method, the Rho-Spearman correlation test was used to test the temporal congruency between gridded Spain02 data and station data in the region.

Seasons were considered as follows: winter, December to February; spring, March to May; summer, June to August; and autumn, September to November. The existence of trends in seasonal and annual mean values of the 3 variables (precipitation, Tmax and Tmin) was then assessed from 1970 to 2007 for each grid point of the dataset. Additionally, we analyzed trends in the mean temperature (calculated as average of Tmax and Tmin) and the diurnal temperature range (DTR, calculated as daily Tmax – Tmin) on an annual basis. The Mann-Kendall nonparametric test (Sneyers 1992) was used to test the existence of significant trends at both the 5 and 10% significance levels. For the sake of simplicity, least-squares linear regression was used to estimate the rate of change, an approach widely used in climate science (e.g. de Luis et al. 2014). In the case of significant trends according to the Mann-Kendall test, the significance of the linear trends was tested (*t*-statistic), as well as the goodness of fit (R^2).

Additionally, to monitor drought conditions, we analyzed the evolution of the SPEI (Vicente-Serrano et al. 2010) at a few locations in southeastern Spain (also from the 1970s onwards, available until 2012). The SPEI is based on monthly precipitation and potential evapotranspiration from the Climatic Research Unit (CRU) of the University of East Anglia; version 3.2 of the CRU dataset was used (Beguería et al. 2010). The SPEI was downloaded from http://

Table 1. Description and correlation coefficients (Rho-Spearman; *p < 0.05, all remaining values p < 0.01) between gridded data (GP) and station data (STAT) for the period 1970–2007. Mean altitude of Spain02 grid points is shown (ALT_GP) as well as station altitude (ALT_STAT). See Fig. 2 for station locations (ID). For 2 grid points (grid0156, grid0122), 2 instead of 1 station are considered (average series)

GP	ALT_GP (m)	ID	STAT	ALT_STAT (m)	Correlation Coefficient			
					Spring	Summer	Autumn	Winter
Precipitation (total seasonal)								
grid0101	126	1	Almería	21	0.984	0.97	0.988	0.983
grid0288	69	2	Murcia	57	0.903	0.673	0.909	0.879
grid0360	114	3	Alicante	82	0.951	0.907	0.897	0.946
grid0156	343	4/5	Gallardos + Lubrín	120 + 500	0.861	0.58	0.83	0.844
grid0247	997	6	Huéscar Icona	955	0.924	0.859	0.854	0.898
grid0280	1545	7	Puebla Fadrique	1198	0.897	0.916	0.812	0.905
grid0096	647	10	Órgiva	450	0.889	0.754	0.786	0.944
grid0122	1239	8/9	Cerecillo + Monterrey	1800 + 1280	0.837	0.633	0.871	0.83
grid0245	1059	11	Pozo Alcón (El Hornico)	993	0.812	0.740	0.633	0.854
Tmax (mean seasonal)								
grid0101	126	1	Almería	21	0.978	0.973	0.983	0.903
grid0288	69	2	Murcia	57	0.815	0.687	0.848	0.742
grid0360	114	3	Alicante	82	0.913	0.908	0.888	0.87
grid0247	997	6	Huéscar Icona	955	0.872	0.33*	0.691	0.471
grid0122	1239	8/9	Cerecillo + Monterrey	1800 + 1280	0.957	0.945	0.923	0.848
Tmin (mean seasonal)								
grid0101	126	1	Almería	21	0.984	0.993	0.966	0.891
grid0288	69	2	Murcia	57	0.894	0.915	0.862	0.903
grid0360	114	3	Alicante	82	0.978	0.99	0.977	0.976
grid0247	997	6	Huéscar Icona	955	0.624	0.845	0.655	0.598
grid0122	1239	8/9	Cerecillo + Monterrey	1800 + 1280	0.761	0.615	0.719	0.721

sac.csic.es/spei/. The SPEI takes into account both precipitation and temperature data (through potential evapotranspiration); hence, it is more realistic in describing drought conditions with respect to indices that consider only precipitation data (Vicente-Serrano et al. 2010). The SPEI is based on the Penman-Monteith estimation of potential evapotranspiration. The SPEI has a multi-scale character, providing timescales between 1 and 48 mo. We focussed on the 12 mo SPEI because we wanted to evaluate dry/wet years and variability in relation to Tmax and Precip annual series.

To gain better insight into the nature of temperature and precipitation changes, we focussed on daily data to study joint temperature–precipitation indices. These indices or modes of co-variability are defined following Morán-Tejeda et al. (2013). First, daily mean temperature (Tmean) is assessed as the arithmetic average of Tmax and Tmin, and the 25th (T25) and 75th (T75) percentiles are calculated. Days with Tmean < T25 are considered 'cold days', and days with Tmean > T75 are considered 'warm days'. These thresholds are used instead of more extreme ones to retain a larger number of days. Because of the skewed distribution of daily precipitation, different thresholds are used for defining the indices to be considered. First, 'dry days' (p < 0.1 mm) are separated and the 25th percentile of precipitation (P25) in wet days (p > 0.1 mm) is calculated. Then, we consider as really 'wet days' those with p > P25. Finally, a combination of simultaneous thresholds is performed to obtain the precipitation–temperature indices: dry–cold, dry–warm, wet–cold and wet–warm days. We first looked for trends in these frequency indices in 1970–2007. Additionally, we analyzed changes in the precipitation intensity of wet–cold days and wet–warm days (Beniston 2009) to discover if some changes in precipitation can be associated with temperature changes.

3. RESULTS

3.1. Validation of the Spain02 dataset

We employed 6 temperature and 11 precipitation station series (Fig. 2, Table 1) and assessed correlation between stations and the corresponding gridded data. This was done on a seasonal basis using seasonal mean Tmax and Tmin and seasonal Precip (Table 1).

We used correlation as a validation method to test the congruency between Spain02 data and station data in the region, i.e. to ensure that the gridded Spain02 data were indeed properly extracted for our domain. It is important to bear in mind that Spain02 gridded data are built from interpolating a number of stations for each grid point (Fig. 23 in Herrera 2011). Results of Rho-Spearman rank correlation tests show that, in general, both station and grid data are well correlated (Rho > 0.8). Lowest correlation coefficients were obtained in mountainous regions for temperature data (i.e. Huéscar, Láujar), which might well be due to the large spatial variability of temperature in altitude gradients in southeastern Spain, especially for Tmin (Pena-Angulo et al. 2014). This led us to be more cautious with temperature results in those regions. Best correlations (Rho > 0.9) were achieved for the main synoptic stations (Alicante, Murcia and Almería).

3.2. Precipitation

Mean values of annual precipitation (period 1970–2007) are shown in Fig. 3a. We can see that dry lands (<350 mm yr^{-1}) go from the most arid SE (Cabo de Gata) and extend to low and middle inter-range areas like the Guadix-Baza region. Middle mountain ranges like Sierra Maria and Sierra Espuña also register low amounts of rainfall. Trends from 1970 to 2007 are depicted in Fig. 3b. Most of the area (80%) depicts no trends in total precipitation. The strongest change is detected in the northern mountains of Cazorla–Segura, the region with the highest average annual precipitation (>750 mm yr^{-1}). There (about 8% of the total area), negative trends are detected at rates between 60 and 200 mm decade^{-1}, i.e. a decrease of about 10 to 30% decade^{-1}. For most of these grid points, linear trends are significant (p-values of the *t*-statistic < 0.05), although linear models represent only a small part of the variability (R^2 ~0.2 to 0.3). By contrast, some positive annual trends (20 to 60 mm decade^{-1}) appear in the dry south to southeastern region (about 11% of the total area), i.e. total annual precipitation has increased there by about 10 to 25% decade^{-1}. At these grid points, linear trends are less significant (p-value of *t*-statistic < 0.05 in half of the grid points; <0.1 in the rest), and linear fit is poor (R^2 ~0.1 to 0.2), which is meaningful given the high inter-annual variability of precipitation in this arid region.

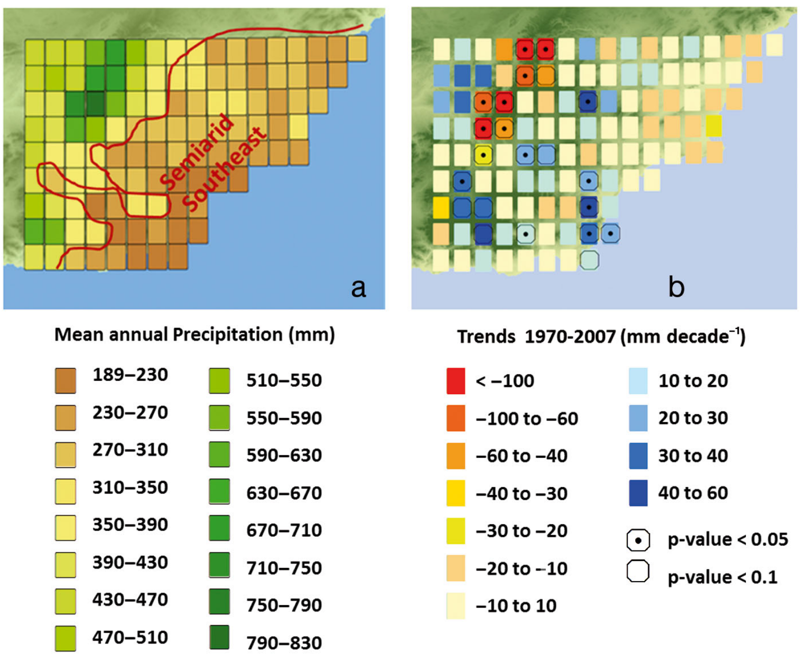

Fig. 3. (a) Average annual precipitation in 1970–2007. The red border approximately surrounds the areas with total annual precipitation below 300 mm (semiarid region). (b) Trends in annual precipitation for the period 1970–2007. Trends are estimated by linear regression, and significant trends at 10% of significance level according to Mann-Kendall test are marked with boxes (trends significant at 5% significance level are marked by an additional central dot)

Mean climatological values and trends in seasonal precipitation from 1970 to 2007 are presented in Fig. 4. First, we note that winter (followed by spring and autumn) is, on average, the rainiest season for western parts, autumn is the rainiest season for the NE and both winter and autumn contributions are equally important for the southeasternmost region. Regarding seasonal trends, a significant increase in winter precipitation (from about 10 to 40 mm decade^{-1}) is observed in eastern and southern parts of the region (Fig. 4b, about 30% of the area with positive trends significant at 10% significance level), which has clearly contributed to the aforementioned annual increase (Fig. 3b). In autumn (Fig. 4h), precipitation also increases in small parts of the SE (Níjar-Lubrín) as well as to the west of the region (10 to 30 mm decade^{-1}) and especially to the W/NW (>30 mm decade^{-1}), totally in about 18% of the area considered. By contrast, a significant reduction in precipitation is detected in the NW

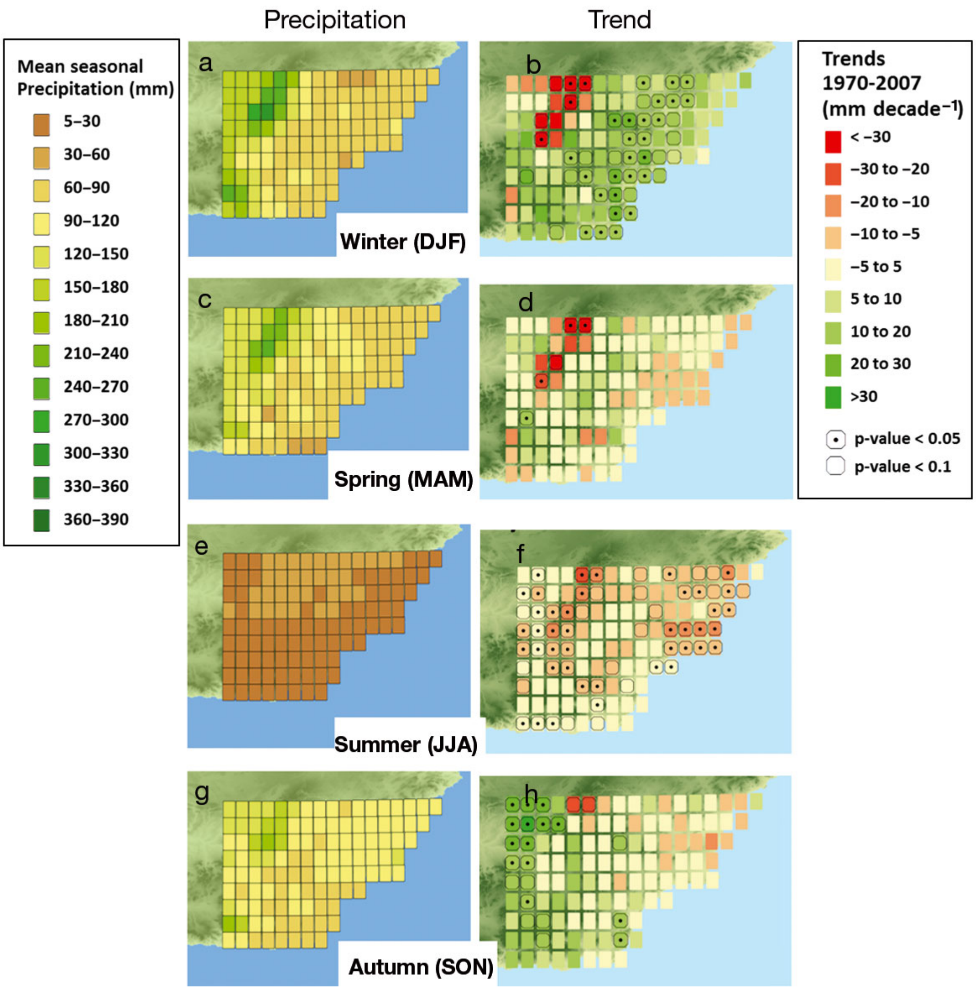

Fig. 4. Seasonal (a,c,e,g) precipitation mean values and (b,d,f,h) trends for the period 1970–2007. Trends are estimated by linear regression and significant trends at 10% of significance level according to Mann-Kendall test are marked with boxes (trends significant at 5% significance level are marked by an additional central dot). DJF = December, January, February; MAM = March, April, May; JJA = June, July, August; SON = September, October, November

mountainous regions in winter and spring (Fig. 4b,d, about 5% of the total area). In summer, a decrease in precipitation is observed (up to 20 mm decade^{-1}), particularly to the N and NE of the region, with significant negative trends in about 50% of the total area.

3.3. Temperatures

Mean values and trends in Tmin and Tmax on both an annual and seasonal basis for the period 1970–2007 are presented in Figs. 5 & 6, respectively. Mean climatological values of Tmin (Fig. 5, left panel) indicate a clear sea-to-mountains gradient in all seasons, from very high values in coastal sites in summer (up to 22°C) to very low values in the highest mountains in winter (down to –2°C). Mean values of Tmax are influenced by altitude and distance to the sea, with highest values (up to 36°C in summer) at lowlands in the interior and lowest values (8°C in winter) in mountainous areas, followed by some coastal areas which are also characterized by relatively low Tmax. Regarding the transition seasons, Tmin and Tmax are both slightly higher in autumn than in spring, which is of significance due to the lag time between maximum insolation and maximum temperatures in maritime regions.

Annual trends in Tmin (Fig. 5b) indicate significant increases in about 85% of the area, with the exception of mountainous regions in the north and centre (Segura and Maria mountains). The areas most affected by increases in Tmin are the NE (Alicante, Murcia) and SW (around eastern Sierra Nevada). By contrast, annual mean Tmax shows larger positive trends (Fig. 6b) to the W/NW (most continental areas) as well as to the SE. Positive trends in Tmax are significant according to the Mann-Kendall test in about 70% of the total area. Tmax increased less or decreased to the NE and western Almería (Campo de Dalías area). Rates of change in both annual Tmax and Tmin range from –0.4 to 1.4°C decade^{-1}.

The magnitudes of trends vary substantially among seasons. The lowest magnitudes for trends are

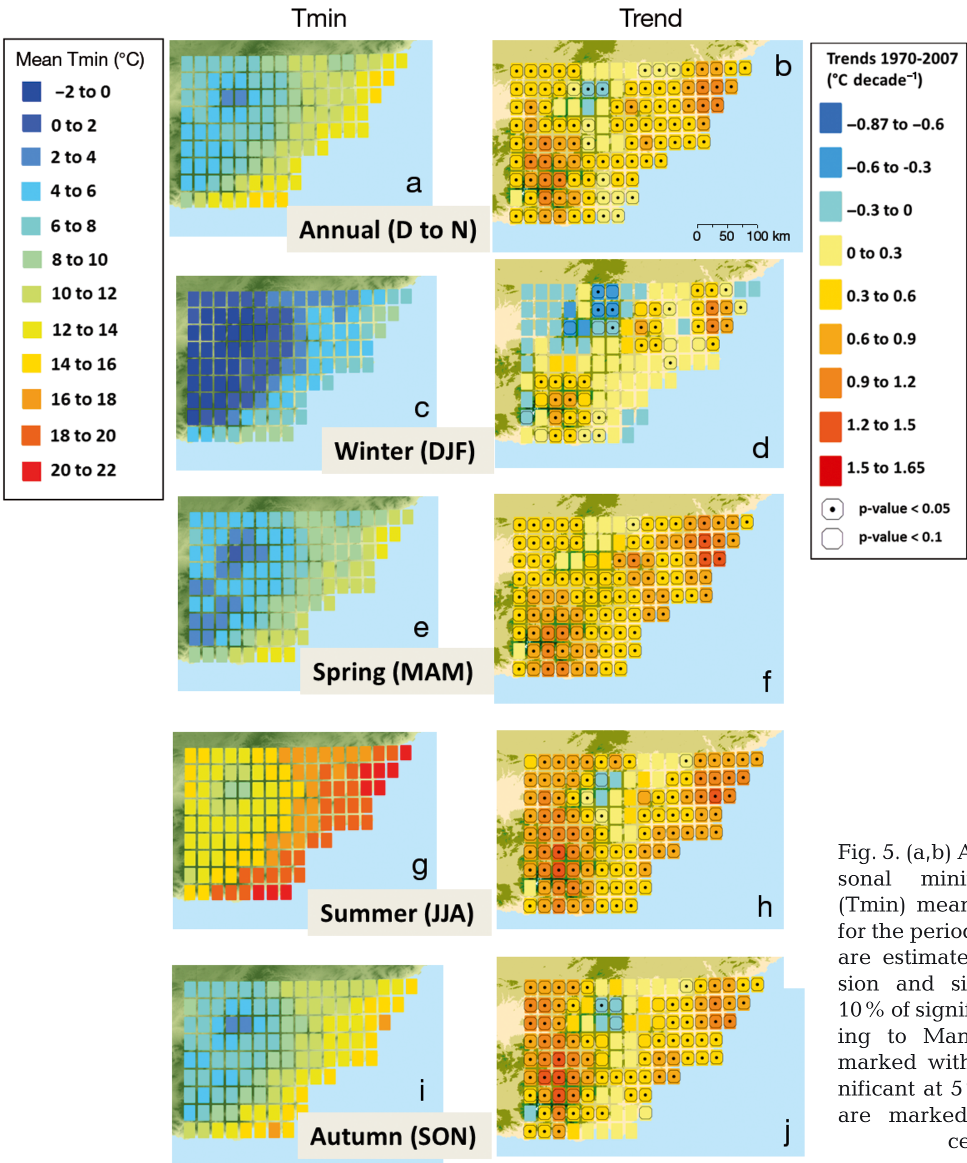

Fig. 5. (a,b) Annual and (c–j) seasonal minimum temperature (Tmin) mean values and trends for the period 1970–2007. Trends are estimated by linear regression and significant trends at 10% of significance level according to Mann-Kendall test are marked with boxes (trends significant at 5% significance level are marked by an additional central dot)

detected in winter: significant uptrends in Tmax are obtained only to the NW. Tmax experienced the highest and most widespread warming in spring and summer. Except for parts in the NE and Campo de Dalías (as on annual basis, about 25% of the total area), the rest of the region has experienced seasonal trends in Tmax that range from 0.6 to 1.6°C decade^{-1}. These linear trends have been tested (*t*-statistic is significant at p-value < 0.05) and the goodness-of-fit assessed (R^2 values range from 0.2 to 0.5).

Trends in Tmin in winter are only significant in about 40% of the total area (Fig. 5d), with moderate positive trends in the NE and SW and negative trends in parts of the N/NW. In spring (Fig. 5f), trends in Tmin are widespread and significant over nearly the whole territory, but the magnitude is not as high as for Tmax. The highest trends in Tmin are detected in summer and autumn, the seasons characterized by largest mean Tmin. Very high rates in Tmin (1 to 1.6°C) are confined to the NE and SW Sierra Nevada regions (like on annual basis). In these grid points, linear trends in Tmin are significant (p-value of *t*-statistic < 0.05) and goodness-of-fit is much higher (R^2 ~0.5 to 0.6) than those for precipitation and are also better than those for Tmax.

Fig. 7 shows trends in annual Tmean and mean annual DTR. Because of space limitations, we do not display seasonal results for these variables. Trends in Tmean (Fig. 7a) are significant at the 5% level according to the Mann-Kendall test in 88% of the area, at rates varying from 0.3 to 1.65°C decade^{-1}. The steepest trends are detected towards the NW

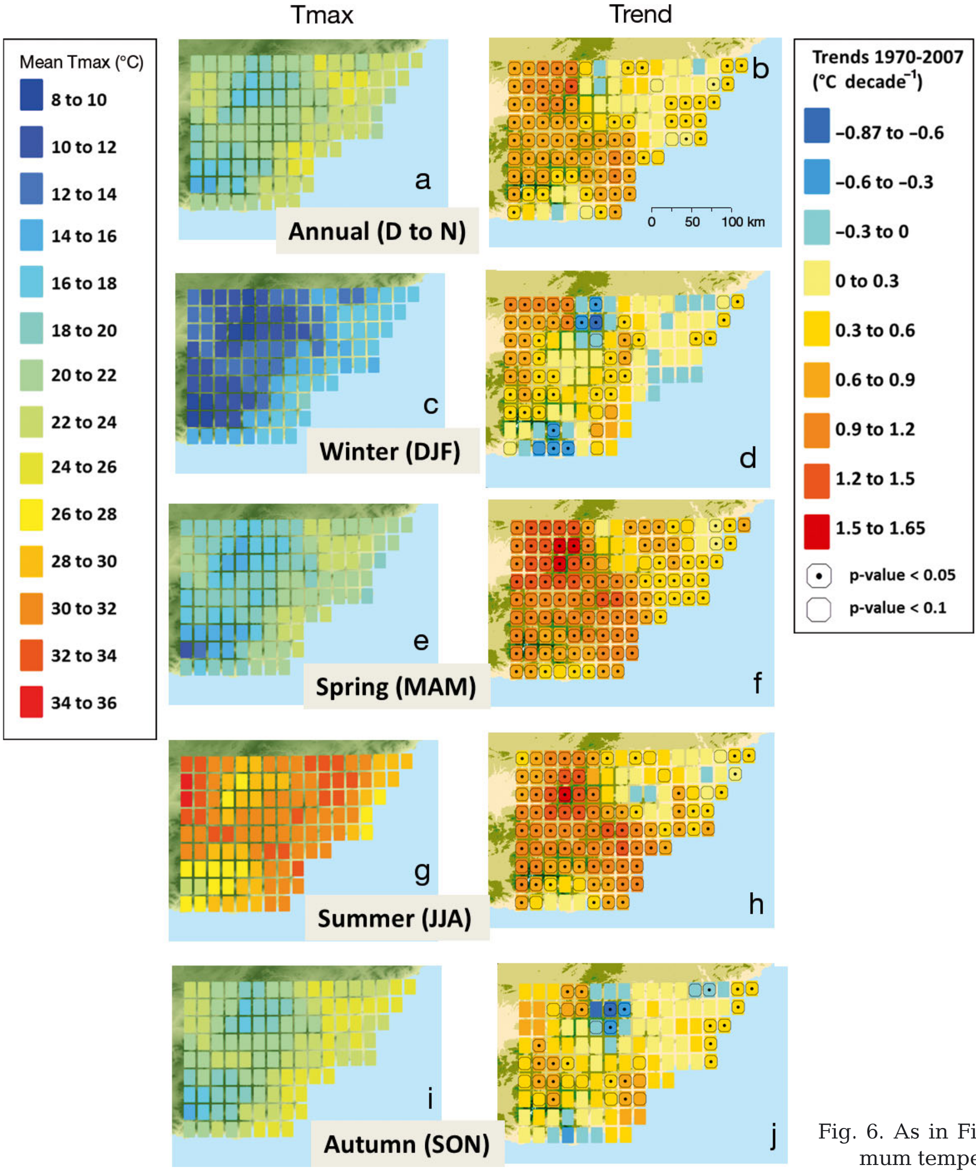

Fig. 6. As in Fig. 5 but for maximum temperature (Tmax)

and W (highest at the inter-range region of Guadix-Baza), congruent with the reported largest trends in both Tmax and Tmin. The DTR (Fig. 7b) shows significant negative trends in 25% of the area, namely the NE region, the northern SE and part of the SW area (eastern Sierra Nevada), congruent with larger increases in Tmin than in Tmax there.

3.4. SPEI

We focussed on the 12 mo SPEI that accounts for precipitation minus potential evapotranspiration during the previous 12 mo as a good indicator of long-term drought periods. For space limitations, we chose just 4 locations (grid points) within the study area which might be representative of some different sub-regions. Two of them belong to the western mountainous areas (S Cazorla to the NW and S Nevada to the SW), whereas the other 2 are representative of the most arid and Mediterranean coastal areas in the Spanish SE (Murcia to the NE and Almería to the south).

Fig. 8 shows the evolution of the 12 mo SPEI in 1970–2012, together with mean annual Tmax and total precipitation in 1970–2007 (available period for the Spain02 database). We observe a strong inter-annual to decadal variability in both SPEI and precipitation data, both being generally in phase (but with a small lag due to the previous 12 mo definition

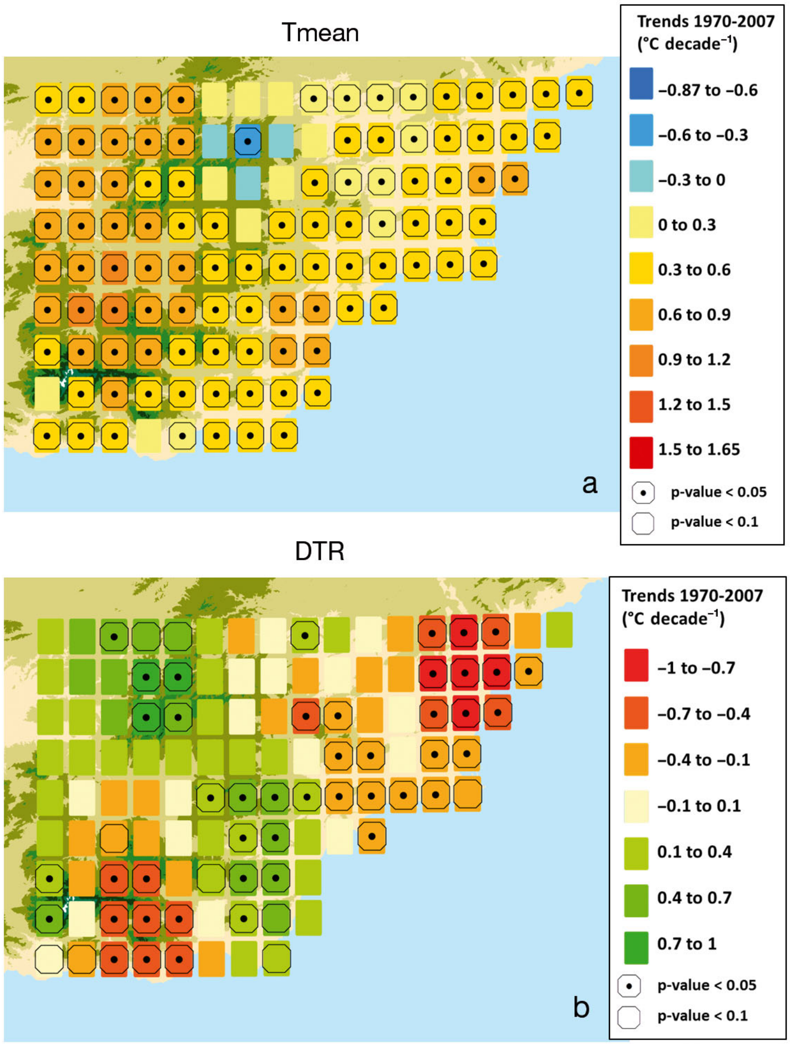

Fig. 7. Trends in (a) annual mean temperature (Tmean) and (b) mean annual diurnal temperature range (DTR) from 1970 to 2007. Trends are estimated by linear regression and significant trends at 10% of significance level according to Mann-Kendall test are marked with rectangles (trends significant at 5% significance level are marked by an additional central dot)

for the SPEI). Wet conditions (i.e. positive anomalies of precipitation and SPEI) are observed in the early 1970s (all 4 locations), late 1980s (eastern locations) and mid- to late 1990s (in west locations), and dry conditions are observed in the 1980s, early to mid-1990s and 2000s (strongest at the 2 northern locations). A recent increase in precipitation and SPEI is evident in all 4 locations in the late 2000s and early 2010s. Temperature depicts some multi-decadal variations, with a clear recent increase in the 1990s and early 2000s in the western mountainous locations and Murcia.

Correlation coefficients (Rho) among the 3 variables, as well as trends in each of them (correlation against time, t) for the period 1970–2007 are also displayed in Fig. 8. To that end, average annual SPEI indices were built from monthly values. The SPEI follows significant downtrends (i.e. increasing dryness) at the 5% level in all 4 locations (Rho [SPEI, t]), being more important at the 2 northernmost ones (S Cazorla and Murcia) (larger Rho coefficients). Nonetheless, the reduction in total precipitation in those locations (Rho, [Prec, t]) is not significant at the 5% level nor at the southern stations (where precipitation has increased slightly). By contrast, the annual series of Tmax follow significant positive trends in all 4 locations (Rho [Tmax, t]). As expected, correlation coefficients between SPEI and annual precipitation are positive and significant at all locations, ranging from 0.39 (Almería) to 0.63 (Murcia). Also as expected, correlation coefficients between SPEI and Tmax are always negative and particularly significant at S Cazorla (Rho = −0.45, 1% level). Finally, correlation coefficients between precipitation and Tmax are generally negative but only significant at easternmost locations (Almería, Murcia). This means that, especially in arid regions of SE Spain, warm periods are often associated with very low precipitation (and vice versa). In summary, one can state that the significant decrease of the SPEI (increase in drought conditions) in all 4 locations examined, beyond being related to precipitation variability, is probably also highly connected to an increase in temperature (significant at the 4 locations).

3.5 Combined precipitation–temperature daily indices

The study of joint modes of temperature and precipitation on a daily scale (dry–cold, dry–warm, wet–cold, wet–warm days) may provide further information about climatic changes in southeastern Spain. Fig. 9 shows the mean percentage of days in each of the combined classes and trends in their frequency in the period 1970–2007. As expected, there is an average predominance of dry–warm days (about 23% of total annual days) followed by dry–cold days (about 18 to 20%) and very low occurrence of wet–cold days

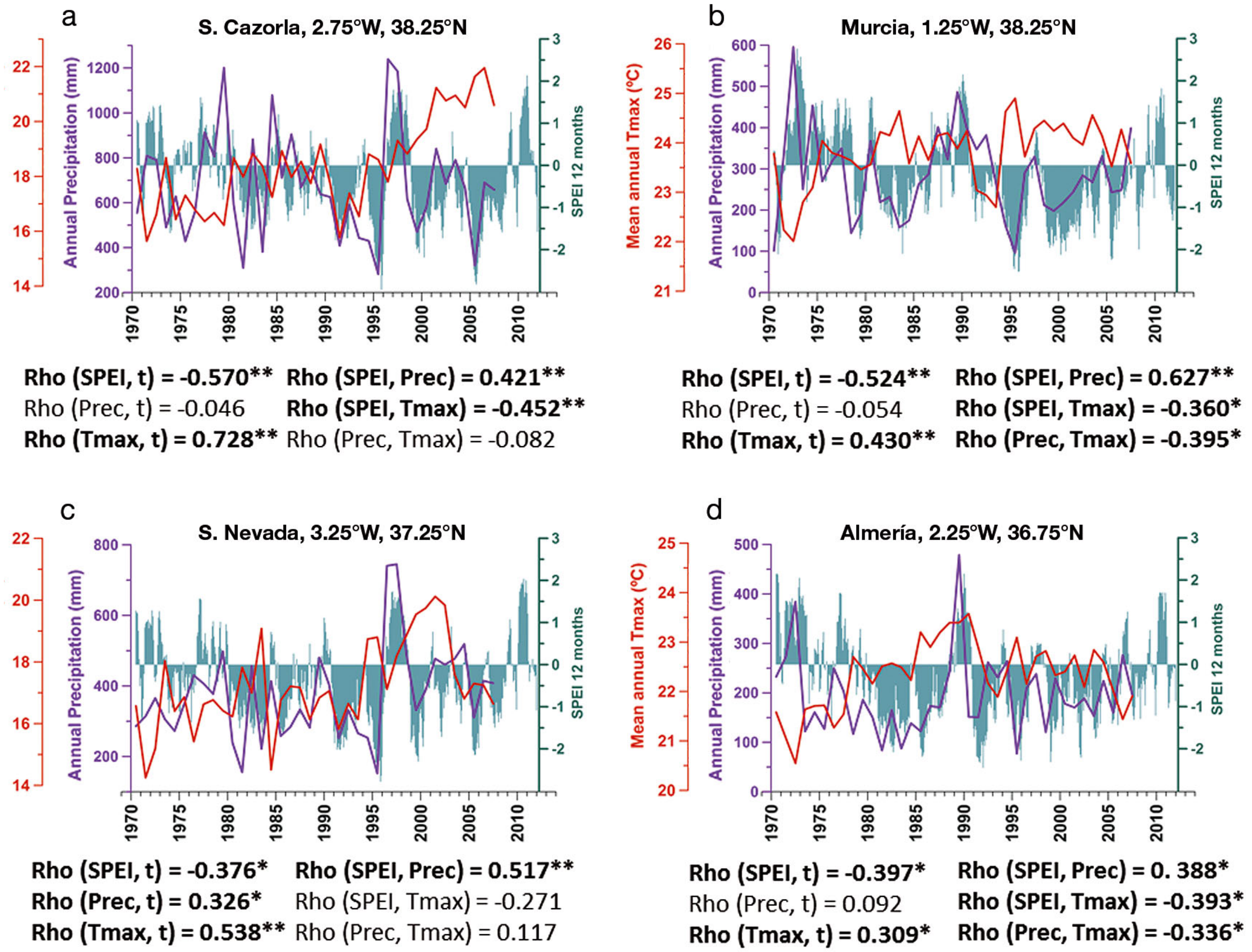

Fig. 8. Standardized precipitation–evapotranspiration index (SPEI) for a 12 mo scale for the period 1970–2012 for (a) Sierra de (S.) Cazorla (NW), (b) Murcia (NE), (c) S. Nevada (SW) and (d) Almería (S). Source: http://sac.csic.es/spei/database.html#p1. Additionally, mean annual maximum temperature (Tmax) (red line) and precipitation (Prec, purple line) are shown from Spain02 gridded data, 1970–2007. Rho-Spearman correlation coefficients among the different variables for the period 1970–2007 are shown, as well as time (t) correlations (Rho against t, for estimation of trends) for SPEI, Precip and Tmax. **Bold:** significant ($^*p < 0.05$, $^{**}p < 0.01$)

(3 to 7%) and wet–warm days (<3%). About half of the total days are none of these extreme modes. Trends in their frequency show a widespread decrease in dry–cold days (rates from –15 to –50% decade^{-1}) together with an increase in dry–warm days (rates from 2 to 50% decade^{-1}), with the only exception of a few grid points in the northern mountains. Therefore, dry–cold and dry–warm days follow opposite trends, although dry–cold days have diminished more towards the coast and dry–warm days have increased more inland. Seasonally (not shown), these signals are strongest in spring and summer, concurrent with larger warming of Tmax in those seasons (Fig. 6). Wet–cold days have decreased significantly to the W/NW and the NE, while wet–warm days have increased more at inter-range areas and also in the W and NE.

Finally, Fig. 10 depicts seasonal changes in mean daily precipitation intensity within wet–cold and wet–warm modes. In general, the areas of increasing/decreasing intensity are coincident with the above-mentioned areas of increasing/decreasing frequency in these days. Within wet–cold days, changes in intensity are barely significant, with the exception of some increases in winter to the SE and negative signals in summer, autumn and spring. However, within wet–warm days, distinctive signals of increasing intensity are found, especially in the transition seasons, over the same regions of increasing frequency of these days (i.e. the western half and NE

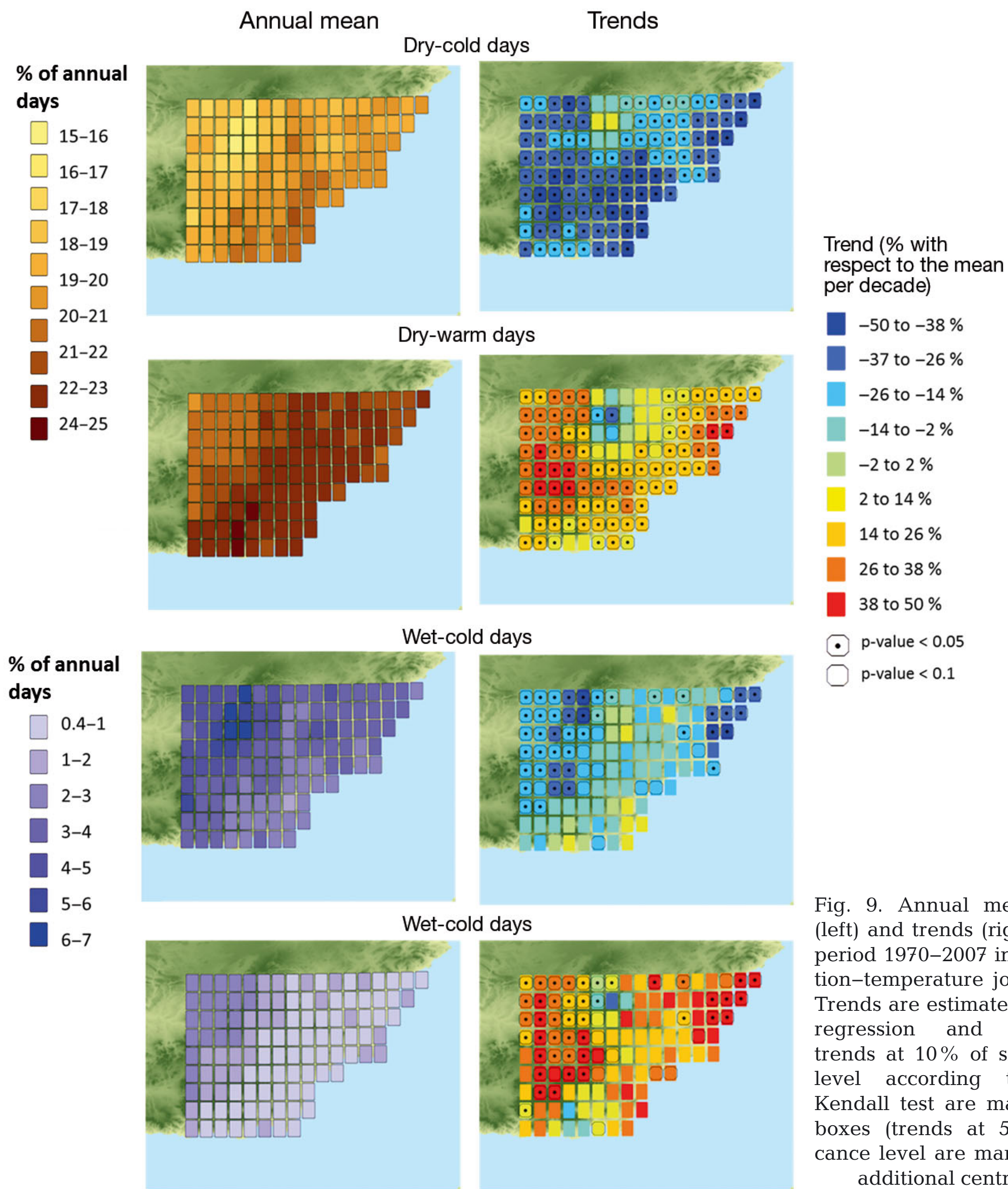

Fig. 9. Annual mean values (left) and trends (right) for the period 1970–2007 in precipitation–temperature joint modes. Trends are estimated by linear regression and significant trends at 10% of significance level according to Mann-Kendall test are marked with boxes (trends at 5% significance level are marked by an additional central dot)

regions). Positive trends in daily intensity within wet–warm days in autumn and spring are significant in about 50% of the total area. Largest trends in the intensity within wet-warm days are detected in autumn (increases up to 6 to 7 mm decade^{-1}).

4. DISCUSSION

4.1. Precipitation trends

Having considered higher spatial resolution and the period 1970–2007, trends detected here in precipitation differ slightly from previously reported trends in this region considering different data and periods (1950–2000 and 1960–2006, by de Luis et al. 2009 and del Río et al. 2011, respectively), even if there is general agreement in the decrease in summer and increase in winter precipitation. Our results, nonetheless, reveal subregional and local patterns, according to the high spatial variability of precipitation in the southeastern Iberian Peninsula (Cortesi et al. 2014). Uptrends in total annual precipitation in the area further E/SE (Fig. 3b) seem mainly due to the winter season (Fig. 4b), consistent with increasing frequency of easterly circulations and associated cyclogenesis (Millán et al. 2005, Fernández-Montes et al. 2012), which in

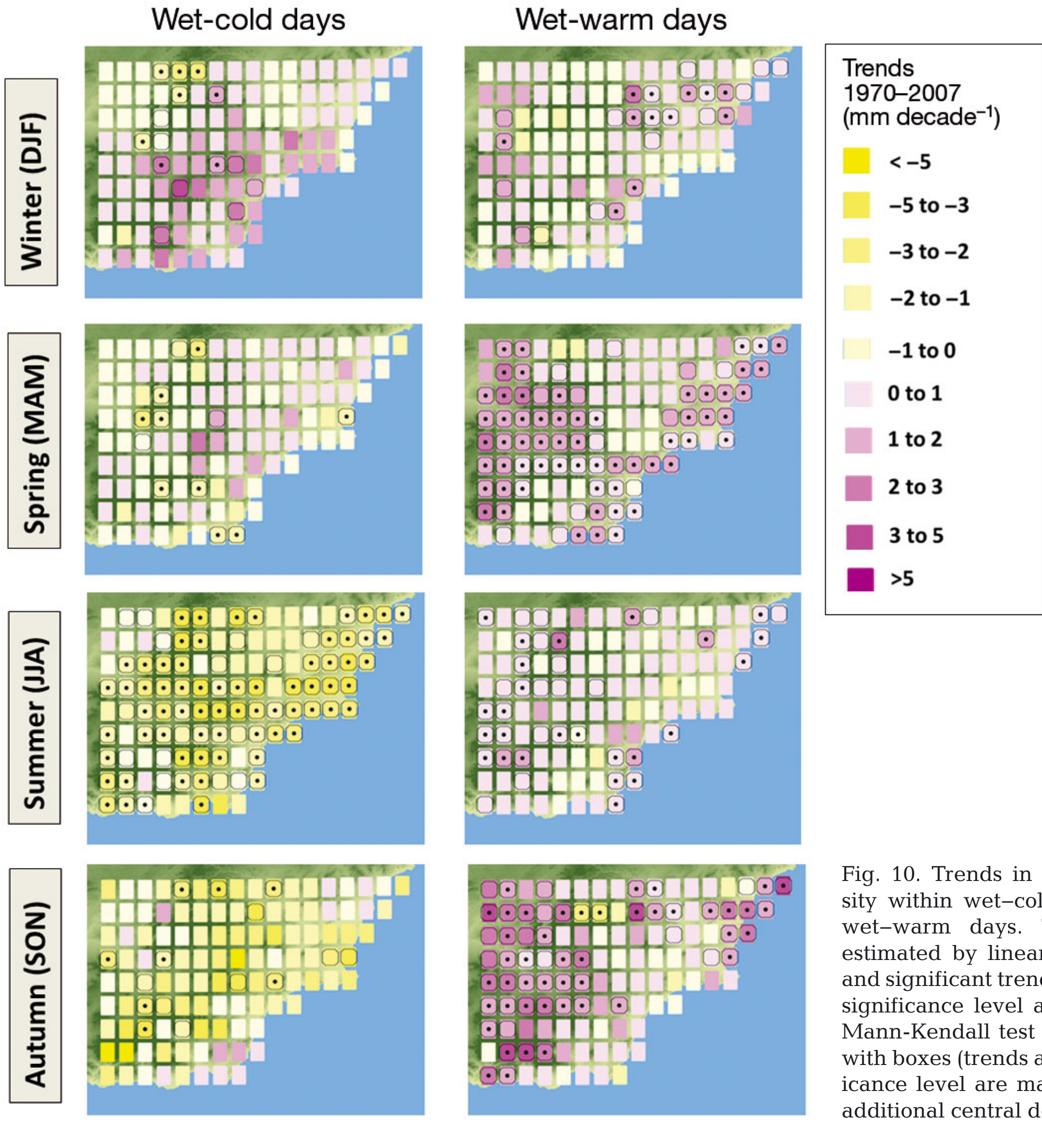

Fig. 10. Trends in daily intensity within wet–cold days and wet–warm days. Trends are estimated by linear regression and significant trends at 10% of significance level according to Mann-Kendall test are marked with boxes (trends at 5% significance level are marked by an additional central dot)

turn is related to more frequent negative phases of the Western Mediterranean Oscillation (WeMO) (López-Bustins et al. 2008). Similarly, uptrends in autumn precipitation in western parts (Fig. 4h) agree with more frequent westerly circulation and cyclones since the mid-1970s in that season (Fernández-Montes et al. 2014). By contrast, negative trends in spring and winter to the NW are explainable by the positive trend in the North Atlantic Oscillation (NAO) index and less frequent Atlantic cyclones crossing the southern Iberian Peninsula (López-Moreno et al. 2011, Fernández-Montes et al. 2012, 2014). Finally, the decrease in summer precipitation might have a connection with a trend towards fewer summer storms in the mountains of the western Mediterranean basin due to an increase in the convective (orographic) condensation level (Millán et al. 2005).

The decrease of precipitation in the NW mountainous area compared to lowlands and coastal eastern regions (Figs. 3 & 4) is in line with results found in other Mediterranean regions with a similar sea-to-mountains gradient (e.g. Slovenia, de Luis et al. 2014). Regarding environmental implications, the observed loss of spring and winter precipitation in the northwestern mountains is likely to have affected river flows and groundwater resources (Castaño et al. 2013), with negative consequences in lowlands as well. However, significant trends have been found only in a few grid points; therefore, most of the region has not suffered a net change in total annual precipitation in the period. Similarly, the slight recovery in precipitation in winter in the eastern region does not balance the deficit in spring and summer (Fig. 4), when rainfall would be more necessary to counteract the high evaporation and warm conditions.

4.2. Temperature trends

Tmax experienced the highest warming in the spring and summer seasons, followed by autumn, in accordance with previous studies in Spain (e.g. Brunet et al. 2007, del Río et al. 2012) and also with studies of SST trends in the western Mediterranean and Alboran Sea (López García & Camarasa Belmonte 2011). Our results add spatial resolution: trends vary between 0.2 and 1.6°C decade^{-1}, and there are some areas (about 20%) with no trends or even negative signals. Besides the sustained increase in greenhouse gases in the atmosphere (Solomon et al. 2007), this large warming in summer, spring and autumn is well related to increased surface solar radiation in 1985–2010 in the eastern Iberian Peninsula (Sánchez-Lorenzo et al. 2013). On the one hand, the largest increase in Tmax detected over the western NW regions seems somehow connected with a decrease in precipitation there (Figs. 4b,d,f & 8a), i.e. daytime temperatures are enhanced by a soil moisture deficit (less evaporative cooling) and more frequent anticyclonic conditions (cloudless sky). But the decrease in precipitation is only significant in the Sierra Cazorla and Segura mountains. Also, biogeophysical changes linked to the increase in forested area (Cortina et al. 2011, Muñoz-Rojas et al. 2011, IFN 2014) and vegetation growth in natural areas (Alcaraz-Segura et al. 2010) might well have driven temperature changes in the region. For example, a decrease in the albedo due to this land use change towards more dense and extended boreal forests (Bonan 2008) is likely to have enhanced daily Tmax in mountainous areas (Fig. 6). Moreover, conifer forests have a low summertime evaporative fraction (Bonan 2008), producing high rates of sensible heat exchange and deep atmospheric boundary layers. This behaviour may also have increased Tmax with respect to previous land cover (e.g. less mature conifer forests). Nonetheless, these and more processes linked to land cover changes and vegetation dynamics (Bonan 2008) are complex and need further investigation.

On the other hand, the differential signals in Tmax to the NE (Murcia–Alicante) and in Campo de Dalías (i.e. less warming or cooling signals with respect to trends in the rest of the region), observed in all seasons, probably point to anthropic land use in those areas. Thus, an increase in albedo because of the growth of large greenhouses in the Almería Campo de Dalías area seems to partially explain a decrease in Tmax, with respect to previous pasture and shrub land cover, as shown by observational data in the area since the 1980s (Campra et al. 2008) and regional simulations (Campra & Millstein 2013). Additionally, an increase in irrigated agriculture areas, both in Almería and especially in the Murcia region (Sánchez-Picón et al. 2011; Fig. 2) has also probably lowered Tmax, because of evaporative cooling. This in turn would also explain the observed Tmin increases (Fig. 5), given the higher heat capacity of the soil when irrigated (Kalnay & Cai 2003). Finally, a drop in Tmax in these areas might also be related to some degree to slightly enhanced sea breezes and easterly winds (Fernández-Montes et al. 2012, 2013), which involve mild temperatures. In this sense, Azorin-Molina et al. (2014) found significant increasing trends in mean wind speed in the Almería station (1979–2008) in all seasons. Nonetheless, the singularity and location of these signals (see Fig. 2 for areas with intensive irrigated agriculture towards the S/SW and NE of the domain) lead us to think that, in addition to natural variability, land use change has probably been a major driver of this temperature change.

In fact, greenhouse farming in Campo de Dalías (also locally known as Poniente) seems to have been very efficient in reducing Tmax over a wide region locally (Fig. 6, about 8 to 10 grid points affected by cooling or no trends). Indeed, this flatland holds the largest concentration of greenhouses in the world (the 'sea of plastic'), increasing from barely 3000 ha in 1975 to around 27 000 ha in 2008 and representing more than half of the total greenhouse area in Spain (Sánchez-Picón et al. 2011 and references therein). Because this is a coastal area, temperatures are smoothed by the sea, and maximum temperatures in summer are typically below 30°C. This means that the potential benefit of a cooling forcing based on the white cool roofs of the greenhouses, as a local climate change adaptation measure, is not nearly as useful here as it would be in warmer inland areas or large cities (Oleson et al. 2010). In this sense, regional adaptation strategies could be devised to develop this economy in a more rational and sustainable way in other areas with higher Tmax, e.g. internal valleys in the region, which in turn present a currently better coupling between water consumption and recharge (Quintas-Soriano et al. 2014).

Rates of change found here in Tmin from the 1970s onwards, from –0.4 to 1.4°C decade^{-1}, are slightly higher but congruent with mean trends detected by del Río et al. (2012) (from 1960) in the SE coastal region (0.3°C decade^{-1}). As for Tmax, trends in Tmin would have been much lower if they had been assessed from the 1950s or 1960s onwards, since those decades were relatively warm in Spain (see e.g. Brunet et al. 2007). By contrast, the 1970s were cooler and a warming period has taken place since the mid-1970s (also on a hemispheric scale and in Atlantic and Mediterranean SST, Fernández-Montes et al. 2013), explaining the large magnitude of trends in temperature detected for the period 1970–2007. Our analysis reveals subregional behaviours also in this variable. The largest increase in Tmin was observed in the NE (Alicante–Murcia area). Again, the intense urbanization process and increase in irrigation in this area since the 1960s (Sánchez-Picón et al. 2011) may well explain this nighttime warming, which is congruent with trends found by del Río et al. (2012) and Acero et al. (2014). As commented above, this area in turn depicted a low Tmax increase, which points to the mentioned role of anthropic land use in regional temperature trends, i.e. decreasing daily and increasing night temperatures (Kalnay & Cai 2003). This behaviour is further confirmed by the negative trends found in the DTR in that area (Fig. 7b). The increase in Tmin as well as the decrease in the DTR observed also in the eastern Sierra Nevada (Figs. 5 & 7) could have been partially motivated by large-scale patterns, since the NAO is more strongly correlated with Tmax (positively) than Tmin (negatively) in this mountainous area (López-Moreno et al. 2011); this and other possible causal mechanisms need further research.

4.3. Combined precipitation–temperature indices

The analysis of the 12 mo SPEI revealed important drought periods in the last 4 decades (1970–2012); the most recent one occurred in the 2000s (decade from 1998 to 2008) and particularly affected the northern part. In 1970–2007, the SPEI is related to both precipitation and temperature evolution (Fig. 8). Although correlations with precipitation are higher, the long-term significant decrease in the SPEI (i.e. increase droughts) in all 4 locations examined seems indeed more motivated by a temperature increase (i.e. in the potential evapotranspiration) than by a precipitation decline. This is in line with findings by Vicente-Serrano et al. (2014) for station series in the whole Iberian Peninsula (including the Murcia and Alicante stations), i.e. increased aridity related to temperature increase. These drought periods are likely to have been harmful both for agriculture and for the natural environment and may have enhanced forest fire risk (Pausas & Fernández-Muñoz 2012).

Regarding daily temperature-precipitation combined indices, the whole region (but especially the NE and western areas) experienced a remarkable change towards increasing warm days and decreasing cold days (Fig. 9), in concordance with the highest temperature increases observed there (Fig. 7a). Related to these changes in extreme temperatures, it has been shown that snow cover suffered a significant decline in the Baetic System in this period (Morán-Tejeda et al. 2013). Similarly, a reduction in the number of cold days, and an increase in Tmin, should involve less frequent fog condensation during the night. Dewfall is a small but constant source of water (especially in winter, spring and autumn) in arid ecosystems in southeastern Spain, which significantly contributes to the local water balance, mainly during dry periods (Uclés et al. 2014). While the NE area was more influenced by nighttime warming, the western regions depicted both night and daytime temperature increases (Figs. 5 & 6), with significant uptrends also in dry–warm and wet–warm days (Fig. 9), which may have resulted in harmful effects to both natural ecosystems and crops.

Moreover, we detected a trend towards increasing precipitation intensity in autumn and spring (and to a lesser extent in summer and winter) within warm days (Fig. 10), which matches in part the positive trend in total autumn precipitation (Fig. 4b). Increased precipitation intensity under increased temperature is explainable because of enhanced convective instability and more water vapour in the atmosphere (e.g. Trenberth 2011). This finding also supports the hypothesis by Millán et al. (2005) regarding intensified autumn torrential events in the Mediterranean basin. Increased intensity involves enhanced risk of these precipitation events, such as soil erosion and floods. Especially vulnerable are the highly populated areas to the NE (Alicante, Murcia, northern Almería), where in turn total spring and autumn precipitation has decreased slightly (Fig. 5d–h).

5. SUMMARY AND CONCLUSIONS

This study analyzes changes in temperature (Tmax, Tmin, Tmean and DTR) and precipitation in the southeastern Iberian Peninsula using the gridded dataset Spain02. Trends are assessed over the most reliable and complete period 1970–2007. We also analyze trends in joint temperature–precipitation daily indices and the evolution of the SPEI drought index (1970–2012) at some representative locations. Main conclusions from the work are as follows:

(1) In most of the area (80%), no significant trends in total annual precipitation were found. Only the wettest mountains to the NW (Cazorla) depicted a significant drop in precipitation, whereas parts in the most arid region to the S/SE experienced a slight increase. Nonetheless, some seasonal changes were notable. In winter, a significant increase was detected in eastern parts (40% of the total area). To the west, precipitation increased in autumn (20% of the area) but decreased in winter and spring (5% of the area). Summer precipitation decreased, especially in the northern half (50% of the area). These trends seem congruent with previously reported changes in atmospheric circulation patterns and mesoscale factors.

(2) About 70% of the area followed significant ($p < 0.05$) uptrends in Tmax (rates from 0.2 to 1.6°C decade^{-1}). The largest increases were detected in spring and summer and especially in northern and central parts (mountains and inter-range areas), as well as towards the SE (Cabo de Gata-Níjar region). These are mainly mountainous areas which may reflect regional manifestations of large-scale warming patterns and where an increase in forested area could have acted reinforcing daily maximum temperatures. Tmax increased less or decreased in small populated areas to the NE (Murcia–Alicante) and southwestern Almería (Campo de Dalías). These differential signals might well be related to evaporative cooling due to increasing irrigation as well as to the albedo by the expansion of greenhouse farming.

(3) Rates of change found in Tmin ranged from 0.2 to 1.4°C decade^{-1} and were significant ($p < 0.05$) in about 85% of the study area, with the exception of the winter season (less increase). Tmin showed a distinctive increase to the NE (Alicante and Murcia), which is likely related to the great urbanization and population growth in that area. To the SW (Alpujarras–Sierra Nevada–Guadix), an abrupt increase in Tmin was also observed, but the causes need further research.

(4) Extreme warm–dry and warm–wet days increased remarkably to west and NE areas, whereas cold–dry days showed a widespread decrease. Cold–wet days also generally decreased. Daily precipitation intensity increased within warm–wet days, especially in autumn and spring, even where non-significant changes in total precipitation amount have occurred.

(5) The 12 mo SPEI (1970–2012) depicted important drought periods since the 1980s, although conditions in the late 2000s and early 2010s were slightly wetter. In spite of the slight recovery in precipitation in some parts of the S/SE, long-term droughts have likely increased (especially in northern locations). Total precipitation has not significantly changed; hence, trends towards drier conditions seem connected to increasing air temperature.

(6) All of these climatic changes have probably had several impacts in the regional environment, such as reduced snow cover, enhanced aridity related to warming, increased flooding risk in the transition seasons, increased summer heat stress and decrease in dewfall. An interesting finding is the increase in the DTR in some mountain and natural areas (15% of total area), which is likely to have affected natural ecosystems. Similarly, the decrease in the DTR due to the large increase in Tmin observed mainly in populated areas (25% of total area) has also probably influenced human nighttime heat-stress and comfort, especially in summer and early autumn.

(7) Future work should deal with a thorough evaluation of both large-scale and local factors involved in precipitation and temperature changes in this region. Thus, we aim to assess the influence of global warming and changing circulation on observed variability patterns. Similarly, the role of biogeophysical and biogeographical processes of land use changes on local and regional climate variability should be analyzed further.

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