CLIMATE TRENDS IN A SPECIFIC MEDITERRANEAN VITICULTURAL AREA BETWEEN 1950 AND 2006

F. LAGET[1], J.-L. TONDUT[1], A. DELOIRE[2] and Mary T KELLY[3]

1: ACH, 84 avenue d'Assas, 34000 Montpellier, France
2: SupAgro, Department of « Plant sciences », 2 place Pierre Viala, 34060 Montpellier, France
3: Centre de formation et de la recherche en œnologie, UMR 1083
« Sciences pour l'œnologie et la viticulture », Faculté de pharmacie, Université Montpellier I,
15 avenue Charles Flahault, 34093 Montpellier cedex, France

Abstract

Aims: An analysis of climate data between 1950 and 2006 in the Hérault department, situated in the Mediterranean of France is presented.

Methods and results: Data presented include the evolution of mean annual and seasonal temperatures, the Huglin index, total solar radiation, night freshness index, the distribution and efficiency of rainfall and potential evapotranspiration (pET). Results showed an increase in mean annual temperatures of +1.3 °C between 1980 and 2006 and an increase in the mean pET which was 900 mm / year since 1999. Also, harvest dates advanced by up to three weeks and sugar concentrations at harvest increased by up to 1.5 % potential alcohol.

Conclusion: The indicators show that in this area certain climatic parameters have evolved over the period studied. Changes are observable in some of the parameters (notably temperature) for the last 30 years whereas others have evolved only in the past few years (e.g. pET). Therefore it is necessary to be circumspect in drawing conclusions on climate change in the area, particularly as regards the possible consequences for viticulture. However, at the plot level, it is clear that irrigation of the vines is becoming increasingly necessary in this region.

Significance and impact of study: Climate is a major factor in vine cultivation and in the understanding of viticultural terroirs and wine typicality. The climate trends observed over a 50-year period are discussed in the viticultural context of a Mediterranean region. However, the interaction between climate change and technical progress in viticulture and oenology complicate the analysis over the time frame under consideration.

Key words : grapevine, Mediterranean climate, Hérault area, berry sugar concentration

Résumé

Objectifs : L'article présente, de 1950 à 2006, une analyse du climat d'un département viticole français, l'Hérault, situé en zone méditerranéenne.

Méthodes et résultats : Les données concernent l'évolution des températures moyennes annuelles et saisonnières, les indices de Huglin et de fraîcheur des nuits, la radiation solaire globale, la distribution et l'efficience saisonnière des pluies et l'evapotranspiration potentielle (Etp). Les résultats montrent une augmentation des températures annuelles moyennes (+1,3 °C de 1980 à 2006), de l'Etp moyenne annuelle (900 mm/an depuis 1999) et un changement dans la distribution saisonnière des pluies. Les dates de vendange sont avancées de 2 à 3 semaines et le degré alcoolique moyen des vins a augmenté de 1,5.

Conclusion : Les données climatiques analysées dans cette étude montrent une évolution de certains paramètres du climat pour cette zone méditerranéenne. Suivant les paramètres étudiées, les changements sont observables depuis environ 30 ans (températures) ou depuis quelques années seulement (distribution des pluies et Etp notamment). Néanmoins, à l'échelle de la parcelle, l'irrigation de la vigne devient de plus en plus une nécessité pour la région considérée.

Signification et impact de l'étude : Le climat est un élément majeur pour la culture de la vigne et pour la compréhension des terroirs et de la typicité des vins. Les tendances climatiques observées sur une période de 50 ans sont discutées dans le contexte viticole d'une région méditerranéenne. L'interaction entre l'évolution du climat et les progrès techniques en viticulture et en œnologie complexifie l'analyse sur la période considérée.

Mots clés : vigne, climat méditérranéen, département de l'Hérault, concentration en sucres de la baie

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*Corresponding author: mary.kelly@univ-montp1.fr

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INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) has predicted that average global temperatures increased by 0.6 °C during the 20th century and the last decade is « very likely » to prove the warmest since meteorological data have been recorded (GIEC, 2001). This evolution is explained by an increase in the concentrations of greenhouse gases in the atmosphere, i.e. an annual increase in carbon dioxide concentration (CO_2) of 1.5 ppm from 1980 to 2000. Similar trends are observed for methane (CH_4) and nitrous oxide (N_2O) (GIEC, 2001). The accumulation of these gases is related to human activities and CO_2 concentrations of 540 to 970 ppm are predicted for 2100, together with an increase in the global average temperature on the earth's surface of 1.4 to 5.8 °C (GIEC, 2001).

From an agronomic point of view, climatologists measure climate change and translate these evolutions into climatic indices relevant to agricultural production. The aim of these endeavours is to enable the impact of climate change on agricultural production to be evaluated. All the more so when the culture of perennial plants is concerned - vines, for example, the plantation of which is renewed on average every 20-30 years, and where the quality and typicality of the product is highly climate-dependent (Vaudour, 2003; Seguin and Cortazar, 2004; Jones *et al.*, 2005).

Mediterranean-type zones share certain characteristics that lend them a special distinction among the world's landscapes. Sun intensity is high, especially in inland areas, due to clear skies and low humidity; evapotranspiration rates can be considerable depending also on the wind speed. Summers are warm to hot, and winters are cool but mild; sub-freezing temperatures do not occur more than 3 % of the total time.

The Hérault department of the Languedoc region of France lies at a latitude of 43.6° North and a longitude of 3.9° east. It extends over a surface of 6,100 km^2 (approximately 100 km long by 60 km wide) and is the northernmost region of the Mediterranean Basin. It may be divided into three principal geographical zones (the coast, the plains and the hills rising to over 1000 m in altitude). Vines are planted over more than 100,000 hectares and the annual wine production is nearly 5 million hectolitres, representing approximately 10 % of the annual French production.

The Association Climatologique de l'Hérault (ACH) is a network of weather stations established since the 1970's, which registers, validates and analyses daily measurements from over 70 different reference posts in the department. The measurements are carried out on a macro and/or meso-climate level, i.e. regional or local production zones (1-20 Km^2) levels. Data analysis carried out by the ACH demonstrated that climate change has principally been occurring since the 1980's and 1990's. Several indicators pointing to this climate change are presented in this article and the potential consequences for viticulture in the region are discussed.

METHODOLOGY

1. Climate data

Data were collected on a daily basis at several reference weather stations. The parameters measured were temperature (maximum and minimum daily values), night freshness index, Huglin index, total solar radiation (joules/cm^2), evapotranspiration (ETP, mm), and rainfall (mm). These measurements were carried out according to international norms and the rules of the International Organisation of Metrology.

2. Viticultural agroclimatic indicators

a- Huglin Index (1978)

The Huglin index (HI) is calculated from April 1st to September 30st in the Northern hemisphere and is defined as follows:

$$IH = \sum_{01/04}^{30/09} \frac{[(Tmean - 10) + (Tmax - 10)]}{2} xk$$

where T mean = mean air temperature in °C
T max = maximum air temperature in °C
k = « length of day coefficient » = 1.03 for latitudes between 42°1' and 44°0'

This index enables different viticultural regions of the world to be classified in terms of the sum of temperatures required for vine development and grape ripening, (Huglin, 1978). Specifically, it is the sum of mean and maximum temperatures above +10 °C - the thermal threshold for vine development. Different grape varieties are thus classified according to their minimal thermal requirement for grape ripening. For example, the HI is 1700 for Chardonnay and 2100 for Syrah. The minimum Huglin index for vine development is 1600.

3. Night freshness index

This is the mean night-time temperature for the month preceding harvest. There are four levels of night freshness as defined by Tonietto and Carbonneau, 2004).

CALCULATIONS

1. Sum

The April to September sum of daily values were calculated in the case of extreme temperatures, solar radiation and ETP.

2. Mean

For the evolution of mean annual and seasonal temperatures, the mean was calculated from daily values over a given time period. For example, the mean annual temperature is the mean temperature from January 1st to December 31st and the mean springtime temperature is the mean temperature from April 1st to June 30st.

3. Percentage

This is cumulative precipitation for a given period as a percentage of total rainfall between April and September. For the type of rainfall (light, medium and heavy) it is the cumulative rainfall divided into four classes (< 10 mm, 11-30 mm, 31-50 mm and <50 mm) and the total rainfall registered between April and September.

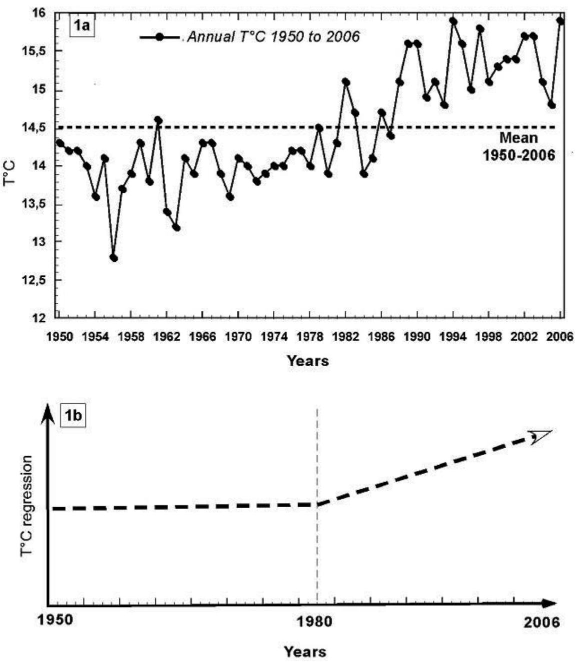


Figure 1 - Evolution of mean annual temperatures from 1950 to 2006 in °C (1a) and regression curve (1b) at a reference weather station in the Hérault.
Two phases may be distinguished in which there is a sharp increase in temperatures since 1980 (0,05 °C per year on average, i.e. +1,3 °C over 27 years).

4. Regression total annual and total seasonal temperatures

They were subjected to linear regression analysis from 1950 to 2006.

RESULTS AND DISCUSSION

1. Average seasonal temperatures (1950 to 2006)

a- Evolution of mean annual temperatures (figure 1)

Temperatures evolved in the Hérault over the period (1950-2006), and figure 1 shows that two distinct periods may be identified: 1950 to 1980 which were cool to cold, and 1980 to 2006 which were mild to hot. It should also be noted that the lowest temperatures in the period 1980-2006 were greater than the highest temperatures in the period 1950-1980. A thermal transition was observed from the beginning of the 1980's (figure 1a) and regression analysis (figure 1b) confirms an increase of +0.2 °C on average for the 30-year period 1950-1980, as compared to +1.3 °C for period 1980-2006. A short period of regular temperature increase was observed from 1972 to 1975, which precedes the dramatic temperature increase in the years following 1980. A similar short period of temperature increase was observed between 1998 and 2001.

b- Evolution of seasonal temperatures (figures 2)

On the basis of regression analysis (table 1) of the two periods (1950-1980 and 1980-2006) certain observations may be made in relation to both the period outside of vegetative growth (autumn and winter) and during vegetative growth (spring and summer):

- Outside the vegetative cycle:

. Autumn temperatures increased by + 1 °C from 1980 to 2006.

. Winter temperatures evolved in a cyclic fashion (cool in the case of 1953-1956 and 1962-1965) or warm (in the case in the case of 1957-1961 and 1988-2002).

- During the vegetative cycle:

. Springtime temperatures increased significantly (by +2 °C) from 1980 to 2006.

Table 1 - Regression calculations of mean temperatures par season for the periods 1950-1980 and 1980-2006.

Season	1950 - 1980	1980- 2006
Spring	-0.3°C	+2°C
Summer	-0.3°C.	+1.6°C
Autumn	-0.1°C	+1°C

Note: Regression analysis may not be applied to winter data, which fluctuate according to the cycles.

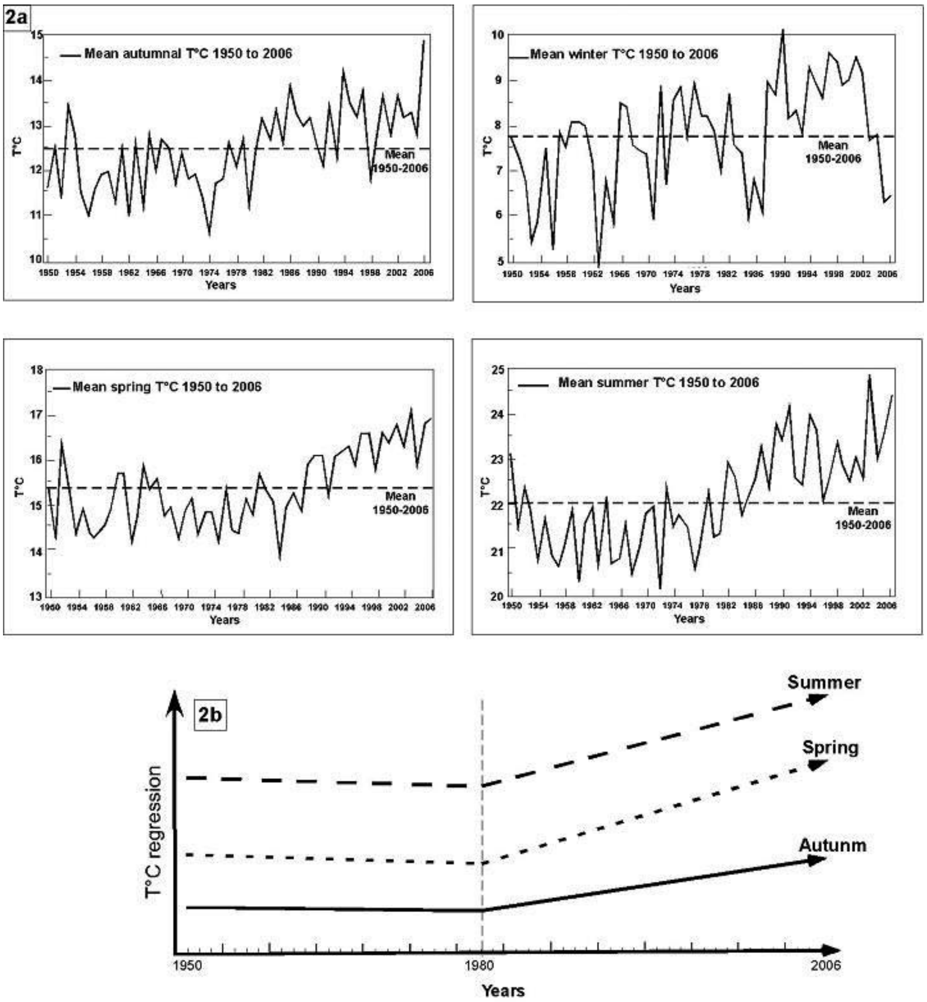


Figure 2 - Comparative evolution of mean seasonal temperatures from 1950 to 2006 (2a) and regression curves (2b) at a reference weather station in the Hérault. Data were obtained from regression analysis. Spring and summer are the two seasons with marked temperature increases (e +1,6°C from 1980 to 2006).

. In summer, temperatures increased by +1.6 °C from 1980 to 2006.

These analyses presented in figure 2 demonstrate that the temperature increase is more significant in spring than in summer, key periods in the vegetative cycle of the vine.

c- Particular case of « extreme » summer temperatures (figure 3)

Summer temperatures are considered to be extreme when maximum temperatures exceed +35 °C in the shade (i.e. more than + 40 °C in the sun). These are so-called « negative » temperatures for the vine, i.e., its physiology and its biochemistry are inhibited or even blocked at temperatures exceeding +35 °C. The consequences of total or even partial inhibition of plant function depend on the duration and frequency of elevated temperatures.

From 1970 to 2006, the number of days with extreme temperatures between June and August has greatly increased, particularly since 2000. Between 2001 and 2006 (apart from 2005) the number of days with extremely high temperatures is always larger than 10, which had never been previously observed. In fact, extremely high June temperatures were recorded on seven days in 2001, six days in 2002, nine days in 2003, and three days in 2005 and 2006. These temperatures were attained from the end of spring onwards and would confirm the trend of summer is extending into springtime. This is the vine's period of bloom - fertilisation, a stage during which the harvest potential - in terms of the number of berries per bunch - is determined. The inhibitory effect of elevated temperatures at this stage has previously been reported (Kliewer, 1977; Huglin and Schneider, 1998).

Table 2 - Evolution of seasonal rainfall distribution from 1976 to 2005.

Stage of vegetative cycle	2001 – 2005 (% of total rainfall over the period)	2000 – 1976 (% of total rainfall over the period)
April - June	35%	54%
July - August	16%	24%
September	49%	22%

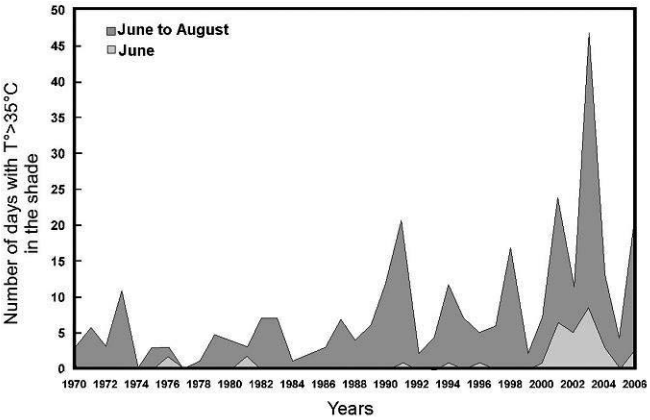


Figure 3 - Evolution of the mean number of days with extreme temperatures (> +35°C in the shade) from 1970 to 2006 at several reference stations.

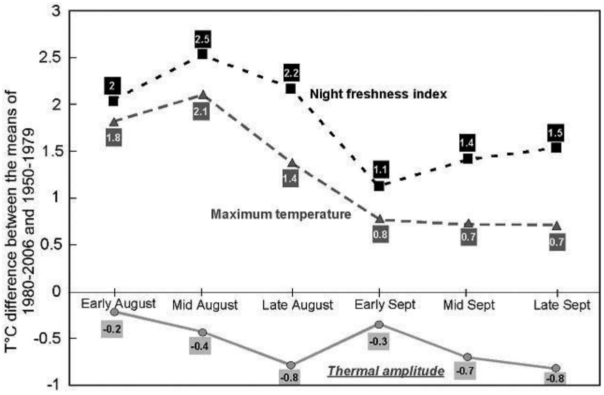


Figure 4 - Temperature spread in °C between the mean 1980-2006 and 1950-1979 values for the three indicators (thermal amplitude, night freshness index and maximum temperature) during grape ripening in Mediterranean climates.

d- Evolution of thermal amplitude, night freshness and maximal decadal temperature indices during grape ripening (figure 4)

Helio-thermic indices are useful in viticultural analysis, notably in the classification of viticultural regions, adaptation of cultivars to climatic conditions, characterisation of terroirs, monitoring of vine physiological and biochemical development, fruit ripening and positioning of phenological stages (Tonietto and Carbonneau, 2004 ; Lorenz *et al.*, 1995 ; Carbonneau *et al.* , 1992 ; Barbeau *et al.*, 1998 ; Huglin and Schneider, 1998 ; Winkler *et al.*, 1974). It would therefore seem important to have the capability to relate helio-thermic indices to grape ripening and the typicality of finished wines.

The following three indicators were compared for the period 1950-1979 and 1980-2006:

. Decadal thermal amplitude: the mean difference in daily maximum and minimum temperatures over a 10-day period;

. Decadal night freshness index: the average night-time temperature over a 10-day period;

. Maximal Decadal Temperature, the mean maximum daily temperature over a 10-day period.

Figure 4 shows that the difference in the night freshness index (1.1-2.5 °C) for the two periods is greater than the difference in thermal amplitude (0.2-0.8 °C) or maximum decadal temperatures (0.7-2.1 °C). Interestingly, the difference in night freshness index parallels that of the maximum temperature from early August to early September; though from mid-September onwards the difference in maximum temperature remains relatively constant, whereas the difference in night freshness index increases. This means that while maximum September daytime temperatures do not greatly increase in the period 1980-2006 by comparison with 1950-1979, the nights would appear to be warmer.

This has considerable implications for viticulture as night-time temperature is important for the development of grape aromas and juice pH in terms of the degradation of malic acid under conditions of sustained elevated temperatures. Night freshness index could be indirectly related to the aromatic intensity of wine and to juice colour of black grape varieties (Carbonneau *et al.*, 2007). Furthermore, a relationship was shown to exist between this index and wine aromas (Carey and Bonnardot, 2004, Tonietto and Carbonneau, 2004.).

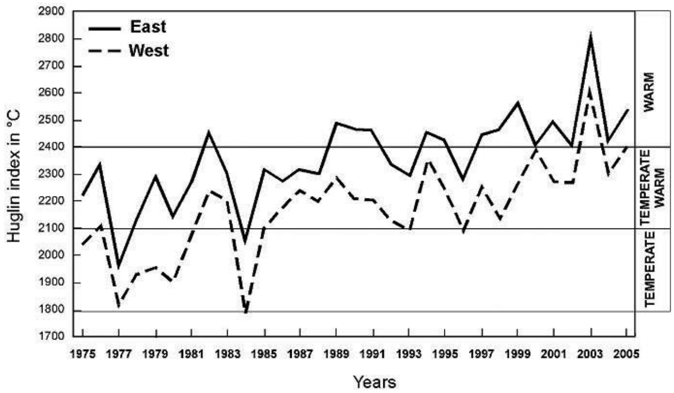


Figure 5 - Evolution of the Huglin index in °C at two reference stations in the Hérault département (county) from 1975 to 2005.

It may be observed that this index evolves for both zones increases with the result that the Eastern departmental zone is reclassified from warm temperate to warm since 1997, and that the Western departmental zone is evolving towards the upper limit of warm temperate.

e- The Huglin Index (figure 5)

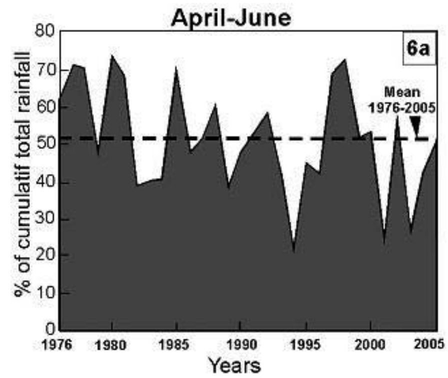
The Huglin index is calculated from mean daytime temperatures, with a base value +10 °C (Huglin, 1978). It is widely used in France as a helio-thermic reference in viticulture in order to compare and classify the major viticultural regions and to determine the plantation of various grape varieties (Tonietto and Carbonneau, 2004; Vaudour, 2003)

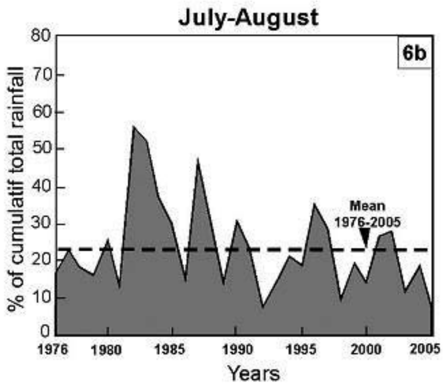
Figure 5 shows that during the period April to September (the complete development cycle of the vine) the Huglin index evolved in all zones of the Hérault, with the result that Central and Eastern zones which were classified as « warm - temperate » (2100 > HI d 2400) between 1975 and 1996 were re-classified as « warm » (2400 > HI d 3000) between 1997 and 2005. Furthermore, from 2000 onwards, the Western zone is at the limit of « warm-temperate » and « warm » in the case of 2000, 2003 and 2006.

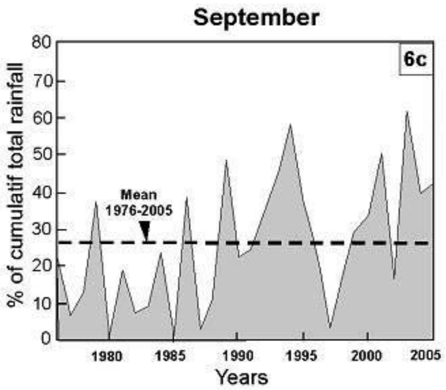
f- Seasonal rainfall distribution and its effectiveness

Seasonal rainfall distribution and its intensity (amount per unit time) determine efficiency in terms of deep soil infiltration and surface run-off (terrain slope effect) after very heavy daily rainfall. For example, daily precipitations of less than 10 mm are of limited efficiency, as the cumulative values are inadequate for in-depth infiltration (Carbonneau *et al.*, 2007). Conversely, cumulative values greater than 50 mm/day with intense precipitations (> 50 mm/hour) do not have time to infiltrate the soil; thus this type of rainfall is of limited efficiency largely due to the fact that it mostly forms surface run-off water, a factor which is exacerbated on steeply sloping soils. Precipitations of 11-30 mm are considered efficient because they penetrate into the soil.

A database (results not shown) covering the period 1906-2006 shows that for the Montpellier area that the







Figures 6 - Evolution of the seasonal rainfall distribution from 1976 to 2005 from April to June (6a); July to August (6b) and September (6c) from a reference weather station in the Hérault.

The rainfall cycle has evolved over recent years showing a tendency towards a greater volumes of rainfall in September, which since 2000 represents between 35 and 60 % of total rainfall during the vegetative cycle (April-September) (with the exception of 2002). Over the period 1976-2005, September rainfall represented less than 30 % of total vegetative cycle rainfall.

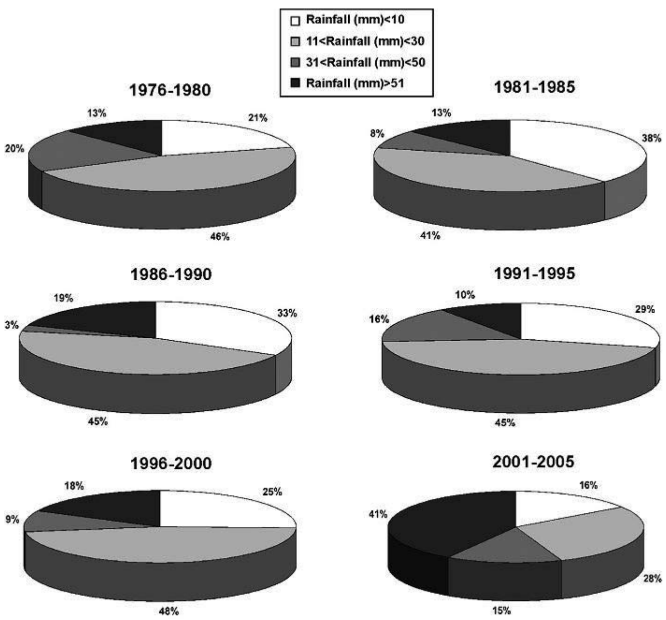


Figure 7 - Evolution of rainfall efficiency of from April to September over the period 1976 to 2005 at a reference weather station in the Hérault.
It may be observed that there are alterations in rainfall efficiencies with high representation of heavy rainfall (> 51 mm/day) since 2000.

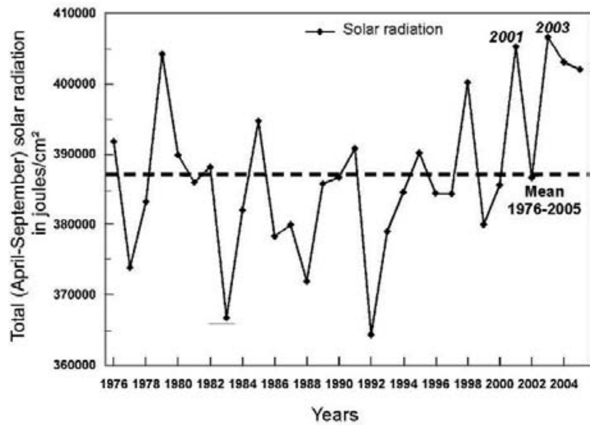


Figure 8 - Evolution of global solar radiation in joules/cm² April to September over the period 1976 to 2005 at a reference weather station in the Hérault.
It may be observed that there is a significant increase since 1992 with record values in recent years (2003).

mean annual rainfall was 764.4 mm and the mean April to September rainfall was 305.2 mm. Over this 100-year period April to Sept rainfall values never exceeded 670 mm; this highest value observed was in 1932. Analysis of this data shows that neither annual nor April-Sept rainfall changed over this period, however, a significant modification of rainfall distribution (figure 6) and efficiency (figure 7) was observed which is more telling than simple average rainfall values.

g- Seasonal rainfall distribution (figure 6)

Data from the Montpellier reference weather station were used to analyse rainfall over three periods, April-June (vine vegetative growth and bloom), July-August (end of vegetative growth, berry development, veraison and ripening-maturity) and September (end of ripening and harvest). Figure 6 shows that rainfall cycles evolved in Mediterranean climates over recent years in that 49 % of total rainfall occurred in September between 2001 and 2005, whereas the figure for the same month between 1976 and 2000 was 22 %. The corresponding figure for April-June were 35 % (2001 - 2005) and 54 % (1976 - 2000). There was also a considerable increase in heavy rainfall at the end of September after the autumn equinox (data not shown).

h- Rainfall efficiency (figure 7)

Using the same data, the 5-year averages of rainfall efficiency may be analysed on the basis of four different thresholds (table 3). From 1976 to 2000, effective rainfalls (11-30 mm per day) are the most represented (40 % of cumulative values). However, for the period 2001-2005, this type of rainfall event only represents a quarter of cumulative values, and the most represented precipitations are those greater than 51 mm per day. Taking 2003 as a specific example, cumulative rainfall in the Montpellier area during the vegetative cycle was close to the normal value, i.e. 400 mm. However, if rainfall distribution and efficiency are taken into account, 2/3 rds of cumulative values are concentrated in September in the form of heavy rainfall.

Table 3 - Efficiency of precipitations by 4-year periods from 1976 to 2005. Four thresholds are presented.

Rainfall threshold in mm	1976 - 1980	1981 - 1985	1986 - 1990	1991 - 1995	1996 - 2000	2001 - 2005
< 10	21%	37%	32%	29%	26%	15%
11 < rainfall < 30	46%	40%	44%	44%	47%	29%
31 < rainfall < 50	20%	9%	4%	17%	10%	15%
> 51	13%	14%	20%	10%	17%	41%

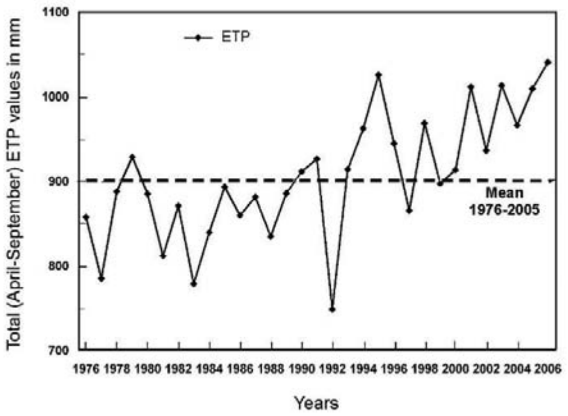


Figure 9 - Evolution of potential evapotranspiration (pET) from April to September over the period 1976 to 2005 at a reference weather station in the Hérault.
The lowest pET values for the period 1993-2005 correspond to highest pET values for the period 1976-1992.

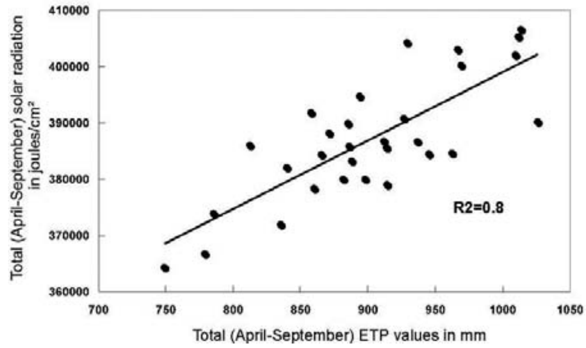


Figure 10 - Correlation curves between pET and global solar radiation from April to September over the period 1976 to 2005 at a reference weather station in the Hérault.
There is a strong correlation between the two indicators. Furthermore pET is an important indicator and integrator of several climatic variables.

2. Global solar radiation and evapotranspiration (ETP)

a- Total solar radiation joules/cm^2 (figure 8)

Total solar radiation is the sum of the solar energy received by the soil in joules/cm^2 over a specific time period. The average value of total solar radiation between April and September from 1976 to 2005 was approximately 390,000 joules/cm^2. A dramatic increase in this parameter was observed between 1992 and 2006 particularly, with a variance of close to 40,000 joules/m^2 by comparison with the mean. From 2003 (where a record of 406,560 joules/cm^2 was attained) to 2005, the cumulative values were significantly greater than the mean, more than 10,000 joules/cm^2, which represents an increase of close to 5 %.

b- Evolution of evapotranspiration (ET) (figure 9)

The potential evapotranspiration (pET) calculated using the Penman formula is the sum of water loss incurred by evaporation from the soil surface and transpiration by plant. Potential (pET) evapotranspiration is always greater than the real ET, as a result of which, specific and optimised cultural techniques are applied in individual cases.

From April to September, the mean pET is 900 mm from 1976-2005, though significant increases in this figure have been observed since 1992. Before this date, it was estimated that for three out of four years, the pET is less then 900 mm whereas since 1993, in only one year has the value been less than this average. In no year since 1999 has the value been less than 900 mm, and the lowest pET values in the period 1993-2005 correspond to the highest values of the preceding period. The question that arises from increased pET is the effect on plant water function, i.e., soil water availability at bud-burst and its evolution during the development cycle of the vine, specifically in interaction with cultural practices (canopy volume, total and exposed leaf areas), bunch load (yield) and density (number of vinestocks per hectare). The pET is a fundamental parameter in calculating water balance (Riou, 1998).

It was recently calculated that the pET in the Hérault increased by 100 mm from 1976 to 2007. By comparison, vine pET (pETv) calculated for the same period increased by 30 mm estimated for a standard vertical shoot positioning training system with a canopy height of 1 m at verasion and a mean plantation density of 5000 vinestocks per hectare, with a distance between the rows of 2 m (ACH, personnal communication).

c- Correlation between climate indicators and pET (figure 10)

There is a good correlation (Pearson correlation coefficient close to 0.8) between pET and total solar radiation expressed in joules/cm^2 over the period April-September. Therefore, this result clearly shows that the more intense the solar radiation, the greater the extent of pET.

3. Observed effects on viticulture

Studies on the effect of climate on viticulture in France really began with the seminal work of Schultz in 2000 (Schultz, 2000). One of the most significant effects of global warming (estimated to be in the region of +0.9 °C in France (Spagnoli, 2002)) in terms of viticulture is that the different phenological stages of grape growth and ripening are occurring earlier. Studies carried out in

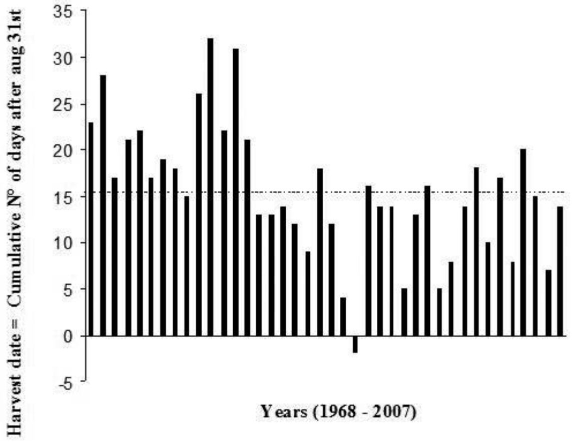
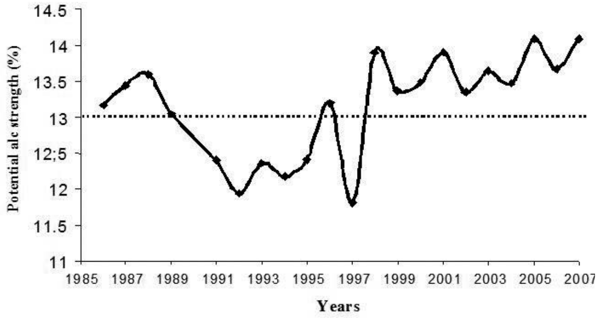
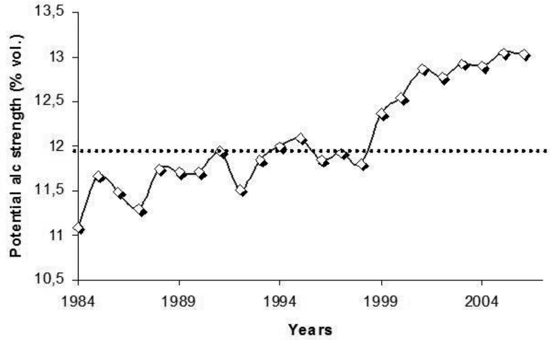


Figure 11 - Example of evolution of harvest date expressed as cumulative n° of days after August 31st before harvest begins.

Data obtained from a single vineyard (Château la Voulte Gasparet) in the Languedoc Region of France. The dotted line represents the mobile mean.





Figures 12 - Example of evolution of sugar concentration expressed as potential alcoholic strength (%vol.) from 1984 to 2007, a) data from Château la Voulte Gasparet; b) data from an oenological laboratory in the Languedoc region; mean values of several million hl of wine per year.

The dotted line represents the mobile mean.

different regions of France indicate that the most significant changes in bud-burst and bloom have taken place in the approximate period 1985-2005: both these stages have advanced by 7-15 days in the case of Alsace (Duchene and Schneider, 2005) and Champagne (Moncomble *et al.*, 2007). Similar effects were observed in the vineyard of Château Lafitte Rothschild (Dubernet, 2007) for which data have been recorded since 1954. The obvious advantage of considering data from a single vineyard is that variations in factors other than climate are virtually non-existent; these include the planted cultivars, the average age of the vines, cultural practices etc. However, it is interesting to note that while harvest opening date in Champagne and Alsace, has, in the same period advanced to a similar degree (approximately 15 days) as budburst and bloom, the latter are significantly less affected than harvesting date in the more southerly vineyards. For example, in Chateauneuf-du-Pape harvest opening dates have advanced from early October in 1945 to early September in 2000 (Ganichot, 2002), an evolution that may be only partially explained by modifications of cultural practices. In a similar study, it was found that harvest opening date in Tavel appellation area of the Southern Rhone advanced by three weeks from 1951 to 2005 and moreover, it appears that the process has been accelerating over the last decade. Likewise, in Chateau Lafitte Rothschild, the average harvesting date in the 1950's and 1960's was October 3rd, whereas it advanced to September 19th for the Decade 1990-2000.

In the Mediterranean region of France, data obtained from a single vineyard (Château la Voulte Gasparet) where vineyard practice has remained virtually unchanged since the late 1960's demonstrated that harvesting has advanced by 12 days (Figure 11).

Another effect of climate change on viticulture is increased sugar content and reduced total acidity of grapes at haverst. For example, Duchene and Schneider (2005) presented results for the evolution of potential alcoholic strength in Alsace between 1973 and 2003. The mean was 9.34 % vol. for the period 1973-1990, whereas it was 10.58 % vol for the period 1991-2003, the highest value of 11.8 % vol. being attained in 2003 (which was an exceptionally hot year). Moreover, it should be noted that there is a greater degree of fluctuation in the values for the first period and the increase is more linear for the second period (r = 0.96).

At Château la Voulte Gasparet in the Languedoc, there has been a steady increase in the sugar concentration at harvest between 1986 and 2007. Figure 12a shows that despite considerable year-to-year variations, the overall trend is upwards, and as was previously observed for Alsace, year-to-year variations tended to diminish in latter years. The average potential alcohol % volume was 12.78 % for the 10-year period 1986-1996 as compared to 13.53 % for the period 1997-2007.

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Data collated by an oenological laboratory in the Mediterranean region representing more than 1 million litres of wine per year over a 20-year period strongly confirm this trend (Figure 12b), i.e. increased potential alcohol strength particularly from the year 2000 onwards, and reduced year-to-year variation in later years. In this case the mean potential alcoholic strength was 11.68 % for the period 1984-1996, and 12.62 % for the period 1997-2006. There is a strong correlation between the year and the alcoholic strength over the 20-year period ($r = 0.927$).

Two other linked oenological parameters that are affected by increasing temperature are pH and total or titratable acidity expressed in terms of g/l H_2SO_4. Results (data not shown) from the set of samples above show an increase in pH and a decrease in titratable acidity; mean pH was 3.55 for the period 1984-1996 and 3.66 for the period 1997-2006. The corresponding values for titratable acidity were 3.72 and 3.38 g/l H_2SO_4, respectively. That the increase in pH and decrease in titratable acidity were not strongly correlated ($r = -0.8$) is explained by the fact that although these two parameters are linked, the relationship between them is complex.

CONCLUSION

It is possible to provide only general information for the consideration of vine and grape physiology and biochemistry in a hot climate context (Razungles *et al.*, 1998 ; Ollat and Gaudillère, 1998 ; Ojeda *et al.*, 2002 ; Deloire and Hunter, 2005 ; Deloire *et al.*, 2005 ; Peyrot des Gachons *et al.*, 2005 ; Choné *et al.*, 2006).

In Mediterranean areas, the « light » factor is not limiting except in cases of certain vine architecture configurations in situations of elevated vine vigour which increases the number of shaded leaves. Nonetheless it is worth stating that it has been suggested, notably in the case of white grapes, that « air conditioning » of the bunches by appropriate management of their microclimate (shading of the bunches by leaves during ripening) could be useful in maintaining aromatic potential (Razungles *et al.*, 1998 ; Marais *et al.*, 1999)

It is likely that the most significant impact of climate change on viticulture will result from an increase in temperature and from the evolution of rainfall distribution and efficiency. The possible consequences of elevated temperatures are multiple: increased transpiration and plant water consumption in addition to a modification of canopy and/or bunch microclimate by leaf fall in the bunch zone, for example. These modifications of plant functioning and vigour can lead to: a) an inhibition of photosynthesis; b) a partial or total inhibition of berry development and biosynthesis of its principal components, notably during vegetative growth of the berry c) inhibition of ripening, d) loss of fruit volume with resulting consequences for yields and harvest concentration; and e) a possible increase in alcohol content of wines produced in such « warm » areas due to the concentration in sugars (loss of water by evapo-transpiration and limited water entering the berry or back flow of water from the berry to the plant).

Accelerated ripening has serious consequences for precocious varieties in that they enter into the final phase of ripening under increasingly warmer conditions. This has potential implications in that high temperatures, especially if associated with drought, can inhibit certain biochemical pathways or physiological processes essential for the production of quality grapes (Deloire *et al.*, 2004).

It may be appropriate to reflect on the evolution of legislation pertaining to viticulture (e.g. irrigation, plantation density, training system, yields, etc.) principally in European areas of geographic denomination. It will also be necessary to adapt oenological practices to musts that are more concentrated and richer in sugar - maceration, yeast activity to compensate for the loss of aroma precursors; de-alcoholisation, partial dilution of musts, more creative blendings, etc.

One of the immediate effects on vine culture in Mediterranean areas is the management of drought and of water resources for the purposes of irrigation. Increased employment of innovative technologies may be envisaged for viticultural cartography on the basis of parameters such as water resource, soil reserve, irrigation strategies, and the determination of harvest potential and harvesting dates according to a desired wine style objective (Hall *et al.*, 2008; Brenon *et al.*, 2005; Vaudour, 2003).

It would be interesting to construct international viticultural climate networks in order to compare the different situations of climate evolutions worldwide, particularly in other Mediterranean climate areas and possibly to exchange expertise in terms of plantation, rootstocks, clones, vineyard practice etc to provide coherent solutions in the face of global climate change.

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REFERENCES

Barbeau G., Morlat R., Asselin C., Jacquet A. and Pinard C., 1998. Comportement du cépage Cabernet franc dans différents terroirs du Val de Loire. Incidence de la précocité sur la composition de la vendange en année climatique normale (exemple de 1988). *J. Int. Sci. Vigne Vin*, **32** (2), 69-81.

Brenon E., Bernard N., Zebic O. and Deloire A., 2005. Maturité du raisin : proposition d'une méthode utilisant le volume des baies comme indicateur. *Rev. Œnol*., **117**, 1-3.

Carbonneau A., Deloire A. and Jaillard, B. 2007. *La vigne : physiologie, terroir, culture*. Ed. Dunod p. 441.

Carbonneau A., Riou C., Guyon D., Riom J. and Schneider C., 1992. *Agrométéorologie de la vigne en France*. Office Publications Officielles Communautés Européennes ed.

Carey V. and Bonnardot V., 2004. A viticultural perspective of meso-scale atmospheric modelling in the Bottelaryberg-Simonsberg-Helderberg wine growing area (South Africa). *Bull. Office Int. Vigne Vin*, **77** (875-876), 20-46

Choné X., Lavigne-Cruège V., Tominaga T., Van Leeuwen C., Castagnède C., Saucier C. and Dubourdieu D., 2006. Effect of vine nitrogen status on grape aromatic potential : flavor precursors (S-cysteine conjugates), glutathione and phenolic content in *Vitis vinifera* L. cv. Sauvignon blanc grape juice. *J. Int. Sciences Vigne Vin*, **40**, 1, 1-6.

Deloire A and Hunter J.J., 2005. Bunches microclimate and berry maturation. *Progrès Agricole Viticole*, **122**, 7, 151 - 157.

Deloire A., Carbonneau A., Wang Z. and Ojeda H., 2004. Vine and water : a review. *J. Sci. Vigne Vin*, **38** (1), 1 - 13.

Deloire A. Vaudour E. Carey V. Bonnardot V. and Van Leeuwen C., 2005. Grapevine responses and terroir : a global approach. *J. Sci. Vigne Vin*, **39** (4), 149-162.

Dubernet, M., 2007. La viticulture face au changement climatique ; Les conséquences pratiques pour le vinificateur *Proceed. Euroviti colloquium*, Montpellier France, Dec 2007.

Duchene E. and Schneider C., 2005. Grapevine and climatic changes: a glance at the situation in Alsace. *Agronomie*, **25** (1) 93-99

Hall A., Louis J.P., Lamb D.W., 2008. Low-resolution remotely sensed images of wine grape vineyards map spatial variability in planimetric canopy area instead of leaf area index. *Australian J. Wine Grape research*, **14**, 9-17.

Huglin P., 1978. Nouveau mode d'évaluation des possibilités héliothermiques d'un milieu viticole. *C. R. de l'Académie d'Agriculture*, France 1117-1126.

Ganichot B., 2002. Évolution de la date des vendanges dans les Côtes-du-Rhône méridionales. *Proceed. 6th Rencontres rhodaniennes*, Orange, France, Institut Rhodanien Editor, pp. 38- 41.

Groupe intergouvernemental sur l'évolution du climat (GIEC), 2001. *Bilan 2001 des changements climatiques : Les éléments scientifiques*, OMM-PNUE.

Huglin P. and Schneider C., 1998. *Biologie et écologie de la vigne*. Ed. Lavoisier Tec et Doc, Paris.

Jones G. V., White M. A., Cooper O. R. and Storchmann K., 2005. Climate change and global wine quality. *Climatic Change,* **73**, 319-343.

Kliewer W.M., 1977. Effect of high temperature during the bloom-set period on fruit-set, ovule fertility, and berry growth of several grape cultivars. *Am. J. Vitic. Enol*., **28**, (4), 215 - 221.

Lorenz D.H., Eichhorn K.W., Bleiholder H., Klose R., Meier U. and Weber E., 1995. Phenological growth stages of the grapevine (*Vitis vinifera* L. ssp. *vinifera*) - Codes and descriptions according to the extended BBCH scale. *Aust. J. Grape Wine Research*, **1**, 100-110.

Marais J., Hunter J.J. and Haasbroek P.D., 1999. Effect of canopy microclimate, season and region on sauvignon blanc grape composition and wine quality. *South African J. Enology Vitic*., **20**, 1, 19 - 30.

Moncomble D., Panigai L. and Descotes A., 2007. Réchauffement climatique, quels impacts probables sur les vignobles ? *Proceed. colloquium*, Dijon, France March 28-30th.

Spagnoli B., Planton S. Déqué M., Mestre O. and Moisselin J.-M., 2002. Detecting climate change at a regionalscale, 2002: the case of France. *Geophys. Res. Lett*., **29**, n°10.

Ojeda H., Andary C., Kraeva E., Carbonneau A. and Deloire A., 2002. Influence of pre and postveraison water deficit on synthesis and concentration of skin phenolic compounds during berry growth of *Vitis vinifera* L., cv Shiraz. American *J. Vitic. Enol*., **53**, (4), 261 - 267.

Ollat N. and Gaudillère J.P., 1998. The effects of limiting leaf area during stage I of berry growth on development and composition of berries of *Vitis vinifera* L. cv Cabernet-Sauvignon. *Am. J. Vitic. Enol*., **49**, 251-258.

Peyrot des Gachons C., Van Leeuwen C., Tominaga T., Soyer J.P., Gaudillère J.P. and Dubourdieu D., 2005. The influence of water and nitrogen deficit on fruit ripening and aroma potential of *Vitis vinifera* L., cv Sauvignon blanc in field conditions. *J. Sci. Food Agric*., **85**, 73-85.

Razungles A., J. Baumes R. L., Dufour C., Sznaper C. N. and Bayonove C. L., 1998. Effect of sun exposure on carotenoids and C13-norisoprenoid glycosides in Syrah berries (*Vitis vinifera* L.). *Sci. Alim.*, **18**, 361-373.

Riou C., 1998. Facteurs explicatifs des critères de qualité de la récolte. Application au réseau modèles qualité en viticulture. *Progrès Agricole Viticole*, **115**, (11), 247 - 252.

Schultz H.R., 2000. Climate change and viticulture: a European perspective on climatology,carbon dioxide and UV-B effects. *Australian J. Grape Wine Research*, **6**, 1-12.

Seguin B. and Garcia de Cortazar I., 2004. Climate warning : consequences for viticulture and the notion of « terroirs » in Europe. *Proceedings 7th Int. Symp. Vineyard Physiology Biotechnology*. 21-25 juin Davis (USA). *Acta Horticulturae*, **689**, 61-70.

Tonietto J. and Carbonneau A., 2004. A multicriteria climatic classification system for grape-growing regions worldwide. *Agricultural Forest Meteorology*, **124**, 81-97.

Vaudour E., 2003. *Les terroirs viticoles. Définitions, caractérisation, protection*. Ed. Dunod, Paris.

Winkler A.J., Cook J.A., Kliewer W.M. and Lider L.A., 1974. *General Viticulture*. 2nd ed. Ed. University of California Press, California.