

Grape harvest and yield responses to inter-annual changes in temperature and precipitation in an area of north-east Spain with a Mediterranean climate

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Received: 22 March 2011 / Revised: 22 July 2011 / Accepted: 9 August 2011 / Published online: 10 September 2011
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Abstract This study presents an analysis of temperature and precipitation trends and their impact on grape harvests in the Penedès region (NE Spain). It includes analyses of maximum, minimum and mean daily temperatures (for both the growing and ripening seasons) and daily rainfall (for the hydrological year, the growing season and each phenological stage) for three observatories in the immediate area. We analysed a series of factors: beginning and end harvest dates; the day on which a given potential alcoholic degree was reached; and yield for several varieties of grape grown in the area in relation to climatic variables. Maximum temperatures increased at all the observatories, with greater values being recorded in recent years (1996–2009) than in previous decades (1960s–2000s): we observed increases in average growing season temperatures of 0.11°C per year for the period 1996–2009 vs 0.04°C per year for the period 1960–2009 at Vilafranca del Penedès. These temperature changes were due mainly to increases in maximum temperatures and an increase in the incidence of extreme heat (number of days with $T > 30^{\circ}\text{C}$). Crop evapotranspiration also increased significantly during the same period. The Winkler index also increased, so the study area would correspond to region IV according to that climatic classification. There were no significant trends in annual rainfall but rainfall recorded between bloom and veraison decreased significantly at the three observatories, with the greatest decrease corresponding to the period 1996–2009. The dates on which harvests started and ended showed a continuous advance (of between -0.7 and -1.1 days per year, depend-

ing on the variety), which was significantly correlated with the average mean and maximum daily growing season temperatures (up to -7.68 days for 1°C increase). Wine-grape yield was influenced by the estimated water deficit (crop evapotranspiration minus precipitation) in the bloom-veraison period; this value increased due to a reduction in precipitation and an increase in evapotranspiration. Yield may have been reduced by up to 30 kg/ha for each millimetre increase in the estimated water deficit. Under these conditions, new strategies need to be followed in this area in order to maintain grape quality and yield.

Keywords Bioclimatic index · Climate change · Phenology · Probable alcoholic degree · Vine

Introduction

Vines—one of the most extensive crops in some parts of the Mediterranean area—are cultivated mainly under rainfed conditions; they may therefore be one of the crops that might suffer most from the consequences of climate change. For vines, although some days with temperatures above 30°C may be beneficial during the ripening period, excessively high temperatures may induce plant stress and premature veraison, and also reduce photosynthesis. Extremely hot ($>35^{\circ}\text{C}$) temperatures at inland vineyards cause severe skin damage in the form of sunburn, which increases the incidence of Botrytis latent infections in grapes (Steel and Greer 2008). Increasing temperatures and solar radiation will have a direct impact on grape composition and thus flavour development via alteration of secondary metabolites such as flavonoids, amino acids and carotenoids (Schultz 2000).

Higher temperatures would also lead to higher rates of evapotranspiration and increase plant water requirements.

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This may be particularly important in rainfed areas, like in the study case, due to the lack of irrigation possibilities. The result would be a shortening of the ripening period, with harvest occurring during the period with high temperatures, which could have a negative impact on wine quality (Salazar Parra et al. 2010; Duchêne and Schneider 2005; Jones and Davis 2000) and yield (Mira de Orduña 2010; Iglesias et al. 2010). Climate change in the future might move the north and south latitude boundaries of areas suitable for good quality wines (Schultz and Jones 2010), and could even lead to improvements in fruit production and quality in some areas (Olesen and Bindi 2002). However, other areas may be negatively affected by high temperatures and water stress due to a reduction in the amount of water available.

One of the most direct effects is the change in onset phenology and the length of the growing season, which further influences final grape quality and productivity. This influence has been analysed in different wine-producing areas of Europe, Canada, the United States and Australia (Jones and Davis 2000; Nemani et al. 2001; Caprio and Quamme 2002; Jones 2005; Jones et al. 2005; Beniston 2008; Petrie and Sadras 2008; Laget et al. 2008; Dalla Marta et al. 2010; amongst others).

The Penedès region, located Northeastern Spain, has a long tradition of wine production, mainly dedicated to white wine and sparkling wines, under the “Penedès and Cava” designation of origin. The main varieties used for this purpose are Macabeo, Parellada and Xarello and, as secondary variety, Subirat Parent. These varieties are quite specific to this region although the method followed to produce the sparkling wines is similar to the champagne method used in France. The response of these varieties to climate change has not been analysed in other studies. Due to the importance of this producing area for Spanish and European viticulture, it is necessary to determine the impacts that climate change have on the growing cycle in this region, which will have further repercussions on grape quality. Thus, the objective of the present work was to analyse changes in temperature, precipitation and water deficits produced in recent years and their effects on grape development in the area corresponding to the “Penedès and Cava” designation of origin. To do this, the harvest dates and yields of some of the wine grape varieties grown in three locations within the area were analysed and related to climate trends and water deficits that resulted along the crop cycle.

Materials and methods

Location of the study area

The study area is located in the Alt Penedès region of Catalonia, Spain (Fig. 1). This region forms part of the

Penedès Tertiary Depression; in this area, the main lithological types are calcilutites (marls), with occasional sandstones and conglomerates. Agriculture is the main economic activity of the people who live in this area, with about 70% of the cultivated area (17,262 ha out of 24,136 ha) (Idescat 2007; CRDOP 2010) being dedicated to the cultivation of vines under the Designation of Origins (DO) Penedès and Cava. These two DOs represent about 4% and 5%, respectively, of the vineyard surface in Spain. Although the DO Cava is shared with other regions, the study area is the most important. White varieties, mainly Xarello, Macabeo, Parellada and Chardonnay, account for about 82% of cultivated grapes in the area, while the main red varieties (about 18%) are Tempranillo, Merlot and Cabernet Sauvignon. During the last two decades, land levelling operations have been carried out in fields to facilitate mechanisation, which has disturbed soil profiles, leaving materials that are poor in organic content near the surface, and a very weak soil structure. This poor soil structure affects water intake and redistribution and has imposed a significant limitation on the availability of water for vines in this rainfed farming area.

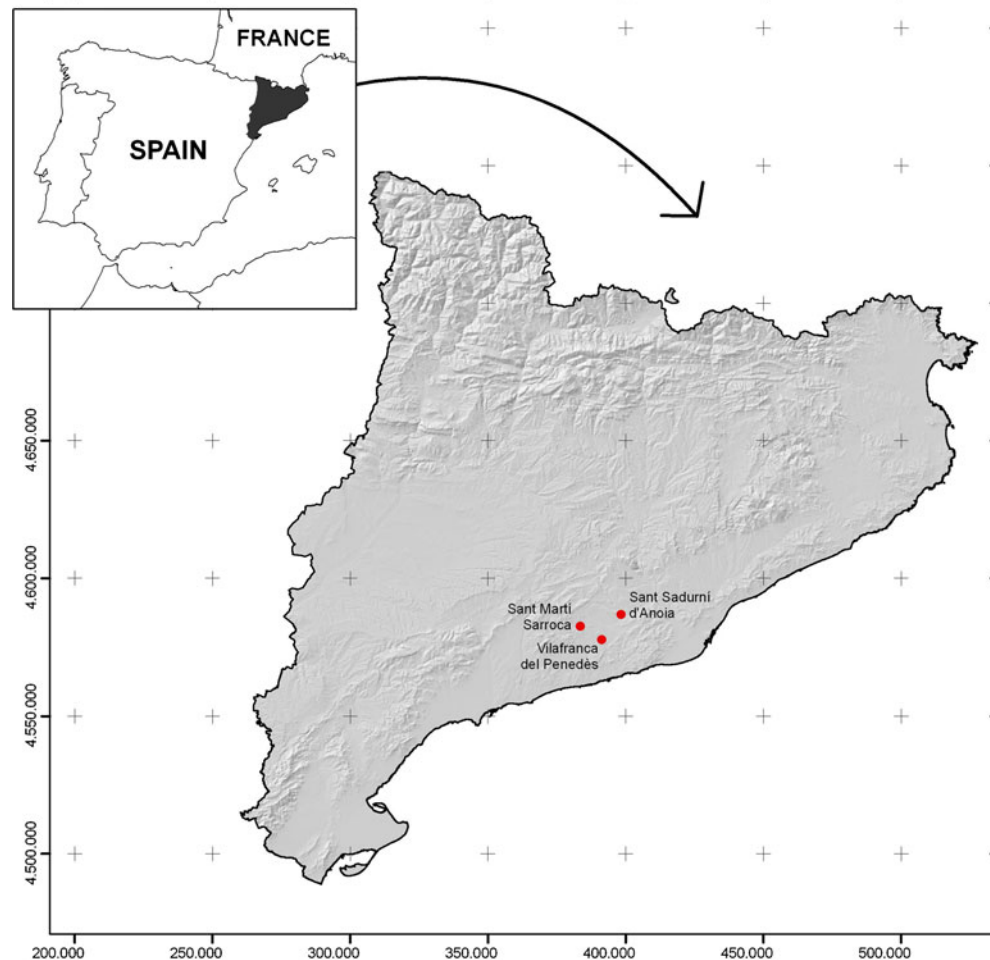
Climate data

The climate in the area is predominantly Mediterranean with a maritime influence. It is characterised by warm, wet winters and hot and dry summers. The climate data used in this work relates to three observatories (Fig. 1):

- Vilafranca del Penedès: data from the INCAVI (Institut Catatà de la Vinya i el Vi) station (latitude: 41°20'50"; longitude: 1°41'59"; elevation: 223 m). Mean, maximum and minimum daily temperatures and daily precipitation (1960–2009) were used.
- Sant Sadurní d'Anoia: data series belonging to AEMET and private data series, an observatory that now belongs to the Servei Meteorològic de Catalunya (latitude: 41°26'; longitude: 1°47'; elevation: 164 m). Mean, maximum and minimum daily temperature (1990–2009) and daily precipitation (1960–2009) were used.
- Sant Martí Sarroca: observatory belonging to the Servei Meteorològic de Catalunya (latitude: 41°23'; longitude: 1°37'; elevation: 257 m). Mean, maximum and minimum daily temperatures and daily rainfall (1997–2009) were used in the analysis.

For each year, each temperature variable was summarised for the whole hydrological year, for the growing season (this varied according to the variety, but on average it ranged from early April to mid-September) and for the ripening period (early August to mid-September). The initial dates for each period were obtained from information

Fig. 1 Location of the study area and observatories



given by farmers for each variety for the years included in this analysis. The relationship between the temperatures at Sant Martí Sarroca and Vilafranca del Penedès was evaluated and the results were taken into account to generate data for the years for which there were no data for Sant Martí Sarroca in order to establish the relationship with phenology. Several bioclimatic indices were also analysed: the number of days with temperatures above 30°C (ndT>30°C), the critical maximum temperature for grape development (Mullins et al. 1992); the number of frost days (ndT<0°C); and the Winkler Index (WI; Winkler et al. 1974), calculated using average temperatures above a 10°C base for April through October.

The precipitation data were summarised for the whole hydrological year (1 October–30 September) and for the different phenological stages (budbreak–bloom; bloom–veraison; veraison–ripening). The dates of each phenological stage were taken from information recorded for each variety by different producers in the area (near Sant Sadurni d'Anoia and Vilafranca del Penedès) from 1994 to 2006. The phenological dates were estimated for the years for which some information was not available by extrapolating the trends observed from the data that were available. Harvesting records from 1984 to

2006 were obtained from other producers and wine cellars in the area. Phenology-related data obtained from the Agencia Estatal de Meteorología (AEMET) and relating to vineyards in the same area (for Piera, Gelida and Sant Sadurni d'Anoia) for the period 1943–1989 were also analysed in order to confirm trends in relation to previous periods. Although these periods (stages 1–5) varied between varieties, the average values were as follows:

- Stage 1: Bud-break–flowering (6 April±8 days–25 May±5 days)
- Stage 2: Flowering–veraison (25 May±5 days–7 Aug±1 day).
- Stage 3: Veraison–grape harvest (7 August ± 1 day–16 September ± 11 days).
- Stage 4: Grape harvest–leaf fall (16 September ± 11 days–15 November±9 days)
- Stage 5: Leaf fall–bud-break (15 November ± 9 days–6 April±8 days)

Crop evapotranspiration for the growing season was also evaluated for each year using the evapotranspiration data obtained from each observatory and the crop coefficients proposed by Allen et al. (1998).

Grape harvest data

Data were collected from vineyards located close to each meteorological station. These data included:

- The beginning of the grape harvest (HBeg) and the end of the grape harvest (HEnd) for certain grape varieties.
- The day on which the different potential alcoholic degrees (dPAD): 8°, 9° and 10° were reached. The potential alcoholic degree was obtained from the Brix [PAD = (0.6757 × Brix) – 2.0839] measured by refractometry.
- Grape yield.

Data relating to the varieties were provided for the three locations by wine cellars, but the reference varieties varied from one place to another. The following data were analysed for each observatory:

- For the Sant Sadurní d'Anoia vineyards, the Subirat Parent (SP), Macabeo (MA), Xarello (XA) and Parellada (PA) varieties were considered. The data referred to the 1985–2006 period, except for Subirat Parent (SP), for which the reference period was 1988–1996 and 1999.
- For the Vilafranca del Penedès vineyards, the Macabeo, Xarello and Parellada varieties were analysed (for the period 1985–2006, but with no information for 1987).
- For the Sant Martí Sarroca vineyards, the Subirat Parent, Macabeo, Xarello and Parellada varieties were analysed for the period 1990–2005.

Trend analysis

Trend analyses of the different climate variables and harvest parameters (beginning and end dates, probable alcoholic degree and yield) were carried out. The interactions between climate and harvest parameter trends were also analysed. The time series were assessed for auto-correlation using the Durbin-Watson statistic. When the time series had autocorrelation, we prewhitened the series as proposed by Von Storch (1995). An ARIMA model was used for prewhitening and the Mann-Kendall test (Mitchell et al. 1966) was applied in order to determine the significance of the trend. A linear regression between temperature variables (TGSM_{max}, TGSM_{min}, TGSM, WI, ndT > 30°C and ndT < 0°C) and harvest dates (beginning and end) as well as the date on which PAD = 9 was reached was applied in order to identify the relationships between the different variables. The relationship between the estimated water deficit (crop evapotranspiration minus precipitation) at different growing stages and grape yield was also analysed by linear regression analysis.

Results

Climate results

Table 1 shows the average values for each of the variables analysed at the Vilafranca del Penedès and Sant Sadurní d'Anoia observatories (the longest series), and for the last 14-year period common to all three observatories (1996–2009). The average maximum temperature was higher in Sant Sadurní d'Anoia than in Vilafranca for both the growing and ripening seasons. However, the differences in minimum temperatures during the growing season were similar for both observatories during the ripening period. When the three shorter series were compared, we observed average maximum growing season temperatures that were slightly higher at Sant Martí Sarroca and Sant Sadurní d'Anoia than at Vilafranca del Penedès. For the minimum temperatures, the average values were slightly higher at Vilafranca del Penedès than at Sant Sadurní and Sant Martí Sarroca. However, there was a significant correlation between the data observed at Vilafranca and Sant Martí Sarroca (coefficients of determination $r^2 = 0.93$; 0.88 and 0.70, respectively, for mean, maximum and minimum temperature).

Differences in the maximum temperatures were also observed in the WI, ranging between 1,882 and 2,061 degree-days. These values mean that, for the period 1960–2009, the area corresponded to Winkler region III, which refers to climates generally favourable for high production of good quality table wines (Winkler et al. 1974). In the last decade, the index increased to about 2,100 degree days as a result of temperature increases; this would locate the area in Winkler region IV. However, the differences between Sant Sadurní d'Anoia and Vilafranca del Penedès were smaller due to the greater similarity in mean temperatures between these observatories as a result of the greater increase in minimum temperature.

One of the main differences between the three observatories was the number of days with extreme temperatures: days with $T < 0^\circ\text{C}$ (ndT < 0°C) and the number of days with $T > 30^\circ\text{C}$ (ndT > 30°C). For the period 1960–2009, fewer cases of both extreme situations ($T < 0^\circ\text{C}$ and $T > 30^\circ\text{C}$) were recorded at Vilafranca del Penedès than at Sant Sadurní d'Anoia. In the previous 14 years (1996–2009), the number of frost days (ndT > 0°C) decreased slightly at both observatories, while the number of warm extremes increased at both observatories, with similar values for Sant Martí Sarroca and Sant Sadurní d'Anoia.

Table 2 shows the trends (change ratios per year) for each variable for long series at Vilafranca del Penedès and Sant Sadurní d'Anoia and for the previous 14 years (1996–2009) for the same observatories plus Sant Martí Sarroca. The results show significantly increasing trends for maximum temperatures, which were higher in the later years

Table 1 Mean values and standard deviation of each temperature and precipitation variable for the long and sort series of each observatory. *TGSM* Mean average growing season temperature, *TGSM_{Max}* mean maximum growing season temperature, *TGSM_{Min}* mean minimum growing season temperature, *TRPM* mean average ripening period temperature, *TRP_{Max}*, mean maximum ripening period temperature, *TRP_{Min}* mean minimum ripening period temperature, *ndT<0°C* number of days with temperature <0°, *ndT>30°C* number of days

with temperature>30°C, *WI* Winkler index, *PH* annual precipitation (hydrological year), *PGS* precipitation recorded during the growing season, *P-Stage 1* precipitation recorded during the budbreak-bloom period, *P-Stage 2* precipitation recorded during the boom-veraison period, *P-Stage 3* precipitation recorded during the ripening period (veraison–harvest), *ETcGS* mean crop evapotranspiration recorded during the growing period

	Vilafranca del Penedès (1960–2009)	Sant Sadurní d’Anoia (1960–2009)	Vilafranca del Penedès (1996–2009)	Sant Sadurní d’Anoia (1996–2009)	Sant Martí Sarroca (1997–2009)
TGSM _{Max} (°C)	24.9±1.0	26.7±1.1	25.8±0.9	26.9±2.6	27.2±1.1
TGSM (°C)	19.6±0.9	20.2±0.9	20.6±0.8	20.5±1.6	20.2±0.7
TGSM _{Min} (°C)	14.2±1.0	13.6±0.9	15.4±0.8	14.1±0.6	13.7±0.6
TRP _{max} (°C)	26.7±1.1	29.4±1.0	28.2±1.3	29.2±2.3	29.1±1.9
TRPM(°C)	21.6±1.1	23±0.84	23.0±1.0	22.9±1.2	22.0±1.8
TRP _{Min} (°C)	16.5±1.1	16.5±0.87	17.9±1.1	16.7±0.9	15.9±1.5
WI (degree-day)	1,882±207	2,061±189	2,104±140	2,126±180	2,015±155
ndT<0°C annual (days)	11±7	30±12	11±8	28±15	26±17
ndT>30°C growth(days)	21±12	48 ±15	28±14	54±15	55±16
PH (mm)	521±128	524.7±156	510±156	542±126	527±127
PGS(mm)	358±112	345±102	374±134	322±120	328±86
P-Stage 1 (mm)	74±46	77±47	79±56	86±51	86±52
P-Stage 2 (mm)	66±36	65±41	59±25	56±31	52±32
P-Stage 3 (mm)	71±52	64±49	74±56	63±49	75±58
ETcGS (mm)	458±23	425±38	467±20	442±58	454 ±27

than in the long series. This points to maximum growing season temperature trends that were greater than 0.1°C per year; this implied an increase with respect to the period

1996–2009 of almost 1.5°C. This trend was consistent with an increase in the Winkler index of up to 35 degree-days per year.

Table 2 Temperature and precipitation trends for each observatory for the long and short series, significant at 90% level or higher. For definitions, see legend to Table 1

Variable	Vilafranca del Penedès (1960–2009)	Sant Sadurní d’Anoia (1960–2009)	Vilafranca del Penedès (1996–2009)	Sant Sadurní d’Anoia (1996–2009)	Sant Martí Sarroca (1997–2009)
TGSM (°C/year)	0.04	0.08	0.11*	0.130*	0.08
TGSM _{Max} (°C/year)	0.04*	0.08	0.11*	0.12*	0.11
TGSM _{Min} (°C/year)	0.03*	NS	0.11*	0.10*	0.11*
TRPM (°C/year)	0.03*	0.05	0.09*	0.10	NS
TRP _{Max} (°C/year)	0.07*	0.13*	0.09	0.10*	NS
TRP _{Min} (°C/year)	NS	NS	NS	0.11	NS
ndT<0°C (days)	-0.26*	NS	NS	NS	NS
ndT>30°C (days)	0.5*	1.5*	1.7*	2.8*	1.6
WI (degree- days)	98	16*	18*	35*	32*
PH (mm)	NS	NS	NS	NS	NS
PGS (mm)	NS	NS	NS	NS	NS
P-Stag 1 (mm)	NS	NS	NS	NS	NS
P-Stag2 (mm)	-0.6*	-0.5	-3.6*	-4.6*	-5.0*
P-Stag3 (mm)	NS	NS	NS	NS	NS
ETcGS (mm)	0.6	1.5	3.8*	9.1*	3.3*

*Significant trends at 95% level, NS no significant trend at 90% level

Annual precipitation was about 520 mm on average, with about 350 mm being recorded during the growing season (Table 1). Due to the high degree of variability from year to year, there was no clear change in total annual precipitation or in the precipitation recorded during the growing season, although a significantly decreasing trend was observed during the period between bloom and veraison. That trend was of greater magnitude during the later years for all the observatories. On the other hand, in the last years of the study, crop evapotranspiration displayed an increasing trend, which pointed to greater water demands with less water available.

Vine parameters

The results relating to the different harvest parameters for the different varieties analysed at each location are shown in Table 3. The mean and standard deviations (in days) for

the beginning (HBeg) and end harvest (HEnd) dates and the mean day on which the probable alcoholic degree (dPAD)=9° and =10° was reached are shown. The trends observed for these dates are also presented for each variable. It was possible to observe a general trend for the beginning and end of the harvest period to advance, by between -0.39 and -1.10 days per year, on average, for most of the varieties grown at the three locations. The maximum trends were observed for Parellada at Sant Sadurní d'Anoia, for both the beginning and end of the harvest. However, at Vilafranca del Penedès, this variety showed the opposite trend (but it was the only one that showed different behaviour). For the Macabeo and Xarello varieties, the trends at the beginning of the harvest period were greater than at its end at Vilafranca del Penedès and Sant Martí Sarroca (but not at Sant Sadurní), with a maximum value at Vilafranca del Penedès, for the beginning of harvest for both varieties.

Table 3 Mean date and standard deviation (in days) and trend of the beginning and ending harvest dates, and the date on which a probable alcoholic degree was reached. *HBeg* Harvest beginning date, *HEnd* harvest end date, *dPAD9* day on which the probable alcoholic degree=9° was reached, *dPAD10* day on which the probable alcoholic degree=10° was reached

Location	Variety	HBeg (date±days) Trend (days/year)	HEnd (date±days) Trend (days/year)	dPAD9 (date±days) Trend (days/year)	dPAD10 (date±days) Trend (days/year)
Vilafranca del Penedès					
	Macabeo	3 September±7 days -0.87*	13 September±7 days -0.49*	22 September±8 days -0.99*	3 September±8 days -0.37
	Xarello	13 September±7 days -0.70*	2 October±6 days -0.56*	4 September±6 days -0.98*	5 September±6 days -0.99*
	Parellada	16 September±7 days -0.54*	2 October ±6 days 0.42*	19 September±6 days -0.35	ND ^a
Sant Sadurní d'Anoia					
	Macabeo	1 September±5 days -0.68*	29 September±7 days -0.69*	5 September±9 days -1.06*	7 September±5 days -0.64
	Xarello	6 September±5 days -0.58*	4 October±8 days -0.83*	9 September±5 days -0.30*	10 September±8 days -0.93*
	Parellada	15 September±9 days -0.88*	6 October±9 days -1.10*	20 September±8 days -1.03*	ND
	Subirat Parent	12 September±5 days 0.08	29 September±10 days -1.73	16 September±6 days -1.08*	19 September±5 days -0.42
Sant Martí Sarroca					
	Macabeo	29 August±5 days -0.57*	23 September±6 days -0.42*	28 August ±3 days -0.58*	3 September±8 days -0.37
	Xarello	2 September±5 days -0.65*	30 September±7 days -0.39*	4 September±6 days -0.98*	5 September±6 days -0.99*
	Parellada	9 September±6 days -0.65*	29 September±6 days -0.39*	16 September±8 days -0.55	ND
	Subirat Parent	1 September±4 days -0.51*	19 September±10 days -1.37*	5 September±7 days -0.53	ND

*Significant trends at 95% level

^a No data

The date at which a potential alcoholic degree (dPAD=9°) was reached showed a significant advance of about 1 day per year for Macabeo at Sant Sadurní d'Anoia and Vilafranca del Penedès, for Xarello at Vilafranca and Sant Martí Sarroca and for Parellada and Subirat Parent at Sant Sadurní (Table 3). For dPAD=10°, a similar trend was observed for Xarello at all three locations.

Relationships between climate parameters and vineyard data

Changes in the beginning and end of the harvest period as well as in the date on which a given probable alcoholic degree (dPAD=9°) was reached were analysed in relation to different climatic variables that had shown significant

trends at all three observatories: mean and maximum and minimum temperatures during the growing season; WI; and the number of days with $T > 30^{\circ}\text{C}$ and $T < 0^{\circ}\text{C}$.

Tables 4 shows the change ratios of these harvest variables [beginning and end dates and the date on which a given probable alcoholic degree (dPAD=9°) was reached] obtained in the regression analysis with some temperature variables (maximum, mean and minimum growing season temperatures, WI and the number of days with $T > 30^{\circ}\text{C}$). The results refer to the three most common varieties for which data are available at each location (Macabeo, Xarello and Parellada) and they make reference to a common period for all three observatories (1990–2006). No significant correlations were found with the number of days with $T < 0^{\circ}\text{C}$.

Table 4 Change ratio significant at 90% level or higher of harvest parameters. For definitions, see Tables 1 and 3

Variety location	Variable	Change ratio				
		TGSM _{Max} (days/°C)	TGSM (days/°C)	TGSM _{Min} (days/°C)	WI (days/DDG)	ndT>30°C (days/ndT>30)
Macabeo						
Vilafranca del Penedès	HBeg	-6.33*	-6.14*	-4.96*	-0.025*	-NS
	HEnd	-7.68*	-7.23*	-5.62*	-0.025*	NS
	dPAD	-12.39*	-9.99*	-6.38*	-0.047*	NS
Sant Sadurní d'Anoia	HBeg	-3.03*	-3.20*	-2.91	-0.017*	-0.21*
	HEnd	-3.15*	NS	NS	NS	-0.21
	dPAD9	-3.98	-4.97	NS	-0.048	-0.43
Sant Martí Sarroca	HBeg	-4.19*	-4.73*	-5.44*	-0.020	NS
	HEnd	NS	NS	-4.46	-0.014	NS
	dPAD9	-5.48	-5.72	-6.49	-0.025	NS
Xarello						
Vilafranca del Penedès	HBeg	-6.30*	-6.58*	-5.21*	-0.027*	-0.27
	HEnd	-7.16*	-6.20*	-4.22*	-0.021*	NS
	dPAD9	NS	-3.19*	-3.29*	-0.019	NS
Sant Sadurní d'Anoia	HBeg	-2.63*	-2.79*	-1.99*	-0.016*	-0.18*
	HEnd	-4.38*	-4.08*	-2.11*	-0.023	-0.26
	dPAD9	NS	NS	NS	NS	-0.36
Sant Martí Sarroca	HBeg	-4.66*	-5.08*	-5.68*	-0.013*	-0.23*
	HEnd	NS	-3.09*	-3.76*	-0.021*	NS
	dPAD9	-6.16	-5.62	-7.77	-0.027*	NS
Parellada						
Vilafranca del Penedès	HBeg	-6.70*	-6.31*	-4.64*	-0.024*	NS
	HEnd	-4.93	NS	NS	NS	NS
	dPAD9	-12.68*	-8.68*	-5.53*	-0.031	-0.45
Sant Sadurní d'Anoia	HBeg	-4.34*	-4.10*	NS	-0.023*	-0.30*
	HEnd	-4.87	-4.63*	NS	-0.026*	-0.29
	dPAD9	NS	NS	NS	NS	NS
Sant Martí Sarroca	HBeg	NS	-3.72	-4.19*	-0.018*	NS
	HEnd	-4.81*	-5.52	-6.18*	-0.026*	NS
	dPAD9	-6.44	-5.72	-5.57	-0.023*	NS

*Changes significant at 95%; NS not significant relationship at 90% level

In most cases analysed, for all the varieties and locations, the date on which harvest began exhibited a negative correlation with the average mean growing season temperature (TGSM). The change ratios with respect to temperature were always greater (in absolute terms) for Vilafranca than for the other observatories, and were relatively greater at Sant Martí Sarroca than at Sant Sadurní d'Anoia. Similar results were found for the average maximum temperature during the growing season (TGSM_{max}), although in that case the fit was not significant for Parellada at Sant Martí Sarroca. The end harvest date was correlated negatively with the average maximum temperatures at Sant Sadurní d'Anoia and Vilafranca for all three varieties and at Sant Martí Sarroca for Parellada. However, at that observatory, there was a significant correlation between the harvest end date and the average minimum temperature, and in six of the nine cases analysed, the correlation was also significant with the mean growing season temperature. As in the previous case, the change ratios in relation to temperature were greater (in absolute terms) for Vilafranca than for the other two observatories. A significant correlation was also found between the harvest date and the WI. The number of days with $T > 30^{\circ}\text{C}$ was significant only in a few cases (at Sant Sadurní d'Anoia for the three varieties; at Vilafranca for Xarello and Parellada and at Sant Martí Sarroca for Xarello harvest dates). Finally, the date on which a given probable alcoholic degree was reached presented a significant negative correlation with the mean and maximum temperatures and with the WI for almost all cases studied (the exceptions were Xarello and Parellada at Sant Sadurní d'Anoia and Xarello at Vilafranca del Penedès). The greatest change ratios (absolute values) were found for Macabeo and Parellada at Vilafranca del Penedès.

As shown in Table 2, the precipitation recorded in spring between bloom and veraison showed a decreasing trend at all the observatories during the most recent years. However, this trend seems to have had very little influence on harvest dates. Although some relationships were found, pointing to an effect that retarded harvest associated with an increase in precipitation, they were significant only at Sant Martí Sarroca.

Yield variations

Yields varied from year to year. The lowest yields corresponded to the driest and hottest years: years in which the highest water deficits were produced during the growing season. No clear relationships were found between temperature parameters and yield. Significant correlations were found only between yield and WI and ndT30 for Macabeo at two of the study areas (Sant Martí Sarroca and Sant Sadurní d'Anoia), and between yield and T_{max}, WI

and ndT30 for Xarello. The change ratios are shown in Table 5. Nevertheless, a negative impact was observed when an increase in crop evapotranspiration was combined with a decrease in accumulated precipitation during the bloom–veraison period. Negative relationships were observed between yield and the estimated water deficit (crop evapotranspiration minus precipitation) during the bloom–veraison period for the three analysed varieties in the three locations. The relationships were significant at 90% or higher level in five of the nine cases analysed (Table 5). According to the grape variety in question, the change ratio ranged from 20 to 30 kg/ha per millimetre of available water recorded in the period.

Discussion and conclusions

The increase in temperature observed over the last 14 years of the study (1996–2009), which is greater than those seen in the previous decades (1960s–2000s), was in agreement with the changes highlighted in the IPCC (2007) report and in line with those observed by Brunet et al. (2007). These latter authors pointed out that warming was associated with higher rates of change for T_{max} than T_{min} , with a reduction in the number of moderately extreme cold days and extremely cold nights, and an increase in the number of moderately extreme warm days and nights.

For vineyards, the increase in the number of days with high temperatures is particularly relevant. Grape production and quality are sensitive to heat waves, especially at certain growth stages, such as flowering and ripening. Prolonged periods with temperatures above 30°C cause a reduction in photosynthesis and may produce premature veraison, berry abscission and enzyme activation and reduce flavour development (Mullins et al. 1992). At the same time, some metabolic processes and sugar accumulation stop, and other parameters related to colour and aroma may also be affected (Coombe 1987; Schultz 2000). In this respect, the observed increase in the number of days with $T > 30^{\circ}\text{C}$ poses a threat to grape quality as it creates a situation of imbalance at maturity (with respect to sugar content, acidity and phenolic and aromatic ripeness). This may particularly relevant for the study area, in which a balance between sugar content and acidity is required for a quality cava production.

On the other hand, the observed increase in the WI, which was consistent with the temperature increase, placed the vineyard study area in the upper half of Winkler region IV when, until now, it would have been considered within region III (Winkler et al. 1974). If this trend continues, some changes may be required in the grape varieties grown, with the introduction of varieties that are better adapted to the new climatic conditions. In this respect, Duchêne et al. (2010) have emphasised the need to create very late

Table 5 Relationship between grapevine yield and temperature variables and estimated water deficit {crop evapotranspiration [ETc_{BB-V} – precipitation (P_{BB-V})]} recorded during the bloom–veraison period significant at 90% level or higher

Variety location	Change ratio					
	TGSMax (kg/°C) (<i>R</i> ²)	TGSM (kg/°C) (<i>R</i> ²)	TGSMin (kg/°C) (<i>R</i> ²)	WI (kg/DDG) (<i>R</i> ²)	ndT>30°C (kg/ndT>30) (<i>R</i> ²)	ETC-PBV (kg/mm) (<i>R</i> ²)
Macabeo						
Sant Sadurní d'Anoia	NS	NS	NS	NS	–131* 40.1*	–30.9 28.2
Vilafranca del Penedès	NS	NS	NS	NS	NS	NS
Sant Martí Sarroca	NS	NS	–5,107* 40.3	12.7* 45.5	NS	–22.1* 66.0
Xarello						
Sant Sadurní d'Anoia	NS	NS	–1,472* 30.0	NS	NS	NS
Vilafranca del Penedès	NS	NS	NS	NS	–158.8* 46.3	–24.1* 45.5
Sant Martí Sarroca	NS	NS	NS	–14.5* 22.8	NS*	–13.7* 16.8
Parellada						
Sant Sadurní d'Anoia	NS	NS	NS	NS	NS	–23.6* 31.8
Vilafranca del Penedès	NS	NS	NS	NS	NS	NS
Sant Martí Sarroca	NS	NS	NS	NS	NS	NS

*Relationships significant at 95%; NS no significant trend at 90% level

ripening genotypes or genotypes that are able to produce high quality wines when submitted to high temperatures.

In this study, changes in temperature had a clear impact on grape harvests. The mean harvest dates were compared with information relating to the dates on which ripening was reached and the grape harvest started, obtained from the Spanish phenology network (AEMET). This information did not separate dates by varieties, but referred to the same study area, including locations belonging to the Penedès DO. For the period 1943–1989, the date on which ripening was reached and the date on which harvest started did not show any significant trends, with a mean value of about 19 September ± 7 days. In our study, for Parellada, the latest ripening of the most common varieties grown in the area, the mean date for the beginning of harvest was 15 September, with a standard deviation of ± 7 days. The harvest dates of the remaining varieties were always earlier. By considering the average date of the beginning of harvest, we were able to identify a mean date of 7 September, which would represent an advance of about 12 days, on average, over the last 14 years of the study compared with that recorded for the period 1943–1989. These results are consistent with those observed in different viticulture areas around the world, particularly in recent decades (over the last 20–30 years).

In the nearest winemaking areas in NE Spain, Saladié et al. (2007) found grape harvest date trends ranging from –0.63 to –0.53 days per year between 1971 and 2006 for Macabeo. Studies carried out in other European countries have also highlighted harvest date advances associated with temperature increases. In southern France, Ganichot (2002) observed that harvest dates advanced by between 18 and 21 days during the period from 1940 and 2000; and Duchêne and Schneider, (2005) working in Alsace (eastern France) found that the harvest was 2 weeks earlier in 2002 than in 1972, a period during which temperature increased by 1.8°C. Jones and Davis (2000) reported changes in the dates of all the phenological events and in the length of the growing season for Cabernet Sauvignon and Merlot in Bordeaux for the period 1952–1997. However, the harvest date was the only phenological event that displayed a significant advance. Jones and Davis' results point to harvest dates having advanced by almost 13 days comparing the end (1997) and the beginning (1950s) of their study period. Koch et al. (2009) also indicated a trend towards earlier harvest dates during the period 1970–2007 with a 5-day advance every 10 years in Klosterneuburg, and an approximate 3-day advance every 10 years in Vienna. Petgen (2007), working in the Weinbaugebiet Pfalz vineyard area (Germany), found that the ripening of Riesling

advanced by about 20 days from 1970 to 2005, whereas annual average temperatures increased by 1.2°C. Amann (2008) found that the average dates for the beginning of maturation of Pinot Noir in Baden (southwest Germany) advanced by 3 weeks from 1976 to 2006, with a temperature increase of 1.3°C from 1961 to 2007.

Similar results were found in the southern hemisphere. Petrie and Sadras (2008) found that, for Chardonnay, Cabernet Sauvignon and Shiraz grown in Australia, the date of designated maturity advanced at rates of between -0.5 and -3.1 days year⁻¹, and that harvest advanced at a rate of between -0.4 and -2.4 days year⁻¹. Even so, the rate of change in the date of designated maturity was correlated with the rate of change in temperature for Chardonnay and Cabernet Sauvignon, but not for Shiraz.

The trends for harvest dates could also be affected by factors other than those directly relating to climate, such as subjective evaluations of optimum fruit ripening or cellar processing activities. However, the whole growing cycle seems to be affected by climatic considerations. Dalla Marta et al. (2010), working in Tuscany (Italy), confirmed the negative correlation between large scale meteorological information at the onset of the phenological grapevine stages, indicating that climatic warming leads to an advance in all grape phenophases. In particular, they found a negative correlation between harvest dates and May–September temperatures at a geopotential height of 500 hPa. In some coastal areas of California, Nemani et al. (2001) found that the start of the growing season advanced by 18–24 days between 1951 and 1997 and that the average annual temperature corresponding to this area increased by 1.13°C.

The relationship between harvest date and the number of days with maximum critical temperatures for vine development seemed to be less significant. In this respect, however, Jones and Davis (2000) reported a strong negative relationship between the number of days with $T > 25^{\circ}\text{C}$ and 30°C during the bloom interval and the timing of veraison and harvest.

With respect to the influence of temperature on the date at which a given probable alcoholic degree (PAD=9°) was reached, the results obtained were not uniform for all varieties and observatories. The greatest impacts were found at Vilafranca del Penedès for the Parellada and Macabeo varieties, with ratios of up to 12 days per 1°C increase, while for other varieties and locations the advance ranged from 4 to 6 days per 1°C increase. The results obtained followed the same general logic as those observed by Ganichot (2002) in France for the probable alcoholic degree. Ganichot reported an increase of 2° in volume, (from 9.7° to 11.7°) for the 20-year period from 1980 to 2001.

The high variability in precipitation from one year to another makes it difficult to confirm trends, although some

other studies have reported clear decreases in total annual rainfall associated with increases in inter-annual variability (de Luis et al. 2009). In our study, we observed decreasing precipitation trends during spring, affecting the water availability for the crop when water demands are greater. In most of the years analysed, the precipitation recorded during the growing season was often below the evaporative demand; this was particularly true during the ripening period.

Deficit irrigation has been implemented as a potential strategy to help crops withstand mild water stress with little or no accompanying loss of yield, and with the possibility of a positive impact on fruit quality (Chaves et al. 2010). Responses to mild-to-moderate water deficits have been considered in various studies (Padgett-Johnson et al. 2003; Greven et al. 2005; López et al. 2007; Reynolds et al. 2007, amongst others) and their effects on berry development and composition have been shown for different varieties and for different vineyard areas.

The lack of water in our study area made it difficult to implement any type of irrigation system, leaving rainfall as the only source of water. In this respect, variations in both the quality and distribution of rainfall throughout the year may have a significant impact on grape development, particularly in some areas where field mechanisation has contributed to create greater irregularities within the plots with differences in water availability (Ramos and Martínez-Casasnovas 2010). As a result, the reduction in precipitation observed in spring, during the bloom–veraison period, constituted a significant result within our precipitation series with respect to grape development. Uncorrected water stress during this stage of development may result in reduced canopy development and an insufficient leaf area to support fruit development and maturation. This is the season during which the vines should not suffer water restrictions, as water availability between bloom and veraison seems to be critical for crop development. Major water restriction in the first days after bloom may reduce the number of berries per cluster as a result of desiccation. The plant water status from fruit set until veraison thus has a great influence on berry size (Ojeda 2007) and on further yields. The effects of water deficits in that stage are irreversible even though the restriction may be lifted in the subsequent stages of crop development. Peacock (1998) and Tourjee (2004) also commented that water stress during this development stage may reduce the following season's crop potential by affecting bud initiation. The trend found with respect to spring precipitation may constitute an important problem in areas in which irrigation is not allowed due to water scarcity.

No relationship was found between harvest date and precipitation. However, yield correlated positively with precipitation recorded during the boom–veraison period.

The tendency for evapotranspiration to increase and for precipitation to decline during this period, and the observed relationship between yield and estimated water deficit (20–30 kg/ha yield reduction per millimetre of water deficit increase), indicate significant yield reductions. Water availability should therefore be the main concern in the vineyard study area under conditions of climatic change in which, due to reduced water resources, irrigation is not easily implemented. In fact, rainfall is, in most cases, the only water resource available for agricultural needs.

In conclusion, the temperature and precipitation trends observed in the area have a significant impact on grape development and yields. Heat accumulation, estimated by the WI, increases change in the area from a Winkler region III to region IV, and produces an advance of phenology timing. In particular, an advance of harvest dates and the date on which a given probable alcoholic degree was reached for the main varieties used for cava production in this area was found. This advance may have negative impacts on the balance between sugar content and acidity required for the quality cava. If the present trend continues, it will be necessary to adopt new strategies and management practices in order to maintain the quality and production targets of the wine sector in the study area.

Acknowledgements This work was developed in the framework of the research project AGL2009-08353 financed by the Spanish Ministry of Science and Technology. The authors want to thank the farmers and cellars for the information given about their vines, and the AEMET for the related climate and phenology information.

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