

# Seasonal temperature and precipitation variability during the last 60 years in a Mediterranean climate area of Northeastern Spain: a multivariate analysis

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**Abstract** This paper presents the analysis of mean daily temperature and precipitation from 1950 to 2010 in an area with Mediterranean climate of NE Spain including some coastal areas near Barcelona and the Penedès and Camp de Tarragona Depressions located between the Coastal Mountain Range and the Mediterranean Sea. Their variability, with especial attention to the frequency of extreme events, was analysed by using 18 indexes: seven for temperature and 11 for precipitation were analysed for four meteorological observatories. A multivariate analysis was performed in order to analyse the temperature and precipitation trends. During the analysed period, an increase in mean annual maximum temperature was observed in all observatories ranging between 1.5 and 2.2°C associated with an increase in the number of days with high extreme temperatures. Minimum temperature only increased significantly in the coast observatories (about 1.4°C). By seasons, temperature trends were greater at Vilafranca del Penedès and Barcelona observatories and lower at Reus airport. Maximum spring temperature increased between 1.5 and 2.5°C, summer temperature increased between 1.6 and 2.5°C and autumn temperature increased by up to 2.2°C. Precipitation presented a high variability from year to year, without significant trends. The most significant results were related to the dry conditions observed in spring 2000s, the wet conditions recorded in summer 2000s and 1980s and the longer dry periods in autumn 2000s. The increase of temperatures determined the increase of evapotranspiration, and due to the higher irregular distribution, water deficits for crop development were

recorded. An advance of phenological dates and a reduction of grape yield are associated to climate trends.

## 1 Introduction

Climate change and its impacts on earth surface, associated with the increase in greenhouse gases and changes in global temperatures, radiation budget and hydrological cycles, have increasingly attracted the attention of researches in different areas. According to the forth IPCC report (IPCC 2007), significant trends in temperature and precipitation were observed around the world but with different magnitudes. The impacts of those trends in the mid-term have been noted in several aspects. In particular, an intensification of the stress of the hydric resources is expected. In this respect, several studies have been carried out to determine the impact on water resources (Middelkoop et al. 2001; Ragab and Prudhomme 2002; Izaurrealde et al. 2003; Arnell 2004; Iglesias et al. 2007; IPCC 2007) and agriculture (EU Directorate Generale Science and Development 1997; Olesen and Bindi 2002; Rosenzweig et al. 2004; Iglesias et al. 2009; Nelson et al. 2009; Ramos and Martínez-Casasnovas 2010a). Precipitation changes, which include a greater number of extreme events and longer dry periods, together with temperature increases, which increase evapotranspiration, will have negative impacts on agriculture. Particularly in Southern Europe, these trends could exacerbate the existing conditions in areas already vulnerable to the climatic variability, reducing water availability. The Mediterranean area may be particularly sensitive. Some authors reported significant changes in precipitation patterns with decreasing precipitation trends for the Mediterranean (Karl 1998; Goubanova 2007; de Luis et al. 2009) and significant changes in extreme events, with higher rainfall concentration in a small number of events and more frequent and extreme droughts (Easterling et al. 2000;

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Houghton et al. 2001; Brunetti et al. 2002; Klein Tank and Können 2003; Ramos and Martínez-Casasnovas 2006; Lana et al. 2009).

This paper analyses mean daily temperature and precipitation for the last six decades (series from 1950 to 2010 for temperature and precipitation) in a Mediterranean climate area of NE Spain in order to evaluate the behaviour and magnitude of their changes. Variability during the last decades with special attention to the frequency of extreme events was analysed by using seven indexes for temperature and 11 indexes for precipitation. A multivariate analysis was performed in order to classify the years and to analyse temperature and precipitation trends.

## 2 Material and methods

### 2.1 Location of the study area

The study area is located in Northeast Spain including some coastal areas near Barcelona and the Penedès and Camp de Tarragona Depressions located between the Coastal Mountain Range and the Mediterranean Sea (Fig. 1). The climate is Mediterranean with maritime influence, characterised by two wet periods (spring and autumn) separated by hot and dry summers. High intensity rainfall events are usually recorded in autumn.

### 2.2 Climate data and indexes

Four long temperature and precipitation series were used in this study: Vilafranca del Penedès (lat: 41°20'50"; long: 1°41'59"; elevation: 223 m.a.s.l.), belonging to the Institut Català de la Vinya i el Vi (INCAVI) and properly located in the Penedès Depression; Barcelona–Fabra (lat 41°25'6"N 2°7'27"E elevation 411 m.a.s.l.), Barcelona airport (lat 41°17'49" N, long 2°4'42" , elevation 4 m.a.s.l.), and Reus airport (lat 41°9', long 1°9'36", elevation 71 m a.s.l) belonging to the Agencia Estatal de Meteorología (Spain), located in the Camp de Tarragona Depression. Mean, maximum and minimum daily temperatures (1950–2010) and daily precipitation (1950–2010) were analysed. Additionally, shorter series from Sant Sadurní d'Anoia station belonging to Servei Meteorològic de Catalunya (lat: 41°26'; long: 1°47'; elevation: 164 m) were also compared. Daily temperature data (1990–2010) and daily precipitation (1960–2010) were analysed.

From this information, seven temperature and 11 precipitation indexes, among those proposed by the Working Group on Climate Change Detection (Peterson et al. 2001) and those used by Hanson and Richard (2007) were calculated (Table 1). Temperature indexes were mean, maximum and minimum daily temperatures, number of days over-

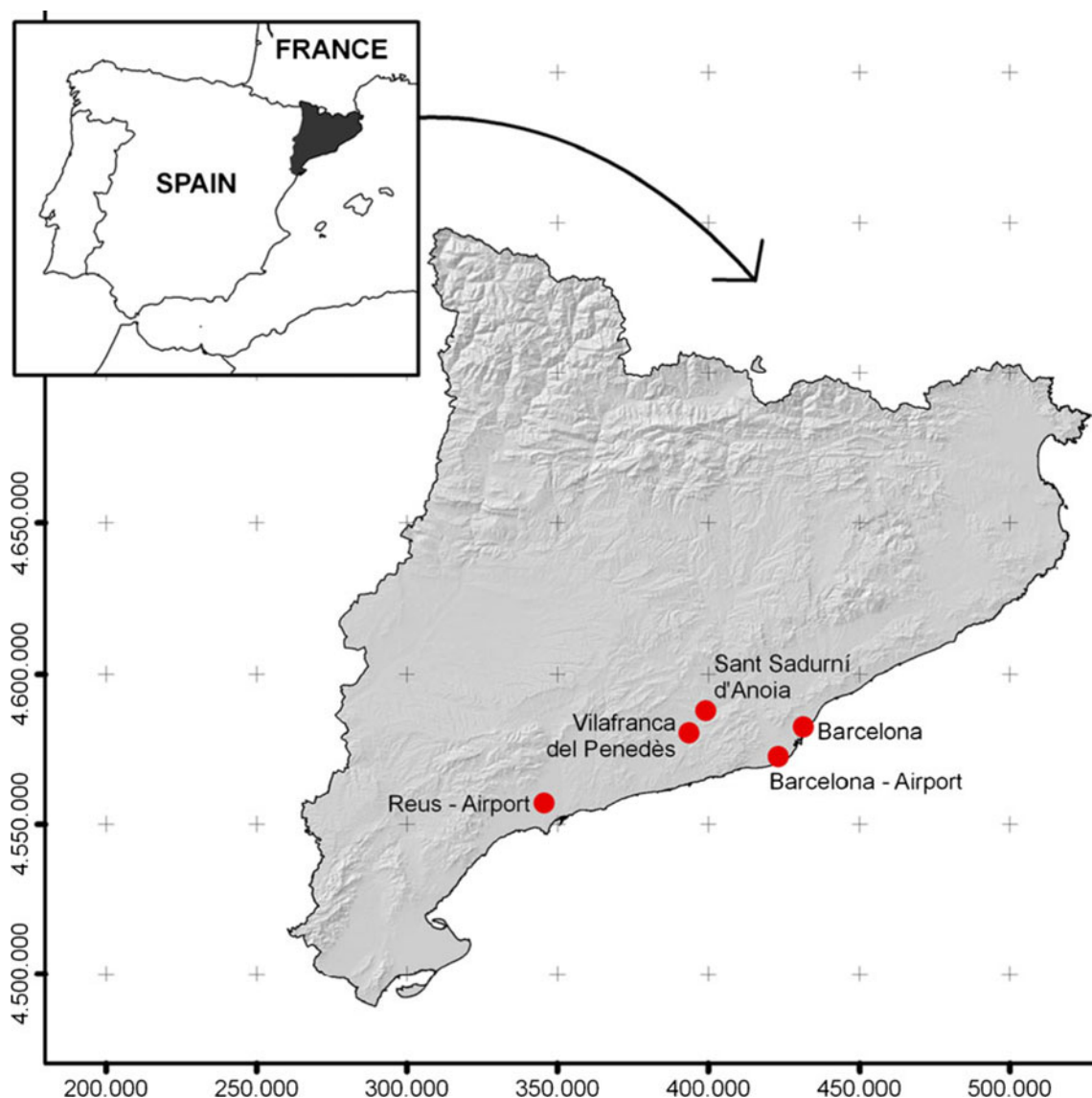
passing some thresholds: 90th percentile (warm extreme), 10th percentile (cold extreme), frost days and a heat wave duration index, defined as the daytime maxima throughout the year exceeding the 90th percentile (Russo 2009). For precipitation, annual and seasonal (spring, summer, autumn and winter) precipitation and some indexes were calculated for each period: number of rainy days, maximum 1-day precipitation, number of days with precipitation greater than the 90th percentile and 95th percentile (wet days) and the fraction of annual total precipitation that those events represent and amount and number of consecutive wet (NCWD) and dry (NCDD) days.

Potential evapotranspiration (ET<sub>o</sub>) estimated according to Hargreaves and Samani (1985) equation was analysed for the analysed period for the Vilafranca del Penedès series. Crop evapotranspiration (ET<sub>c</sub>) was estimated for vines, the main crop in the (IDESCAT 2007), using the crop coefficients proposed by Allen et al. (1998). In order to analyse the impact of climate on grapes, average harvest beginning and ending date series (1950–2006) obtained from a wine-making cooperative (there is no separation of dates by varieties), were analysed and production data from 1994 to 2010 were analysed (data production from some producers around Vilafranca del Penedès).

### 2.3 Statistical analysis

#### 2.3.1 Control quality of data

Quality data were analysed for each series using additional available shorter series in neighbour stations. The length of the series was variable but not smaller than 15 years. The correlation between daily data were analysed in order to detect outliers and anomalies. The shorter series of precipitation used for this purpose belonged to Sant Sadurní d'Anoia (lat: 41°26'; long: 1°47'; elevation: 164 m (1960–2010)), La Granada (41°22'1"; 1.43'25"E; elevation: 238 m a.s.l.) and Els Hostalets de Pierola (41°31'33; 1°48'18"E; elevation: 312 m.a.s.l. (1996–2010), stations belonging to the Servicio Meteorológico de Cataluña), Piera (41°31'1"; 1°44'42"E; elevation: 324 m.a.s.l.), Gelida (41°25'31"; 1°51'58"E elevation: 199 m.a.s.l.) and Esparraguera (41°31'55"; 1°50'E; elevation: 190 m.a.s.l.) (1957–1997), belonging to the Agencia Estatal de Meteorología; and for temperature data from La Granada, Els Hostalets de Pierola (1996–2010), Sant Sadurní d'Anoia (1990–2010), Igualada (41°34'48": 1.39°E; elevation: 48 m.a.s.l., (1991–2010)) and Tortosa (40°48'45"N 0°31'16"E; elevation: 44 m.a.s.l., (1950–2010)) were taken into account. The homogeneity of the climate data was assessed by the standard normal homogeneity test (Alexandersson 1986). A reference series, obtained as a weighted average (based on correlations) from selected neighbouring stations was used to compare



**Fig. 1** Location of the study area

inhomogeneities. The series with higher correlation coefficient were selected ( $R^2 > 0.6$ ). An iterative procedure was used until no anomalies were found. Inhomogeneities found in the analysed series were  $< 5\%$ . Then missing data were replaced. Vilafranca del Penedès and both Barcelona series had no missing data. For Reus airport, the missing values were less than 3%, and they were filled using values of the reference series.

### 2.3.2 Descriptive statistics

The climate indexes were evaluated by basic descriptive statistics and the non-parametric Mann–Kendall (MK) trend test was applied in order to confirm trends (Libiseller and Grimvall 2002), after a pre-whitening of the series in the presence of autocorrelation as proposed by Von Storch (1995). An ARIMA model was used for pre-whitening,

and the MK test was applied to the series to assess the significance of the trends.

### 2.3.3 Cluster analysis (CA)

In order to analyse changes in temperature and precipitation throughout the last six decades, a hierarchical CA was done. The purpose of CA is to place objects into groups in which the objects show some similarity to each other. The dissimilarity between them was measured using the squared Euclidean distance (squared differences between observations). Among the different criteria, the Ward's minimum variance method was used, a criteria pointed out as very efficient (Milligan 1980; Gong and Richman 1995). Ward's method calculates the distance between two clusters as the sum of squares (SS) between the two clusters added up over all the observations. At each generation, the within-cluster SS is minimised over all

partitions obtainable by merging two clusters from the previous generation. This method tends to join clusters with a small number of observations and is strongly biased towards producing clusters with a similar number of observations. This method attempts to minimise the SS of any two (hypothetical) clusters that can be formed at each step. Variables were standardised, i. e., transformed to variables with mean = 0 and variance = 1. The number of clusters to be retained was defined by taking into account the agglomeration distance measuring the inter-cluster continuity and the clustering coefficient. The cutoff point was established when the distance between one step and the next one was greater than twice the average distance.

Years were classified separately for temperature and precipitation indexes using the variables described in Table 1 (for annual and seasonal series) of the four observatories, and the centroids of each cluster were analysed, looking at a decadal classification. In both cases, the results were presented by dendrograms, two-dimensional figures which show the sequence and the distance at which the observations are clustered.

### 3 Results

#### 3.1 Temperature analysis

Table 2 shows the mean values and standard deviation of each temperature variable analysed at an annual scale. Numbers in bold indicate significant trends during the analysed period according to MK test applied to the pre-whitened series

(1950–2010). The temperatures corresponding to the  $T_{\max}$  90th percentile and  $T_{\min}$  10th percentile for each season are shown in Table 4.

The results showed that the mean temperature increased between 0.031°C per year (on average) at Vilafranca del Penedès and 0.012°C per year at Reus airport. This increase was mainly driven by the rise in maximum temperatures (0.038°C per year at Vilafranca and 0.025°C per year at Reus airport). This temperature increase was consistent with a significant increasing NdT90 of 0.555 days per year on average (ranging between 0.527 days per year at Reus and 0.582 days per year at Barcelona airport) and an increase of the HWDI of about 0.416 days per year (ranging between 0.390 days per year at Reus and 0.464 days per year at Barcelona). The temperature trends were similar to those observed in other coastal observatory (Tortosa, Tarragona), despite of the fact that average temperatures were about 2° higher in that observatory (data not shown in this work).

The change ratios (trends) were greater when the period corresponding to the last two decades (1990–2010) were analysed. The results for the period 1990–2010 are also shown in Table 2. The change ratio for  $T_{\max}$  and the HWDI were significant in all observatories and with values nearly twice as much as the average observed for the long series at Reus airport and much higher at Barcelona airport and Barcelona observatories. The HWDI was particularly high, with values greater than 80 days.

Maximum temperature increases were observed at annual scale and also in each season, with the greatest increases observed in spring and autumn at Vilafranca del Penedès

**Table 1** Temperature and precipitation indexes used in the analysis

Variable	Description
$T_m$	Mean annual daily temperature—annual and seasons
$T_{\max}$	Mean annual maximum temperature—annual and seasons
$T_{\min}$	Mean annual minimum temperature—annual and seasons
NdT90	Number of days with temperature higher than that corresponding to the 90th percentile—annual and seasons (warm extremes)
NdT10	Number of days with temperature lower than that corresponding to the 10th percentile—annual and seasons (cold extremes)
FD	Number of frost days—annual
HWDI	Heat wave duration index: maximum number of consecutive days during the year when the daily maximum temperature was greater than 5°C above the normal maximum temperature—annual
$P_{An}$	Annual precipitation
$P_{Sp}$	Accumulated precipitation in spring
$P_{Sum}$	Accumulated precipitation in summer
$P_{Aut}$	Accumulated precipitation in autumn
$P_{Wint}$	Accumulated precipitation in winter
NdP	Number of wet days—annual and seasons
$P_{\max 24}$	Maximum annual precipitation in 24 h—annual and seasons
NdP95	Number of days with precipitation exceeding the 95% percentile—annual and seasons
PercP95p	Percentage of annual rainfall in event with $P > 95\%$ —annual and seasons
NCWD	Maximum number of consecutive wet days (NCWD)—annual
NCDD	Maximum number of consecutive dry days (NCDD)—annual

**Table 2** Mean annual values, standard deviation and trends for the temperature indexes analysed for each observatory (1950–2010)

Observatory	Variable	Mean $\pm$ standard deviation	Trend/year ( $^{\circ}\text{C}/\text{year}$ )	Trend/year (90s–00s) ( $^{\circ}\text{C}/\text{year}$ )
Vilafranca de Penedès	$T_m$ ( $^{\circ}\text{C}$ )	14.9 $\pm$ 0.8	<b>0.031*</b>	<b>0.075*</b>
	$T_{\max}$ ( $^{\circ}\text{C}$ )	19.9 $\pm$ 1.1	<b>0.038*</b>	<b>0.055*</b>
	$T_{\min}$ ( $^{\circ}\text{C}$ )	9.8 $\pm$ 0.8	0.029	
	$\text{NDT}_{\max}90$ (18.6 $^{\circ}\text{C}$ )	35.2 $\pm$ 16.1	<b>0.532*</b>	<b>0.926*</b>
	$\text{NDT}_{\min}10$ (-0.2 $^{\circ}\text{C}$ )	32.8 $\pm$ 12.2	<b>-0.265*</b>	<b>-0.860*</b>
	FD	12.1 $\pm$ 7.6	-0.134	
	HWDI	35.0 $\pm$ 16.7	<b>0.453*</b>	<b>0.422*</b>
Reus airport	$T_m$ ( $^{\circ}\text{C}$ )	15.9 $\pm$ 0.7	<b>0.012**</b>	<b>0.022*</b>
	$T_{\max}$ ( $^{\circ}\text{C}$ )	20.8 $\pm$ 0.8	<b>0.025*</b>	<b>0.067*</b>
	$T_{\min}$ ( $^{\circ}\text{C}$ )	11.0 $\pm$ 0.7	0.003	
	$\text{NDT}_{\max}90$ (18.5 $^{\circ}\text{C}$ )	37.5 $\pm$ 16.4	<b>0.527*</b>	<b>0.762*</b>
	$\text{NDT}_{\min}10$ (-0.2 $^{\circ}\text{C}$ )	35.7 $\pm$ 15.1	0.135	
	FD	10.8 $\pm$ 8.7	0.135	
	HWDI	17.6 $\pm$ 12.3	<b>0.390*</b>	<b>0.762*</b>
Barcelona airport	$T_m$ ( $^{\circ}\text{C}$ )	16.8 $\pm$ 0.8	<b>0.022*</b>	<b>0.052*</b>
	$T_{\max}$ ( $^{\circ}\text{C}$ )	20.0 $\pm$ 0.7	<b>0.020*</b>	<b>0.045*</b>
	$T_{\min}$ ( $^{\circ}\text{C}$ )	11.5 $\pm$ 1.0	<b>0.024*</b>	<b>0.059*</b>
	$\text{NDT}_{\max}90$ (27.2 $^{\circ}\text{C}$ )	37.4 $\pm$ 19.5	<b>0.582*</b>	<b>1.143*</b>
	$\text{NDT}_{\min}10$ (6.2 $^{\circ}\text{C}$ )	37.7 $\pm$ 16.0	-0.236	
	FD	3.8 $\pm$ 4.2	-0.021	
	HWDI	54.9 $\pm$ 21.9	<b>0.358*</b>	<b>1.925*</b>
Barcelona	$T_m$ ( $^{\circ}\text{C}$ )	14.9 $\pm$ 0.8	<b>0.030*</b>	<b>0.044*</b>
	$T_{\max}$ ( $^{\circ}\text{C}$ )	18.5 $\pm$ 0.9	<b>0.037*</b>	<b>0.051*</b>
	$T_{\min}$ ( $^{\circ}\text{C}$ )	11.3 $\pm$ 0.7	<b>0.024*</b>	
	$\text{NDT}_{\max}90$ (18.6 $^{\circ}\text{C}$ )	37.2 $\pm$ 15.8	<b>0.581*</b>	<b>1.397*</b>
	$\text{NDT}_{\min}10$ (-0.2 $^{\circ}\text{C}$ )	38.2 $\pm$ 14.9	<b>-0.262**</b>	
	FD	5.5 $\pm$ 5.7	<b>-0.087*</b>	
	HWDI	51.4 $\pm$ 20.4	<b>0.464*</b>	<b>1.790*</b>

Bold numbers indicate significant trends

\* Significant at 95% level or higher

\*\* Significant at 90% level

and in spring and summer in Barcelona. Mean values and trends of each variable and season are shown in Table 3. Bold numbers indicate significant trends. The temperatures corresponding to the  $T_{\max}$  90th percentile and  $T_{\min}$  10th percentile for each season are shown in Table 4.

The mean  $T_{\min}$  showed significant trends in winter (ranging between 0.019 at Barcelona and 0.029 $^{\circ}\text{C}$  per year at Vilafranca del Penedès) and spring (0.010 at Reus and 0.035 $^{\circ}\text{C}$  per year at Vilafranca del Penedès). Autumn temperatures also increased significantly at Barcelona (0.017 $^{\circ}\text{C}$  per year), but not at rest of observatories. The mean minimum temperature values ranged between 4.0 and 5.6 $^{\circ}\text{C}$  in winter and between 11 and 12.5 $^{\circ}\text{C}$  in spring. The  $\text{NDT}_{10}$  decreased in spring, with significant trends at Vilafranca del Penedès (-0.265 days per year), Barcelona (-0.093 days per year) and Barcelona airport

(-0.121 days per year). It also decreased significantly in winter and summer at Barcelona observatory. The annual number of frost days (FD) only showed a significant decreasing trend at Vilafranca and Barcelona (-0.13 and -0.088, respectively). However, the number of FD was near twice as much as inland areas than in the coast (e.g., 9.1 days at Vilafranca del Penedès and 4.5 days at Barcelona).

Temperature increases imply greater water demands. This is particularly important in agricultural areas where rainfall is the main water resource. An analysis for the Vilafranca del Penedès observatory showed that the ETo increased during the last 60 years. Values ranged between 657 and 887 mm, with a mean value of 773 $\pm$ 40 mm, this being the maximum value recorded in 2009. Taking into account the relationship between temperature and evapotranspiration

**Table 3** Mean values, standard deviation and trends for the temperature indexes at a seasonal scale for each analysed observatory (1950–2010)

Season	Time period/ variable	Vilafranca		Reus airport		Barcelona		Barcelona airport	
		Mean $\pm$ standard deviation	Trend/year (°C/year)	Mean $\pm$ standard deviation	Trend/year (°C/year)	Mean $\pm$ standard deviation	Trend/year (°C/year)	Mean $\pm$ standard deviation	Trend/year (°C/year)
Winter	$T_m$ (°C)	8.9 $\pm$ 1.0	<b>0.034</b> *	10.1 $\pm$ 0.9	0.004	9.0 $\pm$ 1.1	<b>0.033</b> *	10.0 $\pm$ 0.9	<b>0.016</b> *
	$T_{max}$ (°C)	13.9 $\pm$ 1.2	<b>0.039</b> *	15.5 $\pm$ 1.0	<b>0.019</b> *	12.2 $\pm$ 1.2	<b>0.038</b> *	14.4 $\pm$ 0.8	<b>0.014</b> *
	$T_{min}$ (°C)	4.0 $\pm$ 1.1	<b>0.029</b> *	5.1 $\pm$ 1.1	0.004	4.0 $\pm$ 1.1	<b>0.028</b> *	5.6 $\pm$ 1.1	<b>0.019</b> *
	NDT <sub>max</sub> 90 (days)	10.0 $\pm$ 6.3	<b>0.019</b> *	10.0 $\pm$ 5.7	<b>0.138</b> *	10.5 $\pm$ 7.1	<b>0.199</b> *	9.9 $\pm$ 4.5	0.065
	NDT <sub>min</sub> 10 (days)	8.9 $\pm$ 6.8	-0.043	10.2 $\pm$ 7.9	0.004	10.2 $\pm$ 7.3	<b>-0.165</b> *	10.9 $\pm$ 7.5	<b>-0.127</b> *
	FD (days)	9.1 $\pm$ 6.8	<b>-0.130</b> *	6.9 $\pm$ 6.5	-0.002	4.3 $\pm$ 5.0	<b>-0.088</b>	2.7 $\pm$ 3.5	-0.036
Spring	$T_m$ (°C)	16.3 $\pm$ 1.1	<b>0.039</b> *	17.1 $\pm$ 0.8	<b>0.013</b> *	16.4 $\pm$ 1.1	<b>0.029</b> *	16.7 $\pm$ 1.1	<b>0.028</b> *
	$T_{max}$ (°C)	21.6 $\pm$ 1.3	<b>0.043</b> *	22.0 $\pm$ 1.0	<b>0.031</b> *	20.5 $\pm$ 1.3	<b>0.036</b> *	20.9 $\pm$ 1.0	<b>0.025</b> *
	$T_{min}$ (°C)	11.0 $\pm$ 1.1	<b>0.035</b> *	12.2 $\pm$ 0.8	<b>0.010</b> *	12.1 $\pm$ 1.0	<b>0.023</b> *	12.5 $\pm$ 1.3	<b>0.032</b> *
	NDT <sub>max</sub> 90 (days)	9.4 $\pm$ 6.6	<b>0.201</b> *	8.9 $\pm$ 6.1	<b>0.180</b> *	9.9 $\pm$ 7.0	<b>0.152</b> *	8.1 $\pm$ 5.7	<b>0.068</b> *
	NDT <sub>min</sub> 10 (days)	10.5 $\pm$ 6.3	<b>-0.265</b> *	9.2 $\pm$ 4.8	-0.013	10.4 $\pm$ 5.8	<b>-0.093</b> *	8.3 $\pm$ 6.2	<b>-0.121</b> *
	Summer	$T_m$ (°C)	22.3 $\pm$ 0.9	<b>0.038</b> *	23.0 $\pm$ 0.8	<b>0.017</b> *	22.2 $\pm$ 1.0	<b>0.036</b> *	22.7 $\pm$ 1.0
Summer	$T_{max}$ (°C)	27.8 $\pm$ 1.0	<b>0.034</b> *	27.9 $\pm$ 0.9	<b>0.027</b> *	26.4 $\pm$ 1.2	<b>0.041</b> *	27.0 $\pm$ 1.0	<b>0.028</b> *
	$T_{min}$ (°C)	17.0 $\pm$ 0.9	0.028	18.2 $\pm$ 0.8	0.007*	18.0 $\pm$ 0.9	<b>0.020</b> *	18.5 $\pm$ 1.2	<b>0.036</b> *
	NDT <sub>max</sub> 90 (days)	8.4 $\pm$ 6.7	<b>0.200</b> *	11.4 $\pm$ 9.1	<b>0.330</b> *	11.4 $\pm$ 9.2	<b>0.288</b> *	12.5 $\pm$ 11.6	<b>0.359</b> *
	NDT <sub>min</sub> 10 (days)	8.2 $\pm$ 5.9	0.202	8.7 $\pm$ 5.5	0.022	10.2 $\pm$ 6.5	<b>-0.152</b> *	8.9 $\pm$ 7.2	-0.061
	HWDI (days)	3.5 $\pm$ 2.6	<b>0.068</b>	3.9 $\pm$ 4.5	<b>0.130</b> *	4.3 $\pm$ 3.5	<b>0.083</b> *	5.1 $\pm$ 6.4	<b>0.130</b> *
	Autumn	$T_m$ (°C)	12.1 $\pm$ 1.4	<b>0.031</b> *	13.1 $\pm$ 0.9	0.012	11.9 $\pm$ 1.0	<b>0.024</b> *	13.3 $\pm$ 0.9
Autumn	$T_{max}$ (°C)	16.9 $\pm$ 1.6	<b>0.037</b> *	17.9 $\pm$ 0.8	0.014	14.9 $\pm$ 1.0	<b>0.034</b> *	17.6 $\pm$ 0.9	<b>0.013</b> *
	$T_{min}$ (°C)	7.4 $\pm$ 1.2	0.024	8.3 $\pm$ 1.1	0.010	9.0 $\pm$ 1.0	<b>0.017</b> *	9.0 $\pm$ 1.0	0.007
	NDT <sub>max</sub> 90 (days)	2.7 $\pm$ 3.4	<b>0.081</b> *	8.9 $\pm$ 5.3	<b>0.117</b> *	10.0 $\pm$ 6.9	<b>0.212</b> *	10.5 $\pm$ 6.4	<b>0.114</b> *
	NDT <sub>min</sub> 10 (days)	9.7 $\pm$ 5.6	0.202	10.6 $\pm$ 7.1	0.022	10.2 $\pm$ 7.0	-0.0415	6.2 $\pm$ 5.0	0.090

Bold numbers indicate significant trends

\* Significant at 95% level or higher

observed in the analysed series and the temperature trends, the ETc increased during the last decades in about 11%.

### 3.2 Year classification by cluster analysis (CA) (temperature series)

#### 3.2.1 Annual temperatures

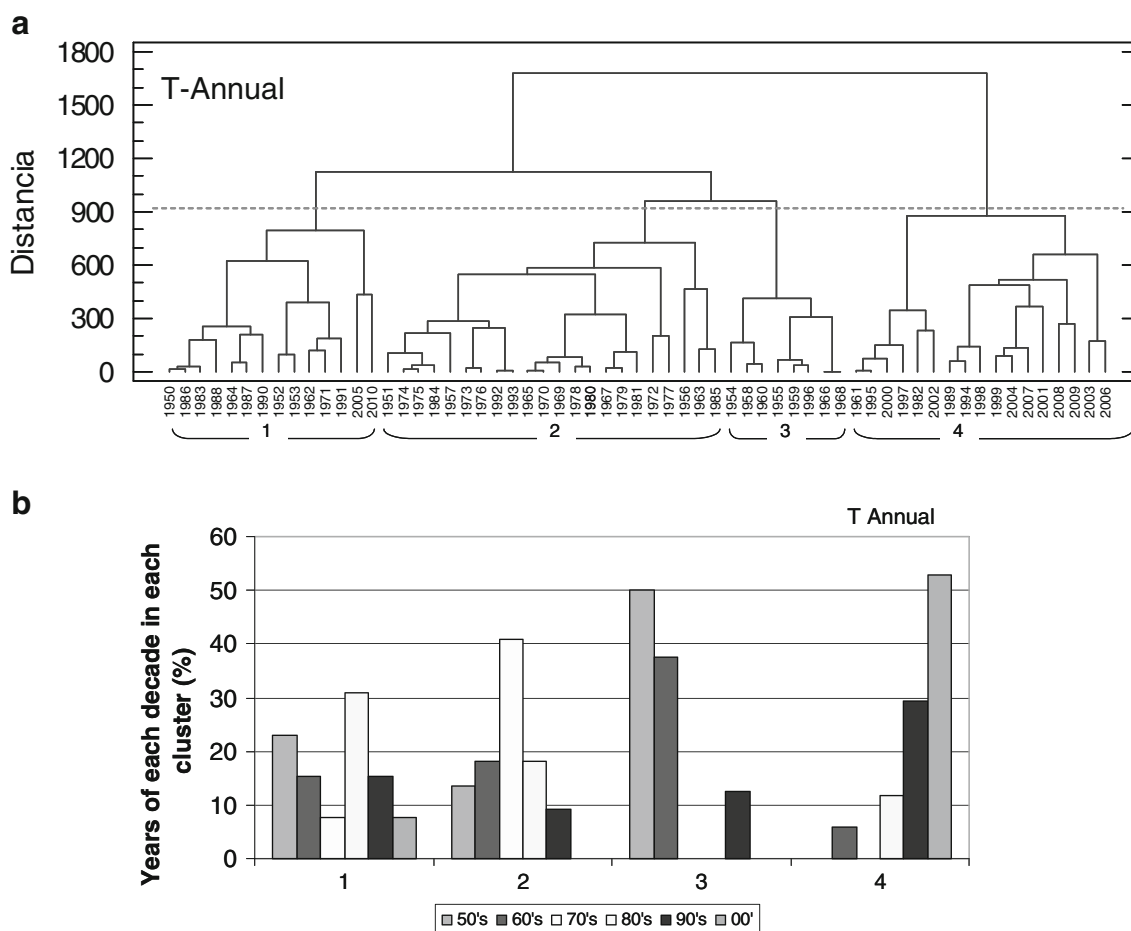
Figure 2 shows the year classification according to the annual temperature variables recorded at the four analysed

observatories. The centroids of each cluster are presented in Table 5. Four groups could be separated: two groups associated with warm years, which respectively represented 22.9% and 27.9% of the analysed years and the other two groups represented 36.1% and 13.1% of the years which were associated with cold years.

Among the first two groups, one of them (cluster 4) included the years with greater temperatures (mean  $T_{max}$ =20.7°C and mean  $T_{min}$ =11.7°C), high Ndt90 (50.7 days) and high HWDI values (about 68 days on average at Barcelona

**Table 4** Temperatures corresponding to the  $T_{max}$  90th percentile ( $T_{max90}$ ) and the  $T_{min}$  10th percentile ( $T_{min10}$ ) for each season and observatory

	Vilafranca del Penedès		Reus airport		Barcelona		Barcelona airport	
	$T_{max90}$	$T_{min10}$	$T_{max90}$	$T_{min10}$	$T_{max90}$	$T_{min10}$	$T_{max90}$	$T_{min10}$
Winter	18.5	-0.2	19.2	0.7	16.7	1.7	17.8	1.9
Spring	27.2	6.2	27.2	7.4	26.4	13.0	25.1	7.2
Summer	31.2	13.4	30.8	14.9	30.3	22.1	29.4	15.4
Autumn	25.1	4.0	23.4	2.2	20.7	3.9	22.9	2.6



**Fig. 2** Annual temperature cluster analysis: **a** dendrogram (Ward's criteria) representing year classification using the temperature indexes of the annual data the four analysed observatories: Vilafranca del

Penedès, Barcelona, Barcelona\_airport and Reus\_airport (NE Spain). **b** Percentage of years of each decade included in each cluster (classified according to annual temperature indexes)

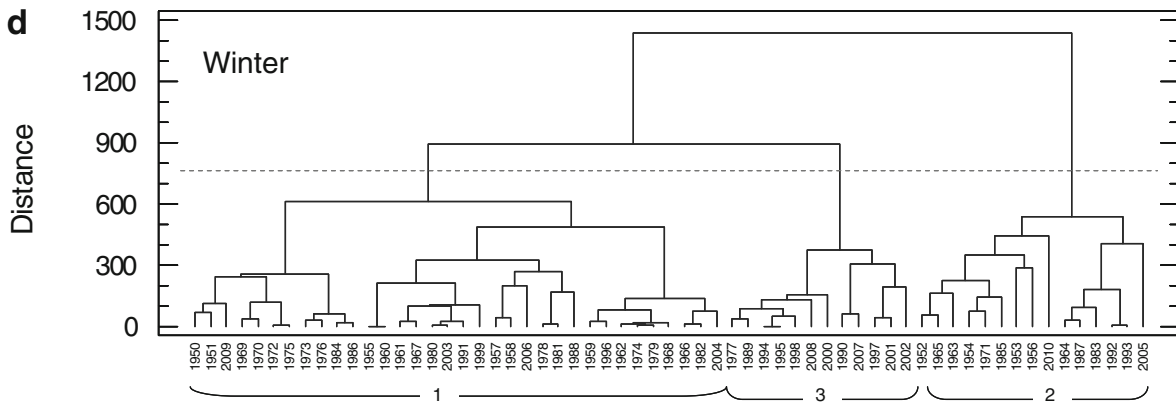
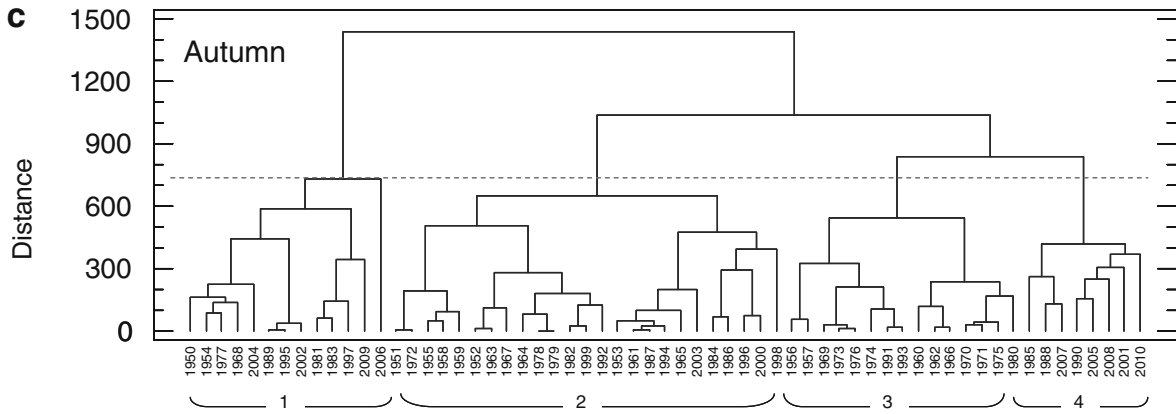
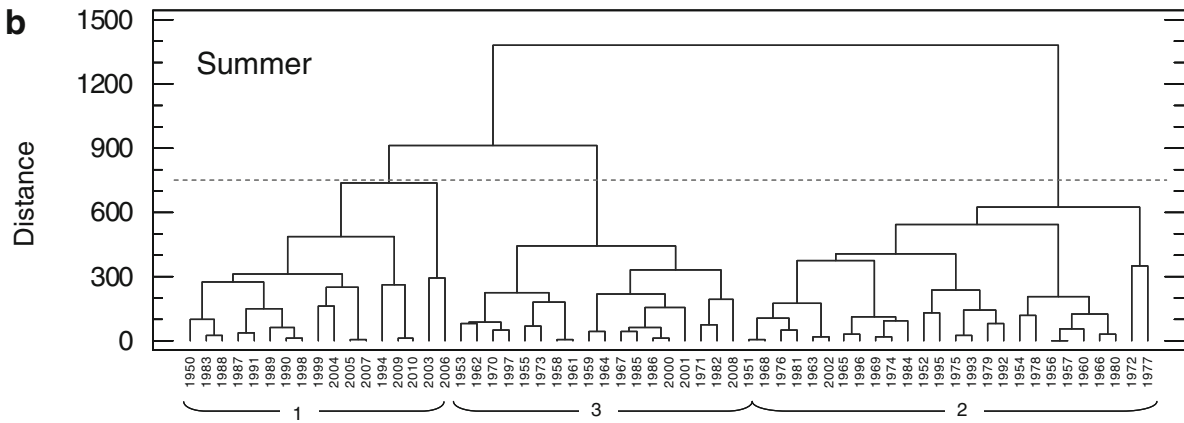
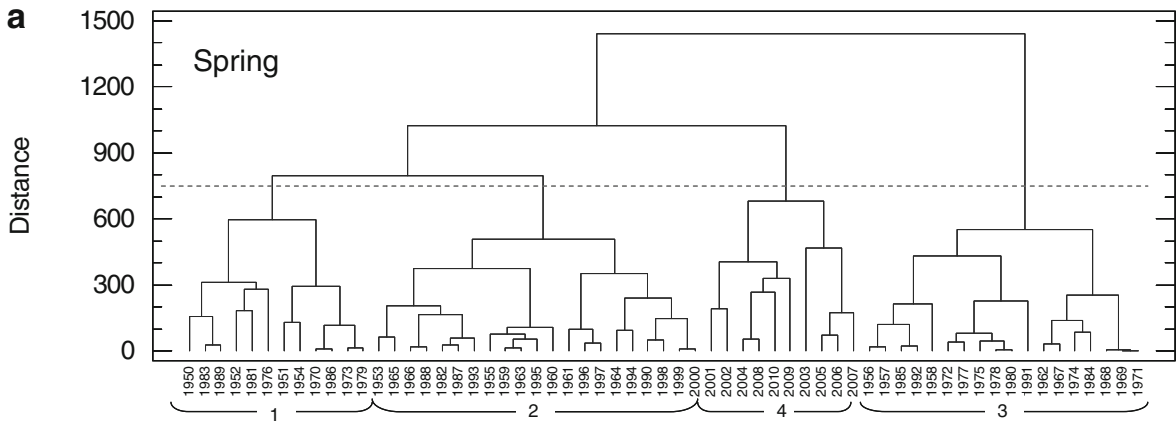
observatories). This group included 9 years of the last decade (between 2000 and 2009), which represent 52.9% of the years grouped in that cluster, and another 29.4% were years from the 90th decade. The second group (cluster 1) recorded similar mean temperatures. However, in that group, not only the Ndt90 was high (42.6 days), but also the Ndt10 (45.3 days), and the number of FD was also greater than in the previous group (12.5 vs. 5.2 days). The years included in that cluster belonged to all decades but with greater percentage to the 1980s and 1950s (30.8%) and the 1990s and 1960s (15.5%).

The cold year clusters (cluster 2 and cluster 3) had similar mean temperatures. They included years with the lowest temperatures and the smallest NDT90 (20.5 days) and HWDI (28.9 days) values. The difference between them was in the number of extremes (both warm and cold), which was smaller in cluster 3. These clusters did not include years from the previous decade (2000–2009). Cluster 2 included years from the rest of decades with a higher percentage from the 1970s (40.9%), while cluster 3 included years from the 1950s (50.0%), 1960s (37.5%) and 1990s (12.5%) (Fig. 2b).

### 3.2.2 Seasonal temperature analysis

**Spring temperatures** The CA of the spring season allowed years to be classified into four groups (Fig. 3a). The centroids of each cluster are presented in Table 6. One group (cluster 4) (16.4% of total years), grouped years with the warmest springs and with the highest number of warm extremes (mean  $T_{max}=22.6^{\circ}C$ ). This cluster included only years from the 2000s (9 of 10 years). The other two clusters (clusters 1 and 2) grouped years with relatively warm springs. Mean temperatures were similar in both clusters (mean  $T_{max}$  about  $21.0^{\circ}C$ ). However, cluster 1, which represented 19.7% of total years, included higher values of both warm and cold extremes. This cluster included years from the 1950s (27.3%), 1970s (36.4%) and 1980s (36.4%). The other group (cluster 2), which grouped 34.4% of total years, included years from all decades except the 1970s, with the highest percentage from the 1990s (38.1%).

The fourth cluster (cluster 3), which represented 29.5%, was characterised by cold springs. Mean  $T_{max}$  ranged





**Fig. 3** Dendrogram (Ward’s criteria) representing year classification using the temperature indexes: **a** spring, **b** summer, **c** autumn and **d** winter data from the four analysed observatories: Vilafranca del Penedès, Barcelona, Barcelona\_airport and Reus\_airport (NE Spain)

between 19.2 and 21.0°C (depending on the observatory), and mean  $T_{min}$  ranged between 10.6 and 11.5°C. Years included in this cluster recorded a high NdT10, the number of cold extremes being quite similar to those recorded in years included in cluster 1. The years included in this cold cluster belonged to all decades except to the 2000s (Fig. 4a).

**Summer temperatures** The CA of summer data allowed years to be classified into three groups (Fig. 3b). Cluster 1 grouped the years with the warmest summers, which represented 29.5% of total years. The mean  $T_{max}$  in that cluster was 28.1 (ranging between 27.5 and 28.8°C), and the mean  $T_{min}$  was 1.2 (ranging between 17.9 and 19.8°C, depending on the observatory) (Table 7). The mean NdT90 was 20.8, much higher than in the other two clusters. However, the mean NdT10 was 6.3 days, slightly greater than in one of the clusters which included years with cooler summers. This warmest cluster grouped a high number of years belonging to the 2000s (35.5%), 1990s (35.3%) and 1980s (23.5%) (Fig. 4b).

Cluster 2 and cluster 3, which represented 41.0 and 29.5%, respectively, grouped the years with cooler summers

(mean  $T_{max}$ =26.2 and 27.2°C, respectively). The main difference between them was the number of cold extremes, which was greater in cluster 2 (mean NdT10=13.8 days, ranging between 12.6 and 14.6, depending on the observatory). That cluster included a high percentage of years from the 1950s (20%), 1960s (24%) and 1970s (28%). Cluster 3 also included a greater percentage from the 1950s and 1960s (22.2%) than from the rest of the decades (Fig. 4b).

**Autumn temperatures** The CA of the autumn temperature data showed four groups: two of them related to cold autumn years and the other two related to warm autumn years. The results are shown in Table 8, Figs. 3c and 4c.

The clusters that grouped the warmest autumn years (cluster 1) represented 21.3% of total years and recorded a mean  $T_{max}$ =17.9°C (ranging between 16.2 and 18.7°C) and a mean  $T_{min}$ =9.6°C (ranging between 8.5 and 10.3°C). The mean NdT90 was 14.2 days on average, and the NdT10 was 5.0 days. However, there were big differences between Vilafranca del Penedès and the rest of the observatories. While at Vilafranca del Penedès NdT90 was 4.6 days, in the rest of the observatories, it ranged between 15.1 and 19.0 days. Cluster 2 grouped 41% of years, which also have warm autumns, with mean  $T_{max}$  of about 16.8°C. The main difference with cluster 1 was in the number of warm

**Table 5** Centroids of each cluster obtained in the year classification using the temperature indexes of the annual data

Cluster	Mean/observatory	$T_{maxA}$	$T_{minA}$	$T_{mA}$	NdT90	NdT10	HWDI	FD
1	Mean	20.0	10.9	15.4	42.6	45.3	44.7	12.5
	VP	20.3	9.7	15.0	42.4	41.7	36.9	21.3
	RA	20.8	11.0	15.9	45.5	46.0	18.5	16.3
	B	18.6	11.4	15.0	43.0	44.5	55.1	6.8
	BA	20.1	11.3	15.7	48.0	49.1	59.9	5.5
2	Mean	19.2	10.3	14.7	26.7	42.9	30.6	9.2
	VP	19.4	9.2	14.3	25.6	39.5	27.4	14.4
	RA	20.2	10.6	15.4	26.2	37.5	11.0	10.2
	B	17.9	10.6	14.3	29.5	46.5	40.2	7.4
	BA	19.5	10.6	15.1	25.6	47.9	43.6	4.8
3	Mean	19.3	11.0	15.2	20.5	28.9	28.8	5.5
	VP	18.8	9.6	14.2	15.1	28.1	20.7	9.1
	RA	20.7	11.6	16.1	27.1	25.2	11.9	5.0
	B	17.9	11.1	14.5	19.5	36.2	36.9	5.5
	BA	19.8	11.7	15.7	20.2	25.9	45.9	2.2
4	Mean	20.7	11.7	16.2	50.7	24.8	53.3	5.2
	VP	20.9	10.8	15.8	49.4	20.3	49.1	6.9
	RA	21.5	11.4	16.4	51.2	33.6	27.7	10.2
	B	19.6	12.1	15.8	51.5	23.6	67.4	2.0
	BA	20.7	12.5	16.6	50.5	21.8	68.9	1.8

$T_{mA}$  annual mean temperature,  $T_{maxA}$  annual mean maximum temperature,  $T_{minA}$  annual mean minimum temperature,  $NdT90$  number of days with  $T_{max}>90$ th percentile,  $NdT10$  number of days with  $T_{min}<10$ th percentile,  $FD$  number of frost days,  $HWDI$  heat wave duration index,  $VP$  Vilafranca del Penedès,  $RA$  Reus airport,  $B$  Barcelona,  $BA$  Barcelona airport

**Table 6** Centroids of each cluster obtained in the year classification using the temperature indexes of the spring data

Cluster	Mean/observatory	$T_{\max}$	$T_{\min}$	$T_m$	NdT90	NdT910
1	Mean	21.0	11.5	16.3	11.8	13.7
	VP	20.9	10.3	15.6	11.7	14.9
	RA	21.7	11.7	16.9	10.7	12.8
	B	20.5	12.1	16.3	13.2	13.5
	BA	20.8	11.7	16.3	11.7	13.5
2	Mean	21.7	12.3	17.0	9.0	7.1
	VP	21.8	10.9	16.3	9.3	9.1
	RA	22.6	12.8	17.7	9.4	6.0
	B	20.9	12.5	16.7	9.1	7.6
	BA	21.38	12.9	17.2	8.1	5.7
3	Mean	20.2	11.2	15.7	3.2	12.8
	VP	21.0	10.6	15.8	3.3	13.2
	RA	20.9	11.4	16.2	3.1	11.9
	B	19.2	11.2	15.2	3.5	14.7
	BA	19.9	11.5	15.7	3.1	11.3
4	Mean	22.6	13.3	17.9	16.6	5.2
	VP	23.2	12.9	18.1	18.0	3.7
	RA	23.1	12.1	17.6	16.4	9.6
	B	22.2	13.6	17.9	19.6	5.6
	BA	21.9	14.1	18.0	12.6	1.9

$T_m$  mean temperature,  $T_{\max}$  mean maximum temperature,  $T_{\min}$  mean minimum temperature,  $NdT90$  number of days with  $T_{\max}>90$ th percentile,  $NdT10$  number of days with  $T_{\min}<10$ th percentile, *VP* Vilafranca del Penedès, *RA* Reus airport, *B* Barcelona, *BA* Barcelona airport

extremes, being smaller in cluster 2 than in cluster 1. The number of cold extremes, however, was slightly greater than in cluster 1. Both clusters grouped years from all decades, but the highest percentage in the cluster with the warmest autumns was from the 2000s (30.1%) and the 1980s (23.1%). In the cluster 2, the highest percentage was from the 1950s (24.0%), the 1960s (20%) and the 1990s (20%) (Fig. 4c).

The years with cooler autumns (cluster 3) represented 14.8% of years, with a mean  $T_{\max}$  of 15.5°C (ranging between 13.5 and 16.9°C, depending on the observatory). This cluster recorded a relatively high NdT10 (11.5 days, ranging between 6.9 and 14). Cluster 4, which grouped 22.95% of years, was also a cluster with cool autumns. This cluster had a mean  $T_{\max}=16.4^\circ\text{C}$  (ranging between 14.5 and 17.1°C). However, the number of cold extremes were greater (mean NDT10=16.2 days, ranging between 12 and 19.3 days), and also, the warm extremes were greater (mean NdT90=0.1 days). Similar to that observed in cluster 1, the NdT90 was more than double in the observatories located near the coast than at Vilafranca del Penedès (up to 13.4 days at Barcelona vs. 4.5 days at Vilafranca del Penedès).

The years included in cluster 3 belonged to the 1950s (22.2%), 1960s (22.2%), 1970s (33.3%) and 1990s (22.2%)

(Fig. 4c). However, in cluster 4, the highest percentage belonged to the 2000s (30.8%), the 1970s (23.1%) and to the 1980s (23.1%). Thus, autumns were slightly cooler during the last decade (2000s) but with higher irregularities in terms of extremes cold and warm.

*Winter temperatures* The whole series were classified into three groups (Fig. 3d). The centroids of each cluster are presented in Table 9, and Fig. 4d presents the contribution of years of each decade to each cluster.

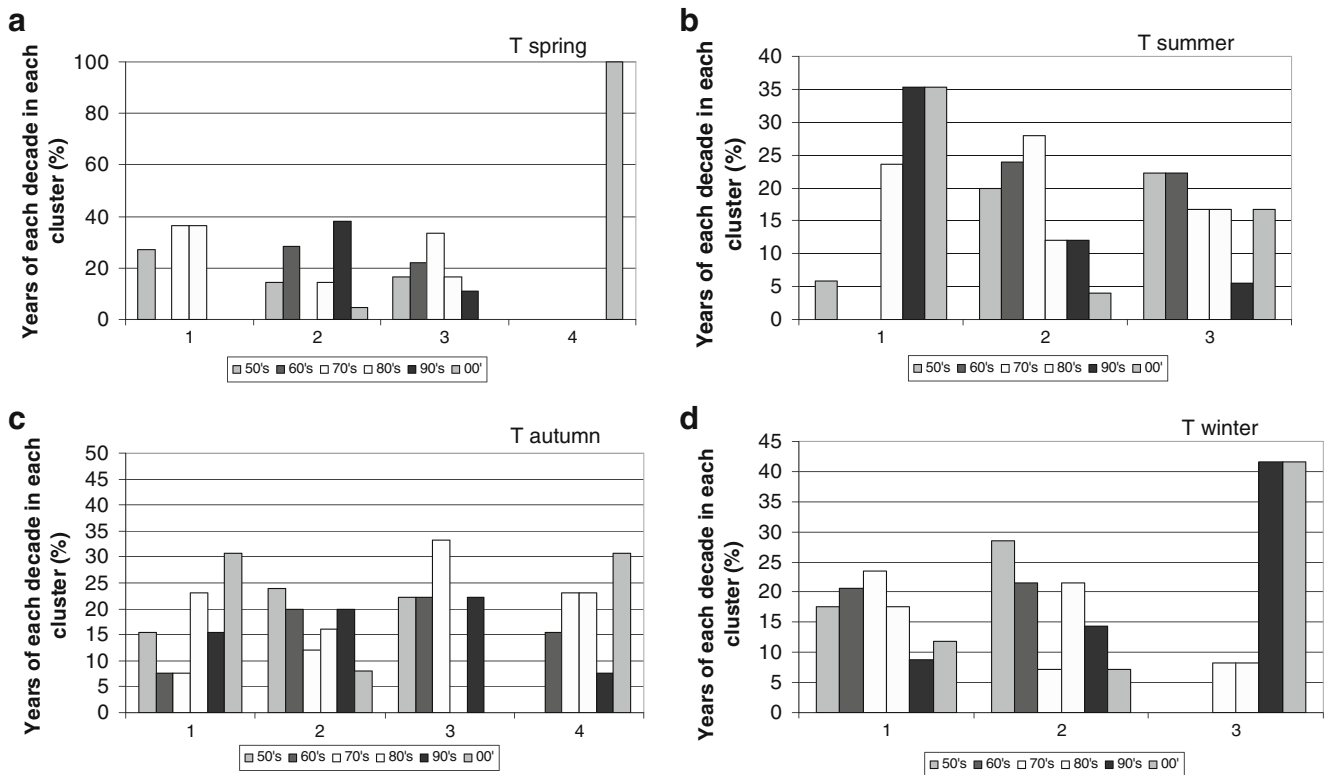
The three clusters were identified as groups of years with cold, warm and intermediate characteristics. Cluster 2, which represented 24.5% of years, was characterised by clustering the years with the coolest winters, with a mean  $T_{\max}=12.8^\circ\text{C}$  (ranging between 11.1 and 13.8°C) and a mean  $T_{\min}=3.9^\circ\text{C}$  (ranging between 2.6 and 4.6°C, always lower at Vilafranca and Reus airport than at Barcelona). The number of cold extremes was high (19.4 days on average), with a mean number FD of 13.1 days, which was higher at Vilafranca del Penedès (=19 days) than at Barcelona (between 7 and 10 days). The years included in that cluster belonged to all decades, but with the highest percentage from the 1950s (28.6%), the 1960s (21.4%) and the 1980s (21.4%).

Cluster 3 represented 19.6% of the years and was characterised by grouping the years with the warmest winters. It had a mean  $T_{\max}=15.4^\circ\text{C}$  (ranging between 14.2 and 15.7°C) and a mean  $T_{\min}=6.2^\circ\text{C}$  (ranging between 5.1 and 7.3°C). The number of cold extremes was low (NdT10 ranging between 2.7 and 6.6 days), and the number of warm extremes was high (between 15.1 and 21.2 days), Reus airport observatory being the one with higher differences in both indexes. The number of FD was 2.0, on average, but with values near 4 at Vilafranca del Penedès and Reus airport but less than 1 in the other observatories. The years included in that cluster mainly belonged to the 1990s (41.7%) and 2000s (41.7%).

The third cluster (cluster 1), which represented 55.7% of years, grouped years with intermediate characteristics. The mean  $T_{\max}$  of years included in that cluster ranged between 12.1 and 14.9°C, and mean  $T_{\min}$  ranged between 4.2 and 5.7°C, depending on the observatory. The number of both warm and cold extremes was near eight (NdT90=8.5 days and NdT10=81 days, on average). The years included in the cluster 1 belonged to all decades, with greater percentages from the 1960s (20.6%) and 1970s (23.5%) (Fig. 4d).

### 3.3 Precipitation analysis

Table 10 shows the mean values and standard deviation of each precipitation variable analysed at annual and seasonal scales for each analysed observatory. The precipitation corresponding to the 95th percentile and the percentage of annual rainfall that it represents were also shown.



**Fig. 4** Percentage of years of each decade included in each cluster classified according to temperature indexes: **a** spring, **b** summer, **c** autumn and **d** winter data the four analysed observatories: Vilafranca del Penedès, Barcelona, Barcelona\_airport and Reus\_airport (NE Spain)

**Table 7** Centroids of each cluster obtained in the year classification using the temperature indexes of the summer data

Cluster	Mean/observatory	$T_{max}$	$T_{min}$	$T_m$	NdT90	NdT910
1	Mean	28.1	19.2	23.7	20.8	5.4
	VP	28.5	17.9	23.2	15.2	5.5
	RA	28.8	18.9	23.8	20.9	8.3
	B	27.5	18.9	23.2	20.5	6.8
	BA	28.1	19.8	23.9	26.5	4.6
2	Mean	26.2	17.5	21.8	5.3	13.8
	VP	27.1	16.6	21.8	4.9	12.6
	RA	27.01	17.6	22.3	5.5	13.3
	B	25.4	17.2	21.3	6.2	14.6
	BA	26.1	17.5	21.8	4.6	14.4
3	Mean	27.2	18.5	22.8	8.8	5.8
	VP	27.1	16.9	22.0	7.5	5.4
	RA	28.0	18.4	23.2	9.4	6.6
	B	26.6	18.4	22.5	9.1	5.9
	BA	26.9	18.7	22.8	9.4	5.3

$T_m$  mean temperature,  $T_{max}$  mean maximum temperature,  $T_{min}$  mean minimum temperature,  $NdT90$  number of days with  $T_{max}>90$ th percentile,  $NdT10$  number of days with  $T_{min}<10$ th percentile, *VP* Vilafranca del Penedès, *RA* Reus airport, *B* Barcelona, *BA* Barcelona airport

The mean  $P_{An}$  ranged between 517 mm at Vilafranca and 610 mm at Barcelona without significant trends, with a  $P_{max24}$  of 62.8 mm at Vilafranca del Penedès and 72.7 mm at Barcelona. The mean  $NdP95$  ranged between 2.8 and 3.2 days, and those days accumulated between 25.3% and 27.7% of annual rainfall, on average. There was no clear trend in annual precipitation during the last six decades, neither in the total amount nor in other indexes like  $P_{max24}$  or the number of extreme precipitation events ( $NdP95$ ). However, the  $NCDD$  presented an increasing trend during the analysed period in some observatories (e. g., 0.392 days per year at Vilafranca del Penedès or 0.148 days per year at Barcelona airport). The  $NCWD$  did not show any significant trend.

By seasons, spring and autumn were the main rainfall periods. Spring rainfall ranged between 131.5 mm at Barcelona airport and 162.3 mm at Vilafranca del Penedès. Autumn rainfall ranged between 155.5 mm at Reus airport and 197.6 mm at Barcelona airport. These wet periods were separated by a drier season but with high variability from year to year and among the analysed observatories. Summer rainfall varied between 63.7 mm at Vilafranca del Penedès and 172.2 mm at Barcelona airport. In winter, mean precipitation ranged between 91.5 mm at Reus airport and  $124.6 \pm 64.3$  mm at Barcelona. Some trends were observed in

**Table 8** Centroids of each cluster obtained in the year classification using the temperature indexes of the autumn data

Cluster	Mean/observatory	$T_{\max}$	$T_{\min}$	$T_m$	NdT90	NdT10
1	Mean	17.9	9.6	13.8	14.2	5.0
	VP	18.0	8.5	13.2	4.6	5.0
	RA	18.8	9.4	14.1	15.1	6.5
	B	16.2	10.3	13.3	18.1	5.3
	BA	18.7	10.2	14.4	19.0	3.0
2	Mean	16.8	8.7	12.7	5.7	6.8
	VP	16.9	7.6	12.3	1.8	7.1
	RA	17.9	8.7	13.3	7.0	7.4
	B	14.8	9.1	12.0	6.6	8.1
	BA	17.6	9.2	13.4	7.4	4.4
3	Mean	15.5	7.2	11.4	2.9	11.5
	VP	15.3	6.1	10.7	0.2	14.0
	RA	16.9	7.2	12.0	3.3	13.1
	B	13.5	7.8	10.7	3.6	12.1
	BA	16.4	7.8	12.1	4.4	6.9
4	Mean	16.4	7.7	12.1	10.1	16.2
	VP	16.6	6.8	11.7	4.5	15.7
	RA	17.4	7.4	12.4	10.6	19.3
	B	14.5	8.5	11.5	13.4	17.6
	BA	17.1	8.3	12.7	12.0	12.0

$T_m$  mean temperature,  $T_{\max}$  mean maximum temperature,  $T_{\min}$  mean minimum temperature,  $NdT90$  number of days with  $T_{\max}>90$ th percentile,  $NdT10$  number of days with  $T_{\min}<10$ th percentile, *VP* Vilafranca del Penedès, *RA* Reus airport, *B* Barcelona, *BA* Barcelona airport

autumn and spring precipitation as well as in the percentage of rainfall recorded in extreme events. However, due to the high variability among years, there were no significant trends. In the same table, the trends observed during the last two decades are also shown. The change ratios were greater in absolute value. Among the significant trends, we could point out the decreasing spring precipitation trend at Vilafranca del Penedès and the increasing winter precipitation at Vilafranca del Penedès, Reus airport and Barcelona as well as the increasing trend of the NCDD at Barcelona and Barcelona airport.

### 3.4 Year classification by cluster analysis (CA) (precipitation series)

#### 3.4.1 Annual precipitation

Due to the lack of precipitation trends, this analysis was done using the total seasonal precipitation in order to analyse possible pattern changes within the year. The analysis included all precipitation variables related to the four seasons as well as some annual variables among the ones

**Table 9** Centroids of each cluster obtained in the year classification using the temperature indexes of the winter data

Cluster	Mean/observatory	$T_{\max}$	$T_{\min}$	$T_m$	NdT90	NdT910
1	Mean	13.8	5.2	9.6	8.5	8.1
	VP	13.8	4.2	9.0	8.5	8.9
	RA	14.9	5.5	10.3	9.3	9.2
	B	12.1	5.6	8.9	8.4	7.5
	BA	14.5	5.7	10.1	7.7	6.6
2	Mean	12.8	3.9	8.5	7.2	19.4
	VP	12.6	2.6	8.0	8.7	18.2
	RA	13.8	3.9	9.0	5.9	19.5
	B	11.1	4.6	7.9	7.2	19.2
	BA	13.4	4.5	9.0	7.2	20.6
3	Mean	15.4	6.2	10.8	18.2	4.2
	VP	15.7	5.1	10.4	19.9	3.7
	RA	16.4	5.7	11.1	16.7	6.5
	B	14.2	7.3	10.8	21.2	2.7
	BA	15.5	6.7	11.1	15.1	3.9

$T_m$  mean temperature,  $T_{\max}$  mean maximum temperature,  $T_{\min}$  mean minimum temperature,  $NdT90$  number of days with  $T_{\max}>90$ th percentile,  $NdT10$  number of days with  $T_{\min}<10$ th percentile, *VP* Vilafranca del Penedès, *RA* Reus airport, *B* Barcelona, *BA* Barcelona airport

that showed some trends (although not significant) such as  $P_{\max}24$ , PercP95 and NCDD. The corresponding dendrogram is presented in Fig. 5a, and the centroids of each cluster are presented in Table 11.

The series were classified into six clusters, which could be associated with six patterns: normal dry years with precipitation close to the average, uniformly distributed throughout the year (cluster 1: 19.7% of years); wet years, in which all seasons recorded precipitation greater than the average (cluster 2: 14.8% of years); normal dry years, with total precipitation slightly smaller than the average, but with wet spring and wet autumns (cluster 3: 24.6%); normal wet years, with total precipitation slightly greater than the average, characterised by higher summer precipitation (cluster 4: 8.2%); wet years with wet autumns and wet winters (cluster 5: 13.1% of years) and finally, years with annual precipitation close to the average with wet springs and wet autumns, (cluster 6: 19.7%). Cluster 2 included the years with the highest values of  $P_{\max}24$  (92.8 days on average, with greater values in both observatories of Barcelona than at Vilafranca del Penedès or Reus airport), while cluster 3 and cluster 6 were the ones that grouped the years in which the higher NCDD were recorded (mean values ranging between 33.2 and 31.1 days per year).

By analysing the years included in each cluster (Fig. 5b) it may be observed that there is no clear trend of any pattern. All clusters included years from all decades except cluster 4, which, on the other hand, represented the less frequent

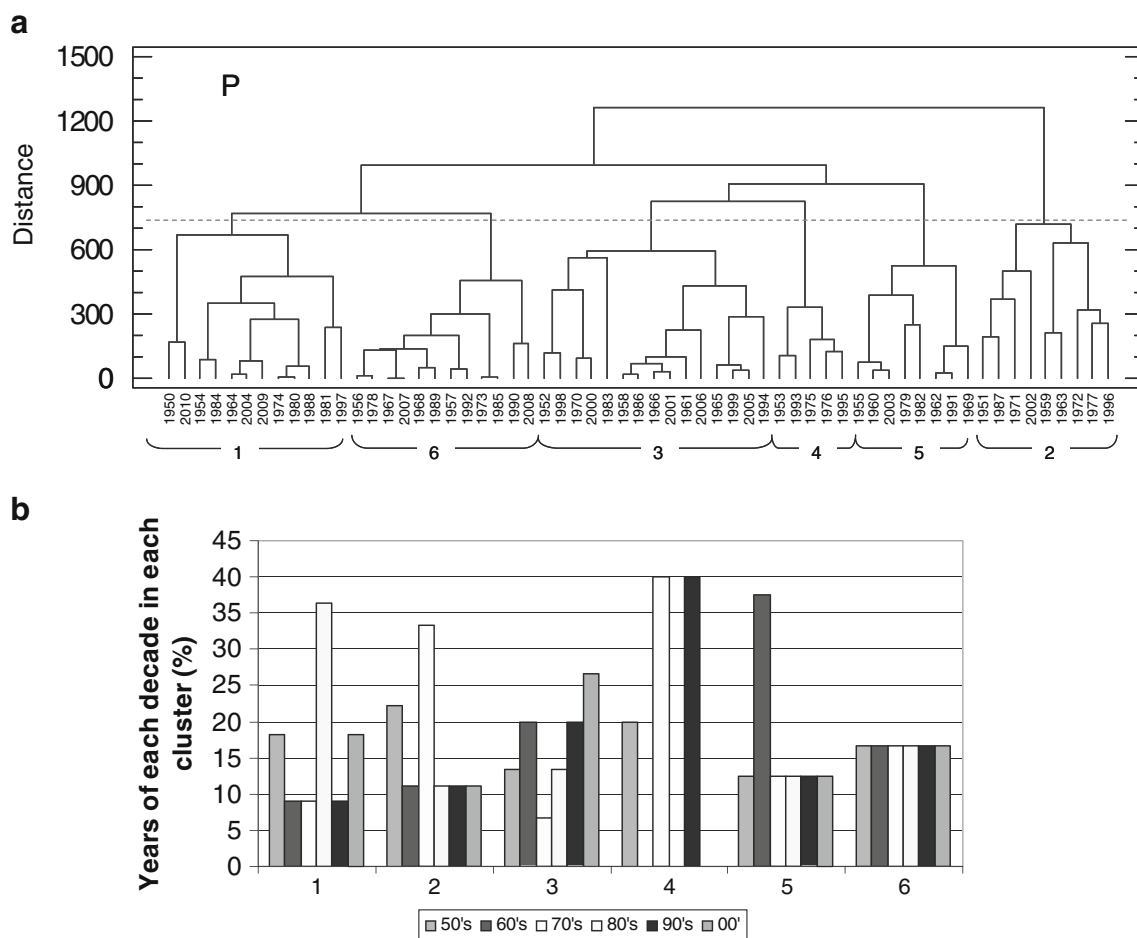
**Table 10** Mean value, standard deviation and significant trends of annual precipitation ( $P_{An}$ ), maximum precipitation in 24 h ( $P_{max24}$ ), number of very wet days (days with precipitation higher than the 95% percentile (NdP95), percentage of annual precipitation felt in very wet days (PercP95p), maximum number of consecutive dry days (NCDD), maximum number of consecutive wet days (NCWD), seasonal precipitation ( $P_{Sp}$  spring,  $P_{Sum}$  summer,  $P_{Aut}$  autumn,  $P_{Wint}$  winter) for the period 1950–2010 recorded at each observatory and for the last two decades (1990–2010)

Observatory	Variable	Mean ± standard deviation	Trend/year (°C/year)	Trend/year (90s–00s) (°C/year)
Vilafranca del Penedès	$P_{An}$ (mm)	517±114	0.220	-7.431
	$P_{max24}$ (mm)	62.8±21.9	0.144	0.239
	NdP95 (30.5 mm)	3.2±1.7	0.019	0.16
	PercP95p (%)	27.7±2.3	0.131	0.429
	NCDD (days)	41.1±19.9	<b>0.392</b>	0.203
	NCWD (days)	5.2±1.5	-0.006	0.094
	$P_{Sp}$	162.3±39.4	<b>-0.413</b>	<b>-2.594</b>
	$P_{Sum}$	63.6±83.4	-0.057	-0.853
	$P_{Aut}$	188.5±39.7	-0.048	-4.814
	$P_{Wint}$	105.0±64.5	<b>0.441</b>	<b>1.729</b>
Reus airport	$P_{An}$ (mm)	521±141	-1.012	-2.822
	$P_{max24}$ (mm)	63.2±26.2	-0.250	-1.243
	NdP95 (34.5 mm)	2.8±1.8	-0.028	0.354
	PercP95p (%)	26.7±16.0	-0.212	-0.527
	NCDD (days)	29.9±9.7	-0.119	-0.011
	NCWD (days)	4.1±1.4	0.008	-0.22
	$P_{Sp}$	136.1±75.3	<b>-0.884</b>	<b>-2.932</b>
	$P_{Sum}$	137.1±80.0	-0.056	0.404
	$P_{Aut}$	155.5±73.4	-0.046	-0.679
	$P_{Wint}$	91.5±57.1	-0.117	<b>0.809</b>
Barcelona airport	$P_{An}$ (mm)	608±204	<b>-1.643</b>	-9.89
	$P_{max24}$ (mm)	72.7±37.0	-0.284	-1.245
	NdP95 (346.5 mm)	3.0±2.1	0.002	-0.433
	PercP95p (%)	26.5±15.5	0.028	0.028
	NCDD (days)	28.7±11.9	<b>0.148</b>	<b>0.715</b>
	NCWD (days)	4.4±1.4	0.005	0.536
	$P_{Sp}$	131.5±69.9	-0.358	-1.377
	$P_{Sum}$	172.2±109.8	-0.769	-1.872
	$P_{Aut}$	197.6±125.4	-1.129	-1.478
	$P_{Wint}$	113.3±56.8	-0.502	0.882
Barcelona	$P_{An}$ (mm)	610±150	0.198	-5.621
	$P_{max24}$ (mm)	65.5±22.8	0.207	-0.732
	NdP95 (34.3 mm)	2.9±1.8	0.014	0.201
	PercP95p (%)	25.3±12.7	0.152	-0.216
	NCDD (days)	25.2±9.1	0.087	<b>0.239</b>
	NCWD (days)	9.9±2.8	0.017	<b>0.239</b>
	$P_{Sp}$	147.2±73.1	-0.228	-1.672
	$P_{Sum}$	143.6±71.0	-0.320	-2.767
	$P_{Aut}$	183.3±98.7	0.226	-3.222
	$P_{Wint}$	124.6±64.3	0.369	<b>2.809</b>

Bold numbers indicate significant trends at 90% or higher

pattern. That cluster did not include years from the 1960s, 1980s nor from the 1900s. Cluster 3 and cluster 6, with rainfall mainly concentrated in spring and autumn, represented the most typical precipitation pattern in the area. The differences between these two clusters were in the total winter precipitation. Cluster 6 included the same number of years from all decades (16.7%), while the highest

percentage of years in cluster 3 belonged to the 1960s (20%), 1990s (20%) and 2000s (26.7%). The years included in cluster 3 had more irregular distribution as noted by the greater mean NCDD values and the greater  $P_{max24}$ , which indicated more extreme events but also longer dry periods. In relation to the patterns corresponding to wet years represented by cluster 2 (with uniform distribution) and cluster 5



**Fig. 5** Precipitation analysis: **a** dendrogram (Ward's criteria) representing year classification using the seasonal precipitation indexes from four observatories). **b** Percentage of years of each decade included in each cluster (classified according to annual and seasonal precipitation indexes)

(with wet winters and wet autumns), the maximum percentage of years belonged to the 1970s and 1960s, respectively. This analysis confirmed, in addition to the variability of precipitation within the observatories, the lack of any trends.

#### 4 Discussion and conclusions

Despite the variability that characterises the Mediterranean climate, the temperature trend analysis in this specific area of NE Spain showed a temperature increase, mainly driven by maximum temperature increases in all seasons (presented in this paper by a long series recorded at four observatories located in the coast (Barcelona and Barcelona airport) and in the Penedès (Vilafranca del Penedès) and Camp de Tarragona (Reus airport) Depressions). The results have been also corroborated for shorter series in other observatories of the area (Ramos and Martínez-Casasnovas 2010b). We could observe some differences between the observatories, the results from Reus airport being the poorest in terms of significance and the observatory in which temperature change ratios were smaller.

During the last 60 years, an increase in  $T_m$  ranging between 1.86 and 2.4°C and in mean  $T_{max}$  up to 2.2°C was recorded, with an increase in the Ndt90 (between 31.6 and 34.9 days during that period). The temperature increase was not uniform throughout the year. It was greater in spring, summer and winter than in autumn. The increase was greater at Vilafranca del Penedès than at Barcelona and at Barcelona airport. During that period, spring maximum temperatures increased by up to 2.58°C at Vilafranca and 2.16°C at Barcelona due to the high number of extremes recorded in that season. The increase in the number of warm extremes in summer (up to 17 days at Barcelona and 21 days at Barcelona airport) was also considerably high.

The results are in agreement with the trends observed at wide scales in Europe and other parts of the world up to the last decade of the past century (Frich et al. 2002; Klein Tank et al. 2002). Brunet et al. (2007), in an analysis of records from 1850 to 2005 of 22 stations, observed maximum temperature increases at a greater rate than minimum temperature increases (0.11 vs. 0.08°C per decade for 1950–2005). However, they noted that the contribution to the

**Table 11** Centroids of each cluster obtained in the year classification using annual and seasonal precipitation indexes.  $P$  precipitation (of each season),  $P_{\max 24}$  maximum 24-h precipitation recorded within the year,  $NCDD$  maximum annual number of consecutive dry days,  $NdP95$  annual number of days with precipitation exceeding the 95% percentile

Cluster	Observatory	$P_{Sp}$	$P_{Sum}$	$P_{Aut}$	$P_{Wint}$	$P_{An}$	NCDD	NdP95	$P_{\max 24}$
1	Mean	153.2	99.5	117.9	127.7	422.0	54.6	1.7	64.1
	VP	171.3	48.6	116.0	137.3	452.8	32.5	2.3	54.4
	RA	123.0	116.8	153.0	95.6	488.6	28.7	2.0	49.9
	B	142.3	112.8	92.5	118.7	570.6	37.3	1.1	41.9
	BA	176.1	119.9	110.2	159.1	176.1	25.3	1.3	110.2
2	Mean	195.9	186.0	259.8	144.5	792.5	22.1	4.6	92.8
	VP	180.8	101.1	240.6	138.6	686.7	23.4	4.4	71.8
	RA	190.6	133.2	167.0	77.2	568.0	30.0	3.5	71.5
	B	206.7	289.4	344.2	160.3	923.5	18.0	5	130.1
	BA	205.5	220.4	287.3	202.1	992.0	16.8	5.4	97.6
3	Mean	98.7	119.0	186.2	94.5	500.9	33.2	2.8	64.7
	VP	97.6	47.2	216.5	94.8	455.8	41.2	3.0	68.0
	RA	134.4	141.4	139.7	105.8	522.0	29.4	2.5	57.9
	B	69.0	149.6	190.3	84.1	538.4	32.5	2.7	63.2
	BA	93.8	137.9	198.6	93.2	487.4	29.7	3.0	69.8
4	Mean	146.5	210.9	130.2	73.75	567.6	29.5	3.7	84.1
	VP	188.8	103.9	187.4	59.1	565.6	33.4	4.6	80.6
	RA	131.8	171.9	97.2	63.3	474.2	26.4	3.6	70.8
	B	136.0	309.3	107.9	87.6	600.4	25.4	3.1	108.4
	BA	129.5	258.5	128.4	85.0	630.2	33.0	3.3	76.5
5	Mean	128.9	126.1	225.9	178.4	662.1	24.4	2.2	67.5
	VP	164.8	70.2	229.2	135.7	612.8	25.8	2.5	54.1
	RA	147.2	125.7	206.0	177.8	656.9	24.5	2.3	76.3
	B	88.0	168.3	249.4	194.1	685.0	23.5	1.8	71.1
	BA	115.7	140.1	219.1	206.1	693.7	23.8	2.1	68.4
6	Mean	178.6	107.7	174.1	61.3	525.0	31.1	4.7	60.2
	VP	199.7	65.1	158.8	44.9	489.5	40.6	4.1	53.3
	RA	165.2	158.7	147.0	64.0	535.2	31.3	5.0	73.1
	B	169.8	117.4	204.8	66.2	524.3	28.4	4.9	58.4
	BA	179.6	89.6	185.8	70.2	551.0	24.3	4.7	56.0

annual warming of autumn and winter was slightly greater than those of spring and summer warm extremes.

Additionally,  $T_{\min}$  increased significantly in winter and spring in all observatories and additionally in summer in the coastal observatories. Those minimum temperature trends indicated a variation of about 1.5°C in winter, about 1.8°C in spring and about 1°C in summer (at Barcelona) during the whole period. In this respect, the results are in agreement with those observed by Klein Tank et al. (2002) who found increasing temperature trends in summer: 0.4°C per decade for the period 1946–1999 and 0.42°C per decade (0.1–0.74) for the period 1976–1999. As pointed by Lund et al. (2001), the use of seasonal data gave smaller errors in the estimates than annual data and more information about temperature trends was obtained. Brunet et al. (2007) also found in Spain a decrease of the number of moderately extreme cold days (0.74 days per decade) and an increase of moderately warm days and nights (0.53 and 0.49 days per decade) over the period 1850–2005.

Looking at the year-by-year analysis, we could observe that during the last three decades and particularly during the 2000s, temperatures recorded during the four seasons were greater than the average: that happened in 6 of 9 years in the 2000s and in 5 of 10 years in the 1990s and the 1980s. Only a few number of years recorded cold temperatures in all seasons in all observatories (1951, 1956, 1975 and 1978) and additionally in three of the four observatories (1957 and 1992). In the rest of years, there was no uniformity among all observatories nor among seasons within a year, with a variety of possibilities: cold winters and hot summers (like in 1964, 1970, 1973, 1985, 1986, 1987 or 2005 and 2010) or warm winters and relatively cold summers (like in 1974 or 1995, among others). The results are in agreement with that pointed out in the IPCC (2007) report referent to the warmest years recorded since 1850: the 12 warmest years are among the years 1995–2006, with a 100-year lineal trend between 1906 and 2005 of 0.74°C (0.56°C–0.92°C) greater

than the average trend of 0.6°C observed between 1901 and 2000 (0.4°C–0.8°C).

In relation to precipitation, the high variability observed from year to year hides any possible trend. As found by other authors in the Mediterranean (Reiser and Kutiel, 2010), no significant trends were found in the annual totals, in the number of rainy days and in the rainy season for the whole analysed period. Nevertheless, in the study, case some trends were observed at seasonal scale although they were not uniform in the analysed observatories. The common trend in the four observatories, significant only at the 90% level, was a decreasing trend of the spring precipitation, being of greater magnitude during the last three decades (1980s to 2000s). There was also an increasing trend in winter precipitation at Vilafranca del Penedès and in summer precipitation at Barcelona, although with high variability from year to year. The high variability during the last two decades was confirmed by the longer dry periods (NCDD increase) and the greater values of daily precipitation (during the last 20 years, more than 50% of years recorded  $P_{\max}24$  higher than the average, with values higher than 100 mm in 24 h). In addition, a positive trend was observed in the percentage that the extreme precipitation represented in relation to the annual precipitation, although those trends were not always were significant at 95%.

This result is in agreement with that observed by González-Hidalgo et al. (2010), who pointed out a negative trend in March and June in all catchments of Spain and a positive trend in October, which was particularly evident in the northwestern catchments. De Luis et al. (2009) and de Luis et al. (2010) referred to notable changes in seasonal precipitation regimes in the second half of the 20th century, which did not only affect the main rainy seasons (spring and autumn) but were also associated with an increase in winter precipitation along eastern coastal areas and to a decrease in precipitation inland associated with an increase in the variability of precipitation in all areas. They also noted a general increase in autumn precipitation.

The results are also in agreement with those found by Vergni and Todisco (2011) in central Italy, who noted negative trends for the growing season (April–September), mainly falling within the May–August subperiod. In the same direction, Hirschi and Seneviratne (2010), in an analysis carried out in France since 1901 to present, found a decreasing trend in the spring to autumn correlations.

In other studies carried out in the Mediterranean region, Altava-Ortiz et al. (2011) indicated that the two decades between 1984/1985 and 2004/2005 have been revealed as some of the driest ones since data are available in central and western Mediterranean, and they point out to the diminution of the spring and winter rainfall as the cause of the driest records since data are available in Western Mediterranean. In relation to summer precipitation, some authors

have concluded that summer precipitation in the Mediterranean region has decreased, based on the comparison of mean precipitation between two arbitrary multi-decadal periods (Pal et al. 2004; Giorgi and Lionello 2008). However, Bladé et al. (2011) observed that summer precipitation in Europe did not exhibit statistically significant negative trends.

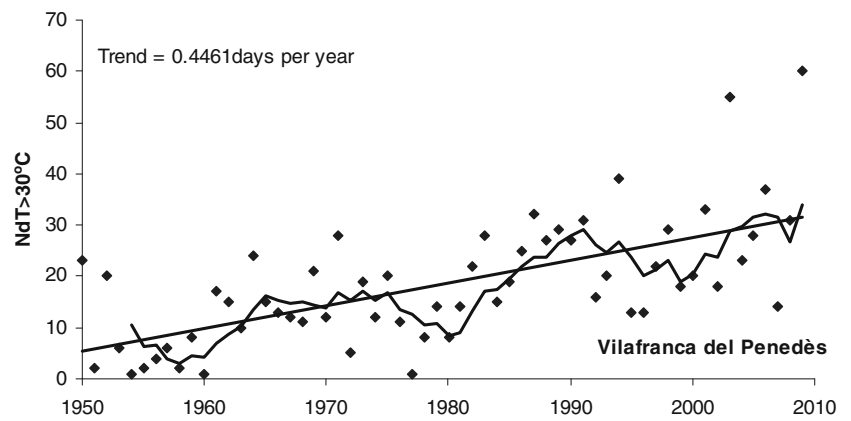
The CA applied to both annual and seasonal temperatures, and precipitation allowed to confirm the changes throughout the time. The years from the last decades were included for all seasons in the clusters that were considered as warm clusters. In particular, those warm clusters included a high percentage of spring 2000s, winter 2000s and 1990s, and autumn and summer 2000s, 1990s and 1980s. For precipitation, the most significant results were related to the dry conditions observed in spring 2000s and the wet conditions recorded in summer 2000s and 1980s and in autumn 2000s. The dendograms allowed the visualisation of the classification of each year in each groups according to the related temperature and precipitation variables.

Several authors (Altava-Ortiz et al. 2011; López-Bustins et al. 2008; Trigo et al. 2008, among others) have related changes in precipitation with teleconnection indexes. Bladé et al. (2011) showed a positive relationship between summer North Atlantic Oscillation index (NAO) and precipitation (referred to the period June–August) and a negative correlation with winter precipitation. Trigo et al. (2008) also indicated a link between the North Atlantic Oscillation index (NAO) index and the trends in winter precipitation in southwest Europe. In the analysed observatories, no significant correlation was found between seasonal precipitation and any index. However, when the analysis was done month by month, significant correlation (0.3) was found between precipitation and the corresponding monthly NAO and East Pacific/North Pacific Oscillation (EP/NP) indexes for August (0.3) and for January (−0.26) in three of the four analysed observatories.

From the point of view of the effects that those temperature changes and higher irregular distribution of precipitation may have on the main agricultural activity of the area, the main factors to take into account are the extreme situations and water availability (Ramos and Martínez-Casasnovas 2010a, b). Most crops are adapted for a given temperature range and are sensible to high temperature episodes out of the suitable conditions. Additionally, the damage produced by high temperatures depends on the stage of development in which the crops are. Within the study area, in the Penedès Depression, one of the main crops is vines, which occupied about 80% of the cultivated surface (cultivated under the “designation of origin” DO. Penedès). For that crop, temperatures higher than 30°C during a long period cause stress, premature veraison, berry abscission, enzyme activation and less flavour development (Mullins et al. 1992). During the analysed period, there



**Fig. 6** Trend of number of days per year with temperatures greater than 30°C for Vilafranca del Penedès (NE Spain)

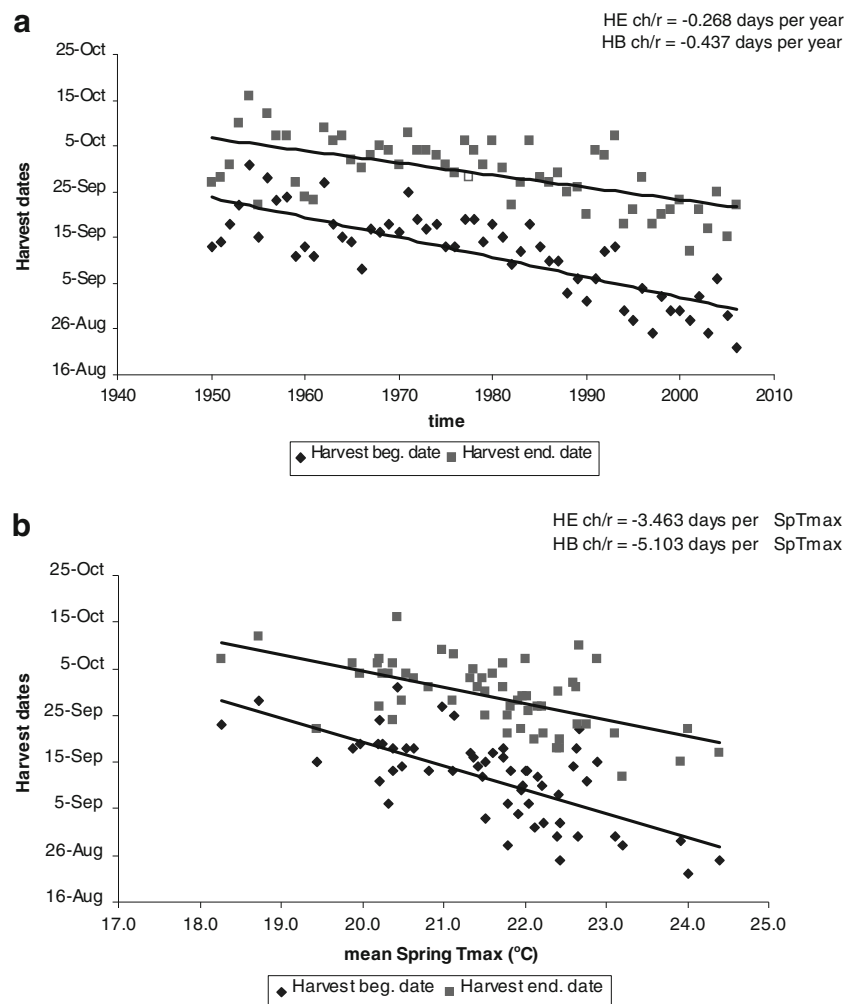


was an increasing trend of the number of days per year in which the temperature of 30°C was overpassed (Fig. 6).

Additionally, the increase of temperature supposes greater crop water demands. According to Vilafranca del Penedès data, crop evapotranspiration ranged between 343 and 471 mm, with a mean value of  $405 \pm 21$  mm. Crop evapotranspiration increased about 11% for the six decades, which is similar to that indicated by Vergni and Todisco (2011) for

some areas of central Italy. These authors indicated expected mean ETo variations of about 12%. Crop evapotranspiration was smaller than annual precipitation in 15.5% of the analysed years. In addition, due to the irregular distribution of rainfall and dry summer season, characteristic of the Mediterranean climate, with a an important amount of rainfall falling in autumn, water deficits were recorded in 75.8% of the analysed years during the grape growing season. In

**Fig. 7** Trends and relationship of beginning and ending harvest dates (Vilafranca del Penedès) with temperature variables: **a** trends throughout the years and **b** relationship with mean spring maximum temperature



those years, water deficits up to 200 mm were recorded during the grape growing season. This greater water demand may really be a problem in areas where the possibilities of irrigation are scarce.

The increase of temperature and the number of extremes have an effect on vine phenology. During the last decades, a progressive advance on harvest dates (both beginning and ending) has been observed, greater for the beginning harvest date (about 4.4 days per decade). That advance was significantly correlated with the increase of temperature. A particular incidence had the temperatures observed during spring and summer, which were the ones that experienced greater increase (as it was shown in the spring temperature analysis, the warmer cluster grouped the years from the 2000s and some years from the 1990s). Figure 7 shows the trends of the average dates with time (Fig. 7a), the relationship between them and the mean spring temperature (Fig. 7b). The beginning of harvest day advanced in about 5 days per 1°C increase of the spring maximum temperature, which is also related to the number of extremes recorded in the same season. This advance, which is in agreement with that observed in other European areas (Amann 2008; Petgen 2007; Jones and Davis 2000) may have negative impacts on the balance between sugar content, acidity and other grape maturity parameters. Water availability is another important factor for grape production. The observed decreasing trend of spring precipitation together with an increase of temperatures, which gives rise to higher evapotranspiration rates, produced higher water deficits. This period includes the budbreak–bloom stage and part of the bloom to veraison stage, in which grape may suffer deficit of suitable development. During the last 15 years, in one of the main varieties characteristic of the Penedès area (Xarello), it has been observed that yield reductions of about 20 kg/ha/ml of water deficit increase during spring, which may imply a significant production reduction in the area and the associated economic impact.

As a conclusion, the results of this analysis confirm the increase of temperature during the last decades, particularly in the last two, mainly due to increase of the maximum temperatures and the number of days with high extreme temperatures. Precipitation presents high variability from year to year, which makes it difficult to establish trends in any season, although longer dry periods and spring precipitation reductions are observed. The increase of temperatures increases evapotranspiration and, due to the higher irregular distribution, gives rise to water deficits. Both temperature and precipitation trends had an impact on phenology and yield of one of the main crops (vines) in the Penedès, particularly in those areas where water resources are scarce.

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## References

- Alexandersson H (1986) A homogeneity test applied to precipitation data. *J Climatol* 6:661–675
- Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration guidelines for computing crop water requirements. FAO, Irrigation and Drainage Papers 56, Rome
- Altava-Ortiz V, Llasat MC, Ferrari E, Atencia A, Sirangelo B (2011) Monthly rainfall changes in Central and Western Mediterranean basins, at the end of the 20th and beginning of the 21st centuries. *Int J Climatol* 31:1943–1958
- Amann R (2008) Wie sich das Klima verändert hat. *Der Badische Winzer* 01(2008):32–35
- Arnell NW (2004) Climate change and global water resources: SRES emissions and socio-economic scenarios. *Glob Environ Chang* 14:31–52
- Bladé I, Liebmann B, Fortuny D, van Oldenborgh GJ (2011) Observed and simulated impacts of the summer NAO in Europe: implications for projected drying in the Mediterranean region. *Clim Dyn* (online). doi:10.1007/s00382-011-1195-x
- Brunet M, Jones PD, Sigró J, Saladié O, Aguilar E, Moberg A, Della-Marta PM, Lister D, Walter A, López D (2007) Temporal and spatial temperature variability and change over Spain during 1850–2005. *J Geophys Res D: Atmospheres* 112 (12), art. no. D12117, pp 29
- Brunetti M, Maugeru M, Nanni T, Navarra A (2002) Droughts and extreme events in regional daily Italian precipitation series. *Int J Climatol* 22:543–558
- de Luis M, González-Hidalgo JC, Longares LA, Štěpánek P (2009) Seasonal precipitation trends in the Mediterranean Iberian Peninsula in second half of 20th century. *Int J Climatol* 29(9):1312–1323
- de Luis M, Brunetti M, Gonzalez-Hidalgo JC, Longares LA, Martin-Vide J (2010) Changes in seasonal precipitation in the Iberian Peninsula during 1946–2005. *Glob Planet Chang* 74:27–33
- Easterling DR, Meehl GA, Parmensan C, Chagnon SA, Karl T, Mearns LO (2000) Climate extremes: observation, modelling and impacts. *Science* 289:2068–2074
- EU Directorate Generale Science, Research and Development (1997) Climate change and agriculture in Europe. Assessment of impacts and adoptions. European Commission. Report EUR 17470 EN
- Frich P, Alexander LV, Della-Marta P, Gleason B, Haylock M, Klein Tank AMG, Peterson T (2002) Observed coherent changes in climatic extremes during the second half of the twentieth century. *Clim Res* 19:193–212
- Giorgi F, Lionello P (2008) Climate change projections for the Mediterranean region. *Glob Planet Chang* 63:90–104
- Gong X, Richman MB (1995) On the application of cluster analysis to growing season precipitation data in North America east of the Rockies. *J Climate* 8(4):897–931
- González-Hidalgo JC, Brunetti M, de Luis M (2010) Precipitation trends in Spanish hydrological divisions, 1946–2005. *Clim Res* 43(3):215–228
- Goubanova K (2007) Extremes in temperature and precipitation around the Mediterranean basin in an ensemble of future climate scenario simulations. *Global Planet Chang* 57:27–42
- Hanson R, Richard WG (2007) Atmospheric hazards: consecutive wet and dry days in Atlantic Canada. Meteorological Service of Canada—Atlantic Science Report Series 2007-02 .26 pp. Cat. No. En57-36/2007-2E

- Hargreaves GH, Samani ZA (1985) Reference crop evapotranspiration from temperature. *Applied Eng Agric* 1(2):96–99
- Hirschi M, Seneviratne SI (2010) Intra-annual link of spring and autumn precipitation over France. *Clim Dynam* 35(7):1207–1218
- Houghton JT, Ding Y, Griggs DJ, Noguer M, van de Linden PJ, Dai X, Maskell K, Johnson CA (eds) (2001) *Climate change 2001: the scientific basis contribution of Working Group I to the Third Assessment Report for the Intergovernmental Panel on Climate Change*. Cambridge University Press
- IDESCAT (2007) Municipis de Catalunya: població, superfície i altitud. Institut d'Estadística de Catalunya. [http://www.idescat.net/cat/idescat/publicacions/anuari/aec\\_pdf/aec-cap20.pdf](http://www.idescat.net/cat/idescat/publicacions/anuari/aec_pdf/aec-cap20.pdf). Accessed 3 September 2007
- Iglesias A, Garrote L, Flores F, Moneo M (2007) Challenges to manage the risk of water scarcity and climate change in the Mediterranean. *Water Resour Manag* 21(5):227–288
- Iglesias A, Garrote L, Quiroga S, Moneo M (2009) Impacts of climate change in agriculture in Europe. PESETA-Agriculture study EUR 24107 EN—2009, Joint Research Centre. Institute for Prospective Technological Studies, JRC 55386, European Commission
- IPCC (2007) Fourth assessment report: climate change 2007. Contribution of Working Group I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team Pachauri RK, Reisinger A (Eds), IPCC, Geneva, Switzerland. pp 104
- Izaurrealde RC, Rosenberg NJ, Brown RA, Thomson AM (2003) Integrated assessment of Hadley Center (HadCM2) climate-change impacts on agricultural productivity and irrigation water supply in the conterminous United States. Part II. Regional agricultural production in 2030 and 2095. *Agr Forest Meteorol* 117:97–122
- Jones GV, Davis R (2000) Climate influences on grapevine phenology, grape composition and wine production and quality for Bordeaux, France. *Am J Enol Vitic* 51(3):249–261
- Karl TR (1998) Regional trends and variations of temperature and precipitation. In Watson RT, Zyinyowera MC, Moss RH (Eds), *The regional impacts of climate change. An assessment of vulnerability*. IPCC. Cambridge University Press. pp. 411–437
- Klein Tank AMG, Können GP (2003) Trend in indices of daily temperature and precipitation extremes in Europe 1946–99. *J Climate* 16:3665–3680
- Klein Tank AMG, Wijngaard JB, Können GP, Böhm R, Demarée G, Gocheva A, Mileta M, Pashiardis S, Hejkrlik L, Kern-Hansen C, Heino R, Bessemoulin P, Müller-Westermeier G, Tzanakou M, Szalai S, Pálsdóttir T, Fitzgerald D, Rubin S, Capaldo M, Maugeri M, Leitass A, Bukantis A, Aberfeld R, Van Engelen AFV, Forland E, Milet M, Coelho F, Mares C, Razuvaev V, Nieplova E, Cegnar T, Antonio López J, Dahlström B, Moberg A, Kirchhofer W, Ceylan A, Pachaliuk O, Alexander LV, Petrovic P (2002) Daily data set of 20th-century surface air temperature and precipitation series for the European climate assessment. *Int J Climatol* 22:1441–1453
- Lana X, Burgueño A, Martínez MD, Serra C (2009) A review of statistical analyses on monthly and daily rainfall in Catalonia. *Tethys* 6:15–29
- Libiseller C, Grimvall A (2002) Performance of partial Mann–Kendall test for trend detection in the presence of covariates. *Environmetrics* 13:71–84
- Lopez-Bustins JA, Martin-Vide J, Sanchez-Lorenzo A (2008) Iberia winter rainfall trends based upon changes in teleconnection and circulation patterns. *Glob Planet Chang* 63:171–176
- Lund R, Seymour L, Kafadar K (2001) Temperature trends in the United States. *Environmetrics* 12(7):673–690
- Middelkoop H, Daamen K, Gellens D, Grabs W, Kwadijk J, Lang H, Parmet BWAH, Schädler B, Schulla J, Wilke K (2001) Impact of climate change on hydrological regimes and water resources management in the Rhine Basin. *Clim Chang* 49(1–2):105–128
- Milligan GW (1980) An examination of the effect of six types of error perturbation on fifteen clustering algorithms. *Psychometrika* 45:325–342
- Mullins MG, Bouquet A, Williams LE (1992) *Biology of the grapevine*. Cambridge University Press, Great Britain, p 239
- Nelson GC, Rosegrant MW, Koo J, Robertson R, Sulser T, Zhu T, Ringler C, Msangi S, Palazzo A, Batka M, Magalhaes M, Valmonte-Santos R, Ewing M, Lee D (2009) *Climate change: impact on agriculture and costs of adaptation*. International Food Policy Research Institute (IFPRI). <http://dx.doi.org/10.2499/0896295354>. Accessed 31 July 2011
- Olesen JE, Bindi M (2002) Consequences of climate change for European agricultural productivity, land use and policy. *Eur J Agron* 16(4):239–262
- Pal JS, Giorgi F, Bi X (2004) Consistency of recent European summer precipitation trends and extremes with future regional climate projections. *Geophys Res Lett* 31:L13202
- eterson TC, Folland C, Gruza G, Hogg W, Mokssit A, Plummer N (2001) Report on the activities of the Working Group on Climate Change Detection and Related Rapporteurs 1998–2001. WMO Rep. WCDMP 47, WMO–TD 1071, Geneva, Switzerland pp 143
- Petgen M (2007). *Reaktion der Reben auf den Klimawandel*. Schweizerischen Zeitschrift für Obst- und Weinbau, 9/07, pp 6–9
- Ragab R, Prudhomme C (2002) Climate change and water resources management in arid and semi-arid regions: prospective and challenges for the 21st century. *Biosyst Eng* 81(1):3–34
- Ramos MC, Martínez-Casasnovas JA (2006) Trends in precipitation concentration and extremes in the Mediterranean Penedès-Anoia region, NE Spain. *Clim Chang* 74:457–474
- Ramos MC, Martínez-Casasnovas JA (2010a) Effects of precipitation patterns and temperature trends on soil water available for vineyards in a Mediterranean climate area. *Agr Water Manage* 97:1495–1505
- Ramos MC, Martínez-Casasnovas JA (2010b) Climate variability and its effects in the Penedès vineyard region (NE Spain). *Proceedings VIII International Terroir Congress. Consiglio di la Ricerca e la sperimentazione in Agricoltura. Centro di Ricerca per la Viticoltura*. 3–23—3–28
- Reiser H, Kutiel H (2010) Rainfall uncertainty in the Mediterranean: time series, uncertainty, and extreme events. *Theor Appl Climatol* (available on line), pp 19, doi:10.1007/s00704-010-0345-0
- Rosenzweig C, Iglesias A, Livermore M, Fischer G (2004) Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environ Chang* 14(1):53–67
- Russo S (2009) Global changes in heat wave duration index from 1950 until 2100. Effects of climate change, 18/3/2009–20/3/2009, Malta, SEAMOCs
- Trigo RM, Valente MA, Trigo IF, Miranda M, Ramos AM, Paredes D, García-Herrera R (2008) North Atlantic wind and cyclone trends and their impact in the European precipitation and Atlantic significant wave height. *Ann NY Acad Sci* 1146:212–234
- Vergni L, Todisco F (2011) Spatio-temporal variability of precipitation, temperature and agricultural drought indices in Central Italy. *Agr Forest Meteorol* 151:301–313
- Von Storch H (1995) Inconsistencies at the interface of climate impact studies and global climate research. *Meteor. Z.* 4 NF, 72–80