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Change in climate and berry composition for grapevine varieties cultivated in the Loire Valley

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ABSTRACT: We analyzed the nature and trends of climate variables and bioclimatic indices for 6 locations situated in the Loire Valley, northwest France, along with the berry composition of the 6 main grapevine varieties cultivated there, from 1960 to 2010. Results show significant increases in mean temperature (by 1.3 to 1.8°C) over the growing season (April to September) throughout the Loire Valley, with maximum temperatures increasing more strongly than minimum temperatures. Temperature variables, such as spring and summer temperatures, the number of days with maximum temperatures >30°C and bioclimatic indices increased significantly. The Huglin Index indicated that the 6 locations in the Loire Valley have shifted from a cool climate to a temperate climate between 1960 and 2010, and increases in growing degree-days were highly correlated with earlier harvest dates. The berry composition of the 6 main white and red grapevine varieties changed significantly, with higher sugar concentrations and lower titratable acidity at harvest. We conclude that these changes in berry composition were significantly influenced by the increases in temperature over the study period.

KEY WORDS: Loire Valley · Climate change · Temperature · Bioclimatic indices · *Vitis vinifera* · Sugar concentration · Titratable acidity

1. INTRODUCTION

Grapevine development and berry composition are significantly related to their physical environment (Branas 1974, Champagnol 1984, Carbonneau et al. 1992, Van Leeuwen et al. 2004, Carey et al. 2008). This strong relationship is displayed in viticultural regions, where wine grapes are grown in unique 'terroirs'. Terroir is a complex concept, which is defined as the combination of the physical environment, climatic parameters, biological factors and cultural practices influencing the quality and typicity of wine (Vaudour 2003, Morlat 2010, OIV 2010). However, studies have shown that weather conditions during the vintage have a greater influence than the other factors on grapevine development and berry composition (Coombe 1987, Van Leeuwen et al. 2004). Today, with the release of the 4th report of the Intergovernmental Panel on Climate Change (IPCC 2007), there is a better understanding and increased certainty about global climate change, raising many questions concerning viticulture and wine quality (Bindi et al. 1996, Jones et al. 2005, Webb et al. 2008, Van Leeuwen et al. 2009). In parallel with significantly increased global surface temperatures (IPCC 2007), the mean temperature in France increased by 0.9°C from 1901 to 2000 (Moisselin et al. 2002). Along with the increases in atmospheric concentrations of carbon dioxide that underlie climate change, a number of other factors are changing, including rates of evapotranspiration, rainfall variability, summer droughts and extreme high-temperature events (such as the summer heat wave that occurred in 2003 in Europe) (IPCC 2007, Brisson & Levrault 2010). The grapevine is responding to these climate changes through advances in the key phenological stages,

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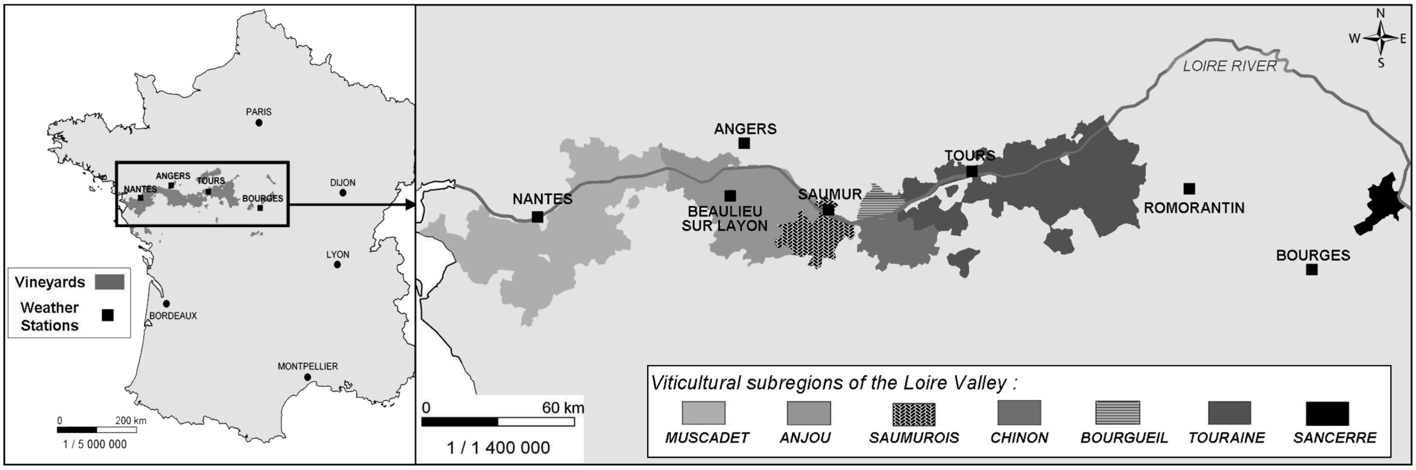

Fig. 1. Loire Valley wine region, situated at 47°N in northwest France, between the viticultural sub regions of Muscadet and Sancerre. Map source: Geoconcept 5.6

such as bud burst, flowering, véraison (also known as 'turning'—the stage of berry colouration) and harvest (Jones & Davis 2000, Ganichot 2002, Ramos et al. 2008, Tomasi et al. 2011). At the same time, grapes are being harvested with lower acidity and higher sugar levels, which is leading to higher alcohol content in wines (Duchêne & Schneider 2005, Barbeau 2007). This study is a contribution to the analysis of climate change in the Loire Valley, France. We analyzed how the character and trends of regional climate during the vine-growing season have changed from 1960 to 2010. Furthermore, changes in berry composition for the 6 principal red and white varieties grown in the Loire Valley were studied, permitting improved understanding of the influence that climate change has had on the viticultural region of the Loire Valley.

2. MATERIALS AND METHODS

2.1. Study region

The Loire Valley wine region, situated at 47° N in the northwest of France, stretches between 1° 33′ W and 2° 50′ E from Nantes to Bourges (Fig. 1). The Loire Valley benefits from an oceanic influence to the west, which decreases towards the interior with a more continental influence to the east. With contrasting climate conditions, along with a rich pedological diversity, 69 different wine producing areas have been established in the Loire Valley region. The French AOP (Appellation d'Origine Protégée) body regulates wine in terms of quality and typicity, where the wine produced should express and have a strong relationship with its unique geographical environment, that is, with its unique 'terroir'. The Loire Valley wine region is the 4th largest viticultural region in France with 70 000 ha of vineyards, and it is the most important AOP white wine producer. It is cultivated with 14 white and red varieties, of which the white varieties represent 55 % of the total surface area. The dominant white varieties are Melon (37 % of total white varieties), Chenin blanc (28 %) and Sauvignon blanc (18 %), whereas the dominant red varieties are Cabernet franc (46 % of total red varieties), Grolleau noir (25 %) and Gamay (15 %). In the Muscadet wine region, Melon dominates the production of dry, light and fresh white wines. From Anjou to Touraine, Cabernet franc, Grolleau noir and Gamay are cultivated for the production of red and rosé wines while Chenin blanc is used for the production of sparkling, dry and liquor wines. Towards the east of the Loire Valley, in Sancerre, Sauvignon blanc is the dominant variety grown to produce dry white wines.

2.2. Climate data

The study was undertaken using the meteorological data from 7 weather stations situated in the Loire Valley (Fig. 1). The temperature and rainfall data were obtained from Météo France for the period of 1960 to 2010 (Table 1), allowing for analysis and characterization of long-term changes in climate. Although these 7 weather stations are not situated within the vineyards, they provide a good indication of the climate structure and trends in each region studied, namely Muscadet, Anjou, Saumurois, Bour-

Table 1. Geographical positions of weather stations and climate data availability at each location. Data source: Météo France

Weather station	Altitude (m)	Location	Period with available climate data: Temperature	Rainfall
Nantes	26	47° 09′ N, 01° 37′ W	1960–2010	1960–2010
Angers	50	47° 29′ N, 00° 37′ W	1960–2010	–
Beaulieu sur Layon	81	47° 19′ N, 00° 36′ W	–	1960–2010
Saumur	69	47° 15′ N, 00° 04′ W	1960–2010	1960–2010
Tours	108	47° 27′ N, 00° 44′ E	1960–2010	1960–2010
Romorantin	83	47° 19′ N, 01° 41′ E	1960–2010	–
Bourges	161	47° 04′ N, 02° 22′ E	1960–2010	1960–2010

geuil, Chinon, Touraine and Sancerre (Fig. 1). For example, the mean growing season temperature (April to September) of Saumur from 1976 to 2010 was significantly correlated ($R^2 = 0.97$, $p < 0.0001$) with the mean growing season temperature of a weather station situated within the vineyards at Montreuil-Bellay, a commune of the AOP Saumur region.

Bonnefoy et al. (2010) studied the homogeneity of the temperature data acquired from these weather stations. They found a significant change point in the maximum temperatures in 1987 for these weather stations using the Pettitt test (Pettitt 1979). However, the minimum temperatures of Nantes and Angers indicated a significant change point in 1980, whereas the minimum temperatures of Tours, Romorantin and Bourges showed a change point in 1987. This significant thermal change point towards the end of the 1980's has also been identified in other viticultural regions in France (Briche et al. 2010, Madelin et al. 2010). Furthermore, it should be noted that the weather station of Tours, which opened in 1959, was repositioned 2 km outside of Tours in 1964. In analyzing the temperature data from Tours, Bonnefoy et al. (2010) identified a decrease in temperature during the 1960s. This decrease in temperature was not experienced by other weather stations in the Loire Valley, and it was concluded that the repositioning of the Tours station caused a discontinuity in the temperature data.

The daily mean, minimum and maximum temperatures were used to calculate several temperature variables and bioclimatic indices. The temperature variables calculated from 1960 to 2010 are

(1) Mean (T_m), minimum (T_n) and maximum (T_x) growing season temperatures (April to September).

(2) Seasonal T_m, T_n and T_x where spring is defined as the period from March to May, summer from June to August, autumn from September to November and winter from December to February (Moisselin et al. 2002).

(3) Number of days with T_x between 25 and 30°C (no. d T_x 25–30°C) and no. d $T_x >$ 30°C. Daytime T_x ranging from 25 to 30°C are critical for optimum grapevine photosynthesis (Carbonneau et al. 1992). However, prolonged days with T_x >30°C will induce plant stress.

The bioclimatic indices assist in defining a viticultural region in relation to its climate: its ability to produce grapes, the varieties that are the best adapted, as well as the precocity and lateness of the phenological stages (Asselin et al. 2001, Tonietto & Carbonneau 2004). The bioclimatic indices calculated from the temperature data from 1960 to 2010 were

(1) The growing degree-days index (GDD), which is calculated as the sum of the daily mean temperatures >10°C for the period April to October in the Northern Hemisphere (Table 2). The calculation uses a thermal base temperature of 10°C, which is the minimum temperature necessary for grapevine physiological activity (Winkler et al. 1974). The interest in the GDD is that many studies have shown that the cumulated heat was significantly correlated with the phenological stages of the vine such as flowering, véraison and harvest (Tesic 2001, Van Leeuwen et al. 2008). However, the GDD index does not take into account an adjustment for the increasing day lengths at higher latitudes and as a result, it will underestimate the grape-producing potential of viticultural regions such as the Loire Valley (Tonietto & Carbonneau 2004). The GDD index is divided into 7 climate classes: the 5 climate classes (Region I-V) originally determined by Winkler et al. (1974), and the upper and lower climate categories identified by Jones et al. (2010) (Table 2).

(2) The Huglin Index (HI) differs from the GDD index, as it is the sum of the T_m and T_x temperatures >10°C from April to September in the Northern Hemisphere (Table 2; Huglin 1978). The HI gives greater weight to the maximum or daytime temperatures, which is when most vine development takes place (Jackson 2008). The calculation takes into account a coefficient of the latitude (k), which is 1.05 for the Loire Valley, permitting the HI to be better correlated with vine growth and sugar concentration in the berries (Huglin 1978, Tonietto & Carbonneau 2004). The HI is divided into 8 climate classes (Table 2).

(3) The cool night index (CI) is calculated as the average minimum temperature during the ripening month, which is September in the Northern Hemi-

Table 2. Characteristics of 2 bioclimatic indices, growing degree-days (GDD) and Huglin Index (HI), calculated for each weather station. Equations: daily maximum (T_x), minimum (T_n) and mean (T_m) temperatures; k = coefficient of latitude

	Calculated period	Class of viticultural climate
GDD[a]		
$\sum_{01.04}^{31.10} GDD = \max[(T_x + T_n)/2 - 10°C, 0]$	1 Apr–31 Oct	Too hot > 2700 Region V = 2222–2700 Region IV = 1944–2222 Region III = 1667–1944 Region II = 1389–1667 Region I = 850–1389 Too cool < 850
HI[b]		
$\sum_{01.04}^{30.09} HI = \max[(T_m - 10°C) + (T_x - 10°C)/2, 0]k$ where k = 1.05 for the Loire Valley	1 Apr–30 Sep	Too hot > 30000 Very warm = 2700–3000 Warm = 2400–2700 Warm temperate = 2100–2400 Temperate = 1800–2100 Cool = 1500–1800 Very cool = 1200–1500 Too cool < 1200

[a]Consists of 7 identified viticultural climate class categories as defined by Winkler et al. (1974) and Jones et al. (2010)
[b]Consists of 8 identified viticultural climate class categories as defined by Tonietto & Carbonneau (2004) and Jones et al. (2010)

sphere (Tonietto 1999). The CI is divided into 4 climate classes: warm (>18°C), temperate (14–18°C), cool (12–14°C) and very cool (<12°C) (Tonietto 1999). It permits the evaluation of the important effects of night or minimum temperatures on the synthesis of secondary metabolites in grapes, such as anthocyanins and grape aromas (Tonietto & Carbonneau 2004). As harvest dates have advanced significantly, the climate conditions during August are also likely to influence the synthesis of various secondary metabolites in grapes. For the purposes of our study, we calculated the CI as the mean daily minimum temperature from 15 August to the end of September, given that harvest dates have advanced by 2 wk (Ganichot 2002, Barbeau 2007).

(4) Diurnal temperature range (DTR) is calculated as the mean thermal variation between the maximum day temperature and the minimum night temperature during the ripening period, from August to September. Studies have illustrated that the thermal amplitude during ripening has a significant influence on berry composition and wine quality (Coombe 1987, Carbonneau et al. 1992, Ribéreau-Gayon et al. 2006, Ramos et al. 2008).

The monthly rainfall data acquired from the 5 weather stations were used to calculate the total rainfall amounts over 3 selected periods from 1960 to 2010 (Table 1). The 3 periods corresponded to the total rainfall from January to September, from April to September (growing season) and from June to August (summer). Daily rainfall data were only obtained for 1 weather station, namely Beaulieu sur Layon. From these data, 2 additional rainfall indices were obtained, for the period from 1960 to 2010:

(1) The dry-spell-mean index, which is the number of days where rainfall is <1 mm (Moisselin & Dubuisson 2006).

(2) The number of days with heavy rainfall, which is when rainfall is ≥10 mm (Moisselin & Dubuisson 2006).

These 2 indices were calculated for 2 selected periods, from April to September (growing season) and from June to August (summer).

2.3. Berry composition data

The 6 principal red and white varieties grown in the Loire Valley wine region were studied, namely Melon, Chenin blanc, Sauvignon blanc, Cabernet franc, Gamay and Grolleau noir. Berry composition data were available for the last 30 yr (1981 to 2010). However, for Cabernet franc grown in the regions of Chinon and Bourgueil, data were available from 1970. The composition data corresponded to measurements of sugar and titratable acidity contents in berries, on a weekly basis from véraison until harvest. These 2 berry components are key parameters influencing the quality and ripeness of grapes at harvest (Jackson 2008). Furthermore, the levels of sugar and titratable acidity are greatly influenced by climatic conditions (Van Leeuwen et al. 2004, Ribéreau-Gayon et al. 2006, Carey et al. 2008), allowing us to analyze the effect of climate change on viticulture in the Loire Valley.

We therefore assessed the concentrations of sugar and titratable acidity, which were measured during the last analysis made prior to harvest. For the period studied, the same reference vineyard plots were studied. Therefore 20 plots of Melon, 19 plots of Chenin blanc, 6 plots of Sauvignon blanc, 24 plots of Cabernet franc, 9 plots of Grolleau noir and 11 plots of Gamay allowed us to generate a representative set of data. From these reference vineyard plots, the berry composition data obtained on the date of the last analysis made prior to harvest were averaged, to obtain a single value for each variety, vintage and region. We recognize that the harvest date is not an accurate phenological stage and that the notion of determining maturity depends on important factors such as the style of wine wanted by the winemaker (Garcia de Cortazar-Atauri et al. 2010), which will influence berry composition. Lastly, the harvest dates studied corresponded to the date when the last berry composition analysis was made prior to harvest, and we assessed the trend in harvest dates for the 6 different varieties.

The above-mentioned climate variables, bioclimatic indices and berry composition data were analyzed using basic descriptive statistics to obtain the mean and standard deviation values of each parameter studied. Each parameter was plotted against a timescale in yr and a trend was determined. To evaluate the statistical significance of each observed trend, the p-value was determined using simple linear regression: using the Fisher's test with a 95% significance level. The non-parametric Friedman's test was also applied to identify whether there was a significant difference in the climate characteristics and trends between the weather stations. The p-value calculated by the Friedman's test allows one to reject the hypothesis that there is no significant difference between the weather stations. Finally, to study the influence that the changes in temperature had on berry composition, multiple linear regression was used to relate the berry composition (dependent) variables to the temperature and bioclimatic (independent) variables. However, an assessment was first made of the degree of co-linearity of each independent variable. It was argued that severe co-linearity existed when a temperature or bioclimatic variable had a tolerance value <0.1 and a variance inflation factor (VIF) value >10 (Quinn & Keough 2002). The number of temperature and bioclimatic variables was therefore reduced using stepwise removal until all remaining variables, namely the GDD, CI, DTR, spring T_m and no. d T_x 25–30°C, had a tolerance value >0.2 and a VIF value <4.

Table 3. Descriptive statistics of the mean (T_m), minimum (T_n) and maximum (T_x) temperatures of the Loire Valley during the growing season (April–September), from 1960–2010. All trends significant at the 95% level ($p < 0.05$). Data source: Météo France

Temperature	Mean (°C)	SD (°C)	Trend (yr^{-1})	Total trend	R^2	p
T_m	16.1	0.8	+0.03	+1.6	0.34	<0.0001
T_n	10.6	0.7	+0.03	+1.3	0.32	<0.0001
T_x	21.6	1.1	+0.04	+2.0	0.29	<0.0001

3. RESULTS AND DISCUSSION

3.1. Climatic characteristics and trends

3.1.1. Temperature variables

The daily T_m of the Loire Valley during the growing season (April to September) was 16.1°C for the period 1960 to 2010 (Table 3). Over this period, T_m, T_n and T_x of the Loire Valley have significantly increased (Fig. 2).

The daily mean temperature increased by 1.6°C, with T_n of the Loire Valley increasing by 1.3°C and T_x by 2.0°C. As a result, the increase in mean temperature during the growing season in the Loire Valley has been driven by a faster rate of change in T_x. Similar results where the T_x increased more significantly have been shown in the viticultural region of Priorat, Spain (Ramos et al. 2008). The 6 weather stations illustrated the same tendency with daily temperatures increasing significantly during the grow-

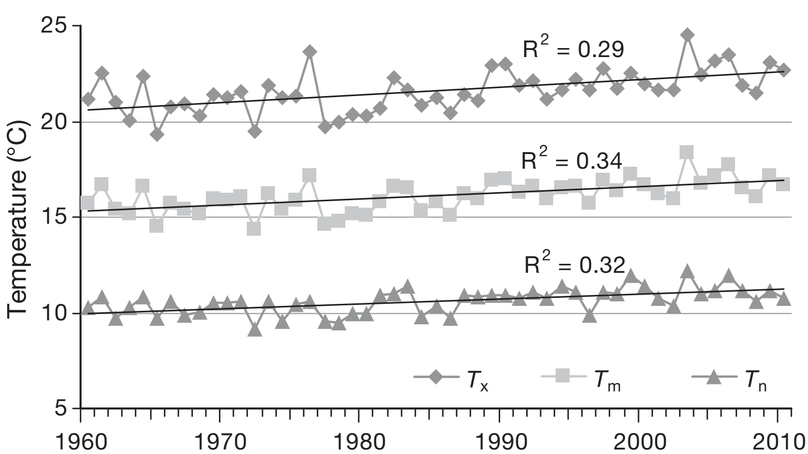

Fig. 2. Linear trends of daily mean (T_m), minimum (T_n) and maximum (T_x) temperatures in the Loire Valley wine region during the growing season (April–September) from 1960 to 2010. Average for 6 weather stations (Nantes, Angers, Saumur, Tours, Romorantin and Bourges). Data source: Météo France

Table 4. Descriptive statistics of the daily mean (T_m), minimum (T_n) and maximum (T_x) temperatures during the growing season (April–September) for 6 weather stations situated in the Loire Valley, from 1960–2010. All trends significant at the 95% level (p < 0.05). Data source: Météo France

	Mean (°C)	SD (°C)	Trend (yr^{-1})	Total trend	R^2	p
***T*$_m$**						
Nantes	16.2	0.8	+0.03	+1.4	0.24	<0.001
Angers	16.1	0.9	+0.04	+1.8	0.38	<0.0001
Saumur	16.7	0.9	+0.04	+1.8	0.35	<0.0001
Tours	15.9	0.9	+0.03	+1.7	0.34	<0.0001
Romorantin	15.5	0.9	+0.03	+1.3	0.25	<0.001
Bourges	16.1	0.9	+0.04	+1.8	0.36	<0.0001
***T*$_n$**						
Nantes	11.2	0.7	+0.02	+1.1	0.23	<0.001
Angers	10.9	0.7	+0.03	+1.5	0.42	<0.0001
Saumur	11.2	0.7	+0.02	+1.2	0.29	<0.0001
Tours	10.6	0.7	+0.03	+1.4	0.31	<0.0001
Romorantin	9.0	0.7	+0.01	+0.6	0.08	0.049
Bourges	10.7	0.8	+0.03	+1.7	0.40	<0.0001
***T*$_x$**						
Nantes	21.2	1.1	+0.03	+1.6	0.20	0.001
Angers	21.4	1.1	+0.04	+2.0	0.29	<0.0001
Saumur	22.3	1.3	+0.05	+2.4	0.32	<0.0001
Tours	21.2	1.1	+0.04	+2.0	0.29	<0.0001
Romorantin	21.9	1.1	+0.04	+2.0	0.28	<0.0001
Bourges	21.5	1.1	+0.04	+2.0	0.28	<0.0001

ing season (April to September) from 1960 to 2010 (Table 4). In all 6 locations, T_m trends have also been influenced by the more significant changes in T_x. Over this study period, Saumur had the warmest daily T_m of 16.7°C (Table 4).

Given the change point in temperature, identified for the Loire Valley as during the 1980s (Bonnefoy et al. 2010), it is observed, for example, that the daily mean temperature of Saumur during the growing season increased from 16.2°C before the change point (1987) to 17.4°C after the change point. At Bourges, it has meant that the mean temperature evolved from 15.6°C before the change point (1960–1986) to 16.7°C after the change point (1987–2010). Furthermore, an even more significant increase in temperature was observed at all 6 locations during the last 20 yr (results not shown). For example, 7 of the 10 warmest years recorded at Saumur during the growing season from 1960 to 2010 occurred during the past 15 yr. Consequently, for Saumur the last decade (2000–2009) was the warmest over the whole period of 1960 to 2010, with a T_m of 17.6°C.

The rate of warming has also not been consistent between the 6 locations. The mean daily temperature increased by 1.4°C in Nantes, 1.8°C in Angers, 1.8°C in Saumur, 1.7°C in Tours, 1.3°C in Romorantin and 1.8°C in Bourges between 1960 and 2010 (Table 4). Friedman's test showed that the changes in T_n and T_x are significantly different between stations. The changes in T_n at Nantes and Saumur are significantly different from those of Tours, Romorantin and Bourges (p < 0.0001), while T_x at Saumur and Romorantin are significantly different from T_x at Nantes, Angers and Tours (p < 0.0001). Bonnefoy et al. (2010) explained that these variations in temperature observed within the Loire Valley are due to factors such as the distance of the weather stations from the Atlantic Ocean or the Loire River, their latitudinal position and the influence of topography on the local area. As studies have illustrated for other viticultural regions in France (Laget et al. 2008, Madelin et al. 2010), the rate of warming has also not been uniform over the period from 1960 to 2010

Because of variability of air temperature during the year and the growing season, seasonal mean temperatures were calculated. Spring and especially summer T_m increased significantly at all 6 locations (Table 5), in comparison with winter and autumn temperatures that did not significantly increase at all sites (results not shown). The rate of warming during spring increased the greatest at Saumur, by 1.8°C, whereas the greatest increase during the summer of 2.4°C occurred at Bourges (Table 5).

The rate of warming during the spring and summer was also influenced by greater increases in maximum temperatures (results not shown). Results

Table 5. Descriptive statistics of spring and summer daily mean temperatures (T_m) during the growing season (April–September) for 6 weather stations situated in the Loire Valley, from 1960–2010. All trends significant at the 95% level (p < 0.05). Data source: Météo France

	Mean (°C)	SD (°C)	Trend (yr^{-1})	Total trend	R^2	p
Spring *T*$_m$						
Nantes	11.1	0.9	+0.03	+1.4	0.24	<0.001
Angers	10.9	0.9	+0.02	+1.7	0.20	<0.001
Saumur	11.4	1.0	+0.04	+1.8	0.32	<0.0001
Tours	10.5	0.9	+0.03	+1.6	0.26	<0.001
Romorantin	10.2	0.9	+0.02	+1.2	0.19	0.002
Bourges	10.5	1.0	+0.03	+1.7	0.27	<0.001
Summer *T*$_m$						
Nantes	18.5	1.1	+0.03	+1.6	0.17	0.003
Angers	18.5	1.2	+0.03	+2.1	0.28	<0.0001
Saumur	19.3	1.2	+0.04	+2.1	0.28	<0.0001
Tours	18.5	1.1	+0.04	+2.1	0.30	<0.0001
Romorantin	18.0	1.0	+0.04	+1.8	0.28	<0.0001
Bourges	18.8	1.2	+0.05	+2.4	0.36	<0.0001

showed therefore that the most significant warming has taken place during the growing season and especially during the period between flowering and véraison (summer period). Jones & Davis (2000) showed that for 2 red grape varieties, the temperature in Bordeaux during the period between flowering and véraison has a significant influence on berry composition. It is therefore likely that these major increases in temperature during the summer in the Loire Valley will also have important influences on berry composition and hence on wine quality in the region.

Given the significant increases in T_x during the growing season, the T_x 25–30°C and no. d $T_x > 30°C$ during the growing season have also significantly increased at all 6 locations between 1960 and 2010 (Table 6).

During the summer, daytime T_x ranging from 25 to 30°C is critical for optimum grapevine photosynthesis (Carbonneau et al. 1992). Consequently, a higher number of days with optimum temperatures during the growing season will favor grapevine development and the sugar concentration in grapes, as sugar accumulation is related to the photosynthetic activity of the vine during maturation (Jackson 2008). However, prolonged days with maximum temperatures >30°C will induce plant stress and result in a decrease in the photosynthetic activity, while at 40°C photosynthesis is completely inhibited (Ribéreau-Gayon et al. 2006, Jackson 2008).

Table 6. Descriptive statistics of no. of days with maximum temperatures between 25–30°C and with $T_x > 30°C$ during the growing season (April–September) for 6 weather stations situated in the Loire Valley, from 1960–2010. All trends significant at the 95% level ($p < 0.05$). Data source: Météo France

	Mean (°C)	SD (°C)	Trend (yr^{-1})	Total trend	R^2	p
25–30°C						
Nantes	31.5	11.3	+0.21	+10.5	0.08	0.048
Angers	35.2	10.8	+0.23	+11.5	0.10	0.023
Saumur	45.6	11.1	+0.27	+13.5	0.13	0.008
Tours	35.2	10.2	+0.31	+15.5	0.20	0.001
Romorantin	40.5	10.5	+0.29	+14.5	0.16	0.003
Bourges	38.4	9.4	+0.30	+15.0	0.22	<0.001
>30°C						
Nantes	8.1	6.4	+0.16	+8.0	0.14	0.008
Angers	9.8	7.6	+0.19	+9.5	0.21	<0.001
Saumur	13.7	9.5	+0.34	+17.0	0.28	<0.0001
Tours	9.4	7.4	+0.18	+9.0	0.13	0.008
Romorantin	12.5	8.1	+0.24	+12.0	0.19	0.001
Bourges	12.4	7.7	+0.19	+9.5	0.13	0.008

3.1.2. Bioclimatic indices

Growing degree-days index (*GDD*). The GDD has significantly increased at all 6 locations in the Loire Valley, with Saumur displaying the greatest increase of 360 GDD, from 1960 to 2010 (Table 7). These increases in GDD imply that all 6 locations have evolved from Region I to II, except for Romorantin, which remained in Region I (Table 2).

Studies have illustrated that the GDD values were well correlated with the phenological stages of the vine (Tesic 2001, Van Leeuwen et al. 2008). Higher values in GDD will therefore likely lead to earlier flowering, véraison and harvest dates. Our results illustrated that the trend in GDD for Saumur and Tours was significantly correlated with earlier harvest dates for Cabernet franc, cultivated in the regions of Chinon and Bourgueil and for Chenin blanc, cultivated in the region of Touraine, from 1970 to 2010 (Table 8).

In the Chinon and Bourgueil regions, the harvest date for Cabernet franc advanced significantly by 15 and 16 d respectively, whereas the harvest date for Chenin blanc advanced by 16 d at Touraine (Table 9). As shown in other studies in France, we

Table 7. Descriptive statistics of the growing degree-days index (GDD) for 6 weather stations situated in the Loire Valley, from 1960–2010. All trends significant at the 95% level ($p < 0.05$)

Station	Mean GDD	SD	Trend (yr^{-1})	Total trend	R^2	p
Nantes	1270	161	+5.36	+268	0.25	<0.001
Angers	1258	165	+6.91	+345	0.39	<0.0001
Saumur	1367	177	+7.20	+360	0.36	<0.0001
Tours	1221	160	+6.47	+324	0.36	<0.0001
Romorantin	1129	144	+5.01	+251	0.27	<0.0001
Bourges	1255	168	+7.02	+351	0.39	<0.0001

Table 8. Correlations between growing degree-days (GDD) at Saumur and Tours and the near-harvest dates of Chenin Blanc cultivated in the region of Touraine, and Cabernet Franc cultivated in the regions of Chinon and Bourgueil, from 1970–2010. All trends significant at the 95% level ($p < 0.05$)

Region	Grape variety (number of plots)	Correlation GDD Saumur	Correlation GDD Tours
Touraine	Chenin blanc (2)	−0.76	−0.77
Bourgueil	Cabernet franc (5)	−0.80	−0.77
Chinon	Cabernet franc (5)	−0.83	−0.81

Table 9. Descriptive statistics of the harvest dates of Chenin blanc cultivated in the region of Touraine and Cabernet franc cultivated in the regions of Chinon and Bourgueil, from 1970–2010. All trends significant at the 95% level ($p < 0.05$). Data source: Laboratoire de Touraine

Region	Variety (number of plots)	Mean (date)	SD (d)	Trend yr^{-1}	Total trend	R^2	p
Touraine	Chenin blanc (2)	30 Sep	9	−0.42	−16.6	0.34	<0.0001
Bourgueil	Cabernet franc (5)	29 Sep	9	−0.41	−16.4	0.30	0.001
Chinon	Cabernet franc (5)	2 Oct	9	−0.38	−15.0	0.27	0.001

observed similarly that harvest dates have advanced in general by 2 wk over this study period (Ganichot 2002, Duchêne & Schneider 2005, Barbeau 2007).

Given earlier harvest dates, the ripening period now occurs in a warmer period of the year. Warmer conditions during the ripening period will have a significant influence on the composition of the grapes, normally resulting in higher levels of sugar and lower titratable acidity concentrations (Coombe 1987). The Loire Valley is a high northern latitude region, where the vine growing cycle is generally short, from April to September. Barbeau et al. (1998) illustrated the importance of an early grapevine vegetative cycle and of harvest date, which ensures good maturation of grapes in the Loire Valley. The increases in GDD within the Loire Valley will lead to earlier phenological stages that will allow varieties to reach an optimum maturity, especially late ripening varieties such as Cabernet franc and Cabernet Sauvignon. Warmer temperatures will therefore favour grapevine growing in the Loire Valley and will influence the berry composition. Earlier phenological stages will allow these late ripening varieties to accumulate greater amounts of sugar, and to have optimum titratable acidity concentrations and more ripened berry flavors (Barbeau 2007). However, early ripening varieties, such as Gamay or Melon, will ripen in warmer than ideal environmental conditions. This will likely lead to phenological stages appearing too early, causing sugars to accumulate too soon, leading to a rapid decrease in titratable acidity given the effect of high temperatures on the rate of respiration and influencing the synthesis of berry flavors (Coombe 1987, Ribéreau-Gayon et al. 2006).

The Huglin Index (*HI*). The HI has significantly increased from 1960 to 2010 at all 6 locations (Table 10). These significant increases in the HI mean that all 6 locations have shifted from a cool climate, which used to characterize the Loire Valley, to a temperate climate (Table 2), which characterizes the traditional Bordeaux wine-growing region (Tonietto & Carbonneau 2004).

Fig. 3 shows the significantly increasing trend of the HI at Saumur. Over the past decade, the HI of certain years at Saumur, such as in 2003, were even situated in a warm temperate climate, which is equivalent to the climate of Montpellier, South of France, 30 yr ago (Vaudour 2003, Tonietto & Carbonneau 2004). Warmer climate categories such as a temperate climate will enable varieties such as Cabernet Sauvignon and Merlot to reach optimum maturity, whereas a warm temperate climate category will enable varieties that are not currently grown in the Loire Valley, such as Syrah and Grenache, to reach maturity (Tonietto & Carbonneau 2004).

The 2003 vintage was characterized by a warm temperate climate at Saumur enabling, during this season, 2 late ripening red varieties to reach maturity. They were Syrah, which is typically grown in the south of France, and Tempranillo, which is traditionally cultivated in Spain. INRA Angers grow these 2 varieties in experimental plots that are situated at Montreuil Bellay. The Syrah grapes were harvested

Table 10. Descriptive statistics of the Huglin Index (HI) for 6 weather stations situated in the Loire Valley, from 1960–2010. All trends significant at the 95% level ($p < 0.05$). Data source: Météo France

Station	Mean HI	SD	Trend (yr^{-1})	Total trend	R^2	p
Nantes	1680	180	+5.63	+282	0.22	0.001
Angers	1698	185	+7.12	+356	0.33	<0.0001
Saumur	1840	205	+7.96	+398	0.33	<0.0001
Tours	1666	181	+6.79	+340	0.31	<0.0001
Romorantin	1681	176	+6.18	+309	0.27	<0.0001
Bourges	1712	187	+7.11	+356	0.32	<0.0001

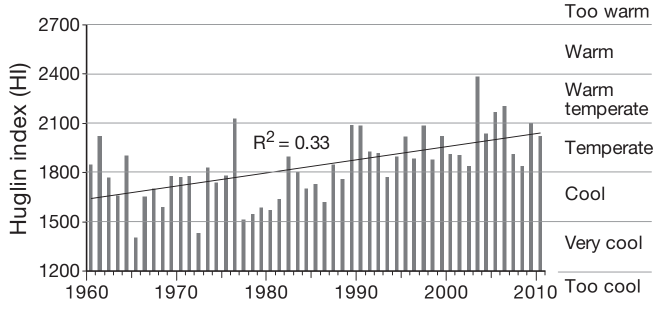

Fig. 3. Linear trend of the Huglin Index (HI) at Saumur from 1960 to 2010. Data source: Météo France

at a sugar concentration of 205 g l^{-1} (12.2° potential alcohol) and a titratable acidity of 4.1 g l^{-1}. The Tempranillo grapes had a sugar concentration of 192 g l^{-1} (11.4° potential alcohol) and a titratable acidity of 3.5 g l^{-1} (G. Barbeau pers. com.). Therefore, as temperatures are predicted to increase during the 21st century in France (Brisson & Levrault 2010), late ripening grape varieties will likely be able to reach maturity, as already observed in 2003.

Cool night index (*CI*). The CI has significantly increased at Angers and Bourges from 1960 to 2010 (Table 11). It increased by 0.9°C at Angers and by 1.1°C at Bourges, which means that for both sites the CI evolved from very cool nights (<12°C) to cool nights (12 to 14°C). In general, warm night temperatures during ripening have the tendency to lead to a loss in aromas, and in red varieties, to a loss in grape color (Carey et al. 2008, Jackson 2008). However, for the Loire Valley, we observed that night conditions were still relatively cool and that minimum temperatures during ripening have not increased as much as maximum temperatures.

Diurnal temperature range (*DTR*). The diurnal temperature range during the ripening period (August to September) displayed significant increases over the study period. It increased by 1.0°C at Nantes, 1.5°C at Saumur and by 1.7°C at Romorantin from 1960 to 2010 (Table 12). These significant increases in DTR are due to maximum temperatures increasing more significantly than minimum temperatures during the ripening period (results not shown). Studies have illustrated that the thermal amplitude during ripening has significant effects on the accumulation of berry components (Coombe 1987, Carbonneau et al. 1992, Ribéreau-Gayon et al. 2006). These studies showed that the synthesis of anthocyanins is favored by a strong difference between the diurnal and nocturnal temperatures. Ramos et al. (2008) illustrated that greater DTR values were correlated with higher quality red wine. The greater DTR values shown for Saumur, where Cabernet franc is mainly grown, will be favorable for the production of quality red wine.

Table 11. Descriptive statistics of the cool night index (CI) for 6 weather stations situated in the Loire Valley, from 1960 to 2010 (15 August–30 September). **Bold:** significant trends at 95% level ($p < 0.05$). Data source: Météo France

Station	Mean CI (°C)	SD (°C)	Trend (yr^{-1})	Total trend	R^2	p
Nantes	12.4	1.0	+0.01	+0.6	0.03	0.241
Angers	12.0	1.0	**+0.02**	**+0.9**	0.08	**0.048**
Saumur	12.1	1.1	+0.01	+0.6	0.03	0.268
Tours	11.7	1.0	+0.02	+0.8	0.05	0.117
Romorantin	9.6	1.2	0.00	0.0	0.00	0.780
Bourges	11.8	1.0	**+0.02**	**+1.1**	0.10	**0.026**

Table 12. Descriptive statistics of the diurnal Temperature Range (DTR) for 6 weather stations situated in the Loire Valley, from 1960–2010 (August–September). **Bold:** significant trends at 95% level ($p < 0.05$). Data source: Météo France

Station	Mean DTR (°C)	SD (°C)	Trend (yr^{-1})	Total trend	R^2	p
Nantes	10.4	1.0	**+0.02**	**+1.0**	0.09	**0.032**
Angers	10.9	1.0	0.00	0.0	0.02	0.244
Saumur	11.5	1.1	**+0.03**	**+1.5**	0.17	**0.003**
Tours	11.0	1.0	+0.02	+0.9	0.06	0.074
Romorantin	13.5	1.5	**+0.03**	**+1.7**	0.11	**0.018**
Bourges	11.1	1.1	0.00	0.0	0.00	0.755

3.1.3. Rainfall variables

During the growing season, it is observed that Beaulieu sur Layon had the lowest mean rainfall with 262.1 mm from 1960 to 2010, whereas Bourges had the highest with 375.2 mm (Table 13). In all 5 locations, no significant evolution in rainfall was observed for the 3 seasonal periods studied, namely

Table 13. Statistics of mean rainfall during 3 seasonal periods (Jan–Sep, Apr–Sep: growing season, and Jun–Aug: summer) studied for 5 weather stations in the Loire Valley from 1960–2010. Data source: Météo France

	Mean (mm)	SD (mm)	Trend (yr^{-1})	Total trend	R^2	p
Jan–Sep						
Nantes	537.7	106.9	−0.11	−5.5	0.00	0.915
Beaulieu sur Layon	419.0	93.0	−0.10	−5.0	0.00	0.907
Saumur	411.5	78.8	+0.77	+38.5	0.02	0.311
Tours	487.6	103.0	−0.43	−21.5	0.00	0.662
Bourges	544.9	107.3	−0.05	−2.5	0.00	0.963
Apr–Sep						
Nantes	319.6	80.5	0.00	0.0	0.00	0.993
Beaulieu sur Layon	262.1	80.4	−0.20	−10.0	0.00	0.805
Saumur	265.4	68.9	+0.51	+25.5	0.01	0.441
Tours	313.1	82.4	−0.45	−22.5	0.01	0.572
Bourges	375.2	83.6	+0.48	−24.0	0.01	0.554
Jun–Aug						
Nantes	136.8	49.7	−0.16	−8.0	0.00	0.732
Beaulieu sur Layon	117.3	55.7	−0.40	−20.0	0.01	0.466
Saumur	118.6	42.7	0.00	0.0	0.00	0.993
Tours	143.7	60.2	−0.31	−15.5	0.01	0.591
Bourges	177.7	62.5	+0.45	−22.5	0.01	0.458

from January to September, April to September (growing season) and from June to August (summer). However, we noted a high variability from year to year, which could be the reason for no significant evolution. The 2 rainfall indices calculated from the daily rainfall data at Beaulieu sur Layon showed no significant trend from 1960 to 2010 (results not shown). Therefore, the number of days where the rainfall was <1 mm and where it was ≥10 mm have not changed over the 2 periods studied (the growing season and summer periods). According to our results, we observed that the rainfall has not changed significantly in all 5 locations from 1960 to 2010.

3.2. Evolution of berry composition

The 6 main white and red varieties cultivated in the Loire Valley have shown a significant change in their berry composition (Table 14). Each variety displayed an increase in sugar concentration and a decrease in titratable acidity, except the titratable acidity concentration of Melon, grown in the Muscadet region, and Sauvignon blanc, grown in the Anjou region, which did not change significantly.

For Chenin blanc, the concentration of sugar increased by 38.2, 38.0 and 39.4 g l^{-1} in Anjou, Saumurois and Touraine, respectively, from 1981 to

Table 14. Descriptive statistics of the concentrations of sugar and titratable acidity for the 3 principal red and white grape varieties cultivated in the Loire Valley. **Bold:** statistically significant trends at 95% level ($p < 0.05$). Data sources—white: CA 44, ATV 49, Laboratoire de Touraine 37, SICAVAC 18; red: ATV 49, Laboratoire de Touraine 37

Grape variety	Region	No. of plots	Mean (g l^{-1})	SD (g l^{-1})	Trend (yr^{-1})	Total trend	R^2	p
Sugar								
White								
Melon	Muscadet	20[f]	174.9	14.8	**+1.05**	**+24.1**	0.25	**0.013**
Chenin blanc	Anjou	8[e]	197.2	18.7	**+1.32**	**+38.2**	0.39	**<0.001**
	Saumurois	2[e]	187.4	18.4	**+1.31**	**+38.2**	0.40	**<0.001**
	Touraine	9[b]	192.7	20.9	**+1.55**	**+48.1**	0.49	**<0.0001**
Sauvignon blanc	Anjou	2[e]	188.1	16.2	**+1.18**	**+38.9**	0.41	**<0.001**
	Touraine	3[e]	188.2	22.6	**+2.01**	**+58.3**	0.62	**<0.0001**
	Sancerre	1[c]	200.0	21.1	**+1.57**	**+45.6**	0.43	**<0.0001**
Red								
Gamay	Anjou	6[e]	184.0	14.7	**+0.87**	**+25.0**	0.27	**0.003**
	Touraine	5[d]	189.7	18.7	**+1.57**	**+47.2**	0.59	**<0.0001**
Grolleau noir	Anjou	5[e]	168.1	16.4	**+1.26**	**+36.5**	0.46	**<0.0001**
	Touraine	4[d]	171.2	21.6	**+1.78**	**+53.5**	0.56	**<0.0001**
Cabernet franc	Anjou	10[e]	184.3	19.6	**+1.61**	**+46.6**	0.52	**<0.0001**
	Saumurois	4[e]	186.9	20.8	**+1.88**	**+54.4**	0.63	**<0.0001**
	Bourgueil	5[a]	185.7	17.6	**+1.03**	**+41.0**	0.49	**<0.0001**
	Chinon	5[a]	187.4	20.4	**+1.30**	**+51.8**	0.58	**<0.0001**
Titratable acidity								
White								
Melon	Muscadet	20[f]	5.9	0.9	–0.03	–0.7	0.05	0.312
Chenin blanc	Anjou	8[e]	6.5	1.2	**–0.07**	**–2.0**	0.27	**0.003**
	Saumurois	2[e]	7.0	1.4	**–0.10**	**–3.1**	0.41	**<0.001**
	Touraine	9[b]	6.4	1.7	**–1.12**	**–3.7**	0.45	**<0.0001**
Sauvignon blanc	Anjou	2[e]	5.8	0.9	–0.03	–1.0	0.09	0.113
	Touraine	3[e]	6.0	1.4	**–0.10**	**–2.8**	0.39	**<0.001**
	Sancerre	1[c]	6.1	1.1	**–0.06**	**–2.7**	0.25	**0.005**
Red								
Gamay	Anjou	6[e]	6.1	1.2	**–0.04**	**–1.2**	0.23	**0.007**
	Touraine	5[d]	6.2	0.9	**–0.08**	**–2.4**	0.57	**<0.0001**
Grolleau noir	Anjou	5[e]	6.1	1.2	**–0.07**	**–2.0**	0.26	**0.004**
	Touraine	4[d]	5.7	1.5	**–0.12**	**–3.5**	0.50	**<0.0001**
Cabernet franc	Anjou	10[e]	6.0	1.2	**–0.08**	**–2.2**	0.33	**0.001**
	Saumurois	4[e]	5.7	1.0	**–0.07**	**–2.0**	0.36	**<0.001**
	Bourgueil	5[a]	5.5	1.4	**–0.07**	**–2.8**	0.37	**<0.0001**
	Chinon	5[a]	5.4	1.2	**–0.07**	**–2.7**	0.42	**<0.0001**

[a]1970–2010; [b]1979–2010; [c]1980–2009; [d]1980–2010; [e]1981–2010; [f]1986–2009

2010, while its titratable acidity decreased by 2.0, 3.0 and 3.1 g l^{-1} respectively. For Cabernet franc, the concentration of sugar increased by 46.6, 54.4, 41.6 and 42.5 g l^{-1} in Anjou, Saumurois, Chinon and Bourgueil, respectively, from 1981 to 2010, and its concentration of titratable acidity decreased by 2.2, 2.0, 1.9 and 2.6 g l^{-1}, respectively. Accordingly, greater sugar levels mean that the potential alcohol level of grapes at harvest has increased. For example, the potential alcohol level increased by 2.3° for Chenin blanc grown in Anjou, from 10.7 to 13° between 1981 and 2010; Simultaneously, its titratable acidity decreased from 7.5 to 5.5 g l^{-1}. Consequently, these changes in berry composition will likely influence the quality of the wine produced, in that further increases in the potential alcohol level and lower concentrations of titratable acidity could produce unbalanced wines.

3.3. Influence of changes in temperature and bioclimatic indices on berry composition

Considering that the berry composition of the main grape varieties has changed significantly, it is necessary to understand the influence that the changes in temperature variables and bioclimatic indices may have had on the concentrations of sugar and titratable acidity. The results of multiple linear regression between temperature and bioclimatic variables and the 2 berry components (dependent variables) are illustrated in Table 15. Results illustrate that the variations in sugar concentrations and titratable acidity are significantly related to the climate variables. For example, in Chinon, 75 % of the variability in Cabernet franc sugar levels and 67 % of the acidity levels were explained by the climate variables, from 1970 to 2010. Increases in temperature have therefore significantly influenced the changes in berry composition, consequently leading to higher concentrations of sugars and lower concentrations of titratable acidity. However, not all the variability in sugar and titratable acidity was explained by the climate variables (Table 15). Grapes are grown in unique ‘terroirs’, which means that the berry composition is influenced also by factors such as the soil characteristics and cultural practices (Morlat 2010). Barbeau (2007) explained that viticultural practices have evolved during the last 30 yr in the Loire Valley, leading to important influences on berry composition. Moreover, warmer climate conditions allow the vine-growers to delay the harvest date, allowing the grapes to reach a greater maturity. Consequently, it is likely that the style of wine sought by vine-growers has changed (Garcia de Cortazar-Atauri et al. 2010). Complementary studies should therefore be undertaken on the evolution in viticultural practices and their influence on vine development and berry composition.

Table 15. Multiple linear regression between the climate variables (GDD, CI, DTR, spring T_m and no. of days with T_m at 25 to 30°C) and the grape variables for the main grapevine varieties cultivated in the middle Loire Valley

Grape variety	Region	R^2	p
Sugar			
Chenin Blanc	Anjou[a,b]	0.68	<0.0001
	Touraine[c,d]	0.68	<0.0001
Gamay	Anjou[a,b]	0.63	0.000
	Touraine[d,e]	0.71	<0.0001
Grolleau Noir	Anjou[a,b]	0.48	0.006
Cabernet Franc	Anjou[a,b]	0.68	<0.0001
	Bourgueil[f,g]	0.70	<0.0001
	Chinon[f,g]	0.75	<0.0001
Titratable acidity			
Chenin Blanc	Anjou[a,b]	0.81	<0.0001
	Touraine[c,d]	0.73	<0.0001
Gamay	Anjou[a,b]	0.53	0.003
	Touraine[d,e]	0.59	<0.0001
Grolleau Noir	Anjou[a,b]	0.65	<0.0001
Cabernet Franc	Anjou[a,b]	0.75	<0.0001
	Bourgueil[f,g]	0.64	<0.0001
	Chinon[f,g]	0.67	<0.0001

[a]Data series is from 1981–2010
[b]Maturation data of Anjou were analyzed with the climate variables from the weather station at Angers
[c]Data series is from 1979–2010
[d]Maturation data of Touraine were analyzed with the climate variables from the weather station at Tours
[e]Data series is from 1980–2010
[f]Maturation data of Bourgueil and Chinon were analyzed with the climate variables from the weather station at Saumur
[g]Data series is from 1970–2010

4. CONCLUSION

The temperatures during the growing season (April to September) have significantly increased between 1960 and 2010 at all 6 locations situated in the Loire Valley. The mean growing season temperatures have increased by 1.3 to 1.8°C, with Saumur illustrating the greatest increase in temperatures. However, the increase in temperature has been driven by more significant changes in maximum temperatures than minimum temperatures. Moreover, the rate of warming has been neither uniform over the period from 1960 to 2010, nor consistent between the 6 weather stations situated in the Loire Valley. The increase in spring and summer temperatures was greater than the autumn and winter temperatures at all 6 locations. The results illustrate that the no. d 25–30°C and the no. d T_x >30°C increased significantly between 1960 and 2010. The significant increases in GDD have resulted in harvest dates advancing by 2 wk on average. The trend in HI illustrated that the 6 locations situated in the Loire Valley have evolved from a cool climate to a temperate climate, which means late ripening varieties are more likely to reach maturity. The 6 main varieties cultivated in the Loire Valley have reacted to these climate changes, as levels of titratable acidity were lower and sugar levels were higher at harvest, which has led to higher potential alcohol concentrations. The trends in sugar and titratable acidity concentrations for the 6 varieties were significantly correlated with temperature variables and bioclimatic indices. Results indicate that the observed increase in temperature has significantly influenced the berry composition of the main grape varieties cultivated in the Loire Valley.

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