Suitability of Some Climatic Parameters for Grapevine Cultivation in South Africa, with Focus on Key Physiological Processes

J. J. Hunter[1] & V. Bonnardot[2]*

(1) ARC Infruitec-Nietvoorbij, the Fruit, Vine and Wine Institute of the Agricultural Research Council, Private Bag X5026, 7599 Stellenbosch, South Africa & Department of Viticulture and Oenology, Stellenbosch University, Private Bag XI, Matieland 7602, South Africa (hunterk@arc.agric.za)
(2) ARC-Institute for Soil, Climate and Water (ISCW) of the Agricultural Research Council, Private Bag X5026, 7599 Stellenbosch, South Africa. (Current address: University Rennes 2, COSTEL LETG-UMR 6554 CNRS, 2 Place Recteur H. Le Moal, 35 043 Rennes Cedex, France (valerie.bonnardot@uhb.fr)

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To optimise the functioning of the grapevine in a specific environment and to improve grape and wine quality, suitability of climatic parameters for key grapevine physiological processes needs to be assessed at fine scales. This paper presents methodology using hourly weather data in three wine producing regions of South Africa (Coastal Region – Stellenbosch district; Breede River Valley – Robertson district; Central Orange River Region – Upington district) during the pre- (November to December) and post-véraison (January to February) periods. Durations inside and outside an optimum climatic range and of extreme climatic conditions were calculated over a 5-year period (1999/2000 to 2003/2004) to quantify a climatic profile related to grapevine physiological requirements. Climatic requirements for optimum photosynthetic activity were defined as follows: temperature 25°C to 30°C, windspeed <4 m/s, relative humidity 60% to 70%. Unsuitable climatic periods for vine performance were calculated as <20°C and >35°C, >4m/s, <50% and >80%. A coefficient was assigned to each climatic parameter according to an assumed importance level for physiological processes. Optimum temperature requirements for other physiological parameters were also investigated. A diurnal minimum/maximum temperature range of 25°C to 30°C was used for sugar content and organic acid levels and a maximum night/day temperature range of 15°C/25°C for colour and flavour. Light intensity was accepted as being sufficient. Stations were classified according to their potential for meeting the climatic requirements of each physiological parameter. Marked variation in climatic profiles and available time for optimal physiological functioning occurred between regions. All factors considered, the climatic profile of the Coastal Region (Stellenbosch district) seemed to best satisfy the climatic requirements of the physiological parameters studied.

INTRODUCTION

Soil and climate are the primary environmental factors to which the grapevine is subjected. For this reason, terroir-related studies mainly focused on the effects of soil and climate on typicity and quality expression of wine (Saayman, 1977, 1992; Saayman & Kleynhans, 1978; Noble, 1979; Conradie, 1988; Morlat, 1989, 1997; Falcetti, 1994; Falcetti & Iacono, 1996; De Villiers, 1997; Vaudour, 2000; Conradie *et al.*, 2002; Carey *et al.*, 2003; Bálo *et al.*, 2010). The seasonal morphological development of bunches and eventual chemical composition of the berry result from the interaction between the chosen soil and accompanying climate and the consequences of long term practices (e.g. establishment techniques, row orientation, vine spacing, and trellising, training and pruning systems), short term practices (e.g. seasonal irrigation, fertilisation and canopy management) and harvest criteria applied by the grower (Jackson & Lombard, 1993; Hunter & Archer, 2001a,b; Deloire *et al.*, 2002; Hunter *et al.*, 2004). All of these have an integrated effect on physiological processes and the distribution of carbon in the grapevine (Hunter, 2000; Carbonneau & Deloire, 2001).

Grapevine growth is usually determined by the climatic potential of a region, calculated with different thermal indices for viticulture, such as the Winkler or Huglin indices (Winkler *et al.*, 1974; Huglin, 1978). These indices (heat summations over the growing season) result in classification of climatic regions broad enough to take short-term variation in climate into account. Research on climatic suitability for vine cultivation usually focuses on these temperature analyses at monthly or seasonal scales (Jones *et al.*, 2010). Different climatic parameters (temperature, wind, rainfall and relative humidity) are seldomly combined at global scale (Tonietto & Carbonneau, 2004) or at regional and local scales (Pythoud, 2004; Knight, 2006) and little consideration is given to finer temporal scales and specific periods during the growth season (for example an

Corresponding author: valerie.bonnardot@uhb.fr

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hourly scale during pre- and post-véraison, respectively; Hunter & Bonnardot, 2002), which would express the phytoclimate (Seguin, 2002). This becomes all the more important in the light of a global climate change which may impact on growth, grape composition, wine style and spatial distribution of grapevines (Cyr & Shaw, 2010; Hunter *et al*., 2010; Jones, 2010; Ladányi *et al*., 2010; Tonietto *et al*., 2010).

Despite the dependence of proper physiological functioning of the grapevine on climate, i.e. temperature (Kriedemann, 1968; Kliewer, 1971, 1977; Lakso & Kliewer, 1978; Coombe, 1987; Marais *et al*., 1999), humidity (Champagnol, 1984) and wind velocity (Freeman *et al*., 1982; Kobriger *et al*., 1984; Hamilton, 1989), threshold values of regions and terroirs for various physiological processes, such as photosynthesis of the leaves as well as grape color development, sugar and organic acid formation, mineral accumulation and flavor development, were only briefly referred to in the past (Buttrose *et al.,* 1971; Pirie, 1979; Coombe, 1987; Iland, 1989; Yamane *et al*., 2006; Mori *et al*., 2007). It is therefore necessary to assess at fine scale the climatic suitability (in terms of duration) of regions/environments for grapevine cultivation, and more specific, the physiological requirements of the grapevine, affecting the accumulation of components that are viticulturally and oenologically important. This is critical to optimise the functioning of the grapevine in a specific environment and to improve grape and wine quality.

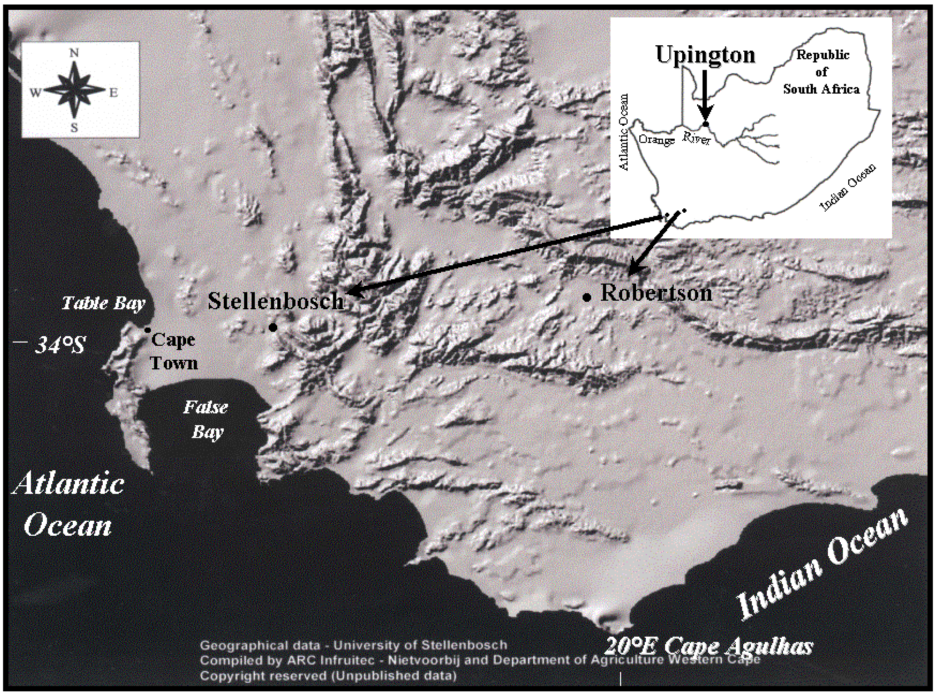
Temperature ranges for optimum photosynthetic activity were previously studied in three wine producing districts of South Africa (Stellenbosch, Robertson and Upington) during the pre- and post-véraison growth periods (Hunter & Bonnardot, 2002). In this paper, the profile suitability of some climatic parameters for optimal grapevine functioning and production of high grape and wine quality is further elaborated by considering temperature, wind speed and relative humidity profiles for photosynthesis as well as other parameters of significance to grape and wine quality.

MATERIALS AND METHODS

Daily and monthly temperature and rainfall data from three mechanical weather stations located in the main town of each of three South African regions, namely the winter-rainfall Coastal Region (Stellenbosch), the semi-arid Breede River Valley Region (Robertson) and the semi-arid Central Orange River Region (Upington) were used to describe the general climate of the regions (Fig. 1).

The Winkler and Huglin indices (Winkler *et al*., 1974; Huglin, 1978) were calculated to assess the basic climatic potential of the regions for viticulture. Hourly climatic data from the automatic weather station network of the Institute for Soil, Climate and Water (ISCW) of the Agricultural Research Council in the three grape growing regions were used (Table 1). The Stellenbosch district (14 stations, S01 to S14), Robertson district (12 stations, R01 to R12) and Upington district (4 stations, U01 to U04) are referred to as Stellenbosch, Robertson and Upington.

The climatic requirements of the physiological processes were studied using hourly temperature, wind speed and relative humidity data of five seasons (1999/2000 to 2003/2004) during pre- and post-véraison periods (November to December and January to February, respectively). The mean hourly climatic profile of each location (mean hourly temperature, relative humidity and wind speed) was drawn. The period between 09:00 and 15:00 (time is expressed as for South African Standard Time: Greenwich Meridian Time +2) was taken as window for optimum photosynthetic activity. The temperature



Geographical data - University of Stellenbosch
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FIGURE 1
Location of the three grape growing districts studied in South Africa (Stellenbosch, Robertson and Upington).

TABLE 1
List and characteristics of the automatic weather stations used in the study.

Weather station	Altitude (m)	Wine producing region	Wine producing district
S1	146	Coastal Region	Stellenbosch
S2	423	Coastal Region	Stellenbosch
S3	147	Coastal Region	Stellenbosch
S4	200	Coastal Region	Stellenbosch
S5	250	Coastal Region	Stellenbosch
S6	230	Coastal Region	Stellenbosch
S7	235	Coastal Region	Stellenbosch
S8	130	Coastal Region	Stellenbosch
S9	225	Coastal Region	Stellenbosch
S10	56	Coastal Region	Stellenbosch
S11	33	Coastal Region	Stellenbosch
S12	153	Coastal Region	Stellenbosch
S13	260	Coastal Region	Stellenbosch
S14	177	Coastal Region	Stellenbosch
R1	300	Breede River Valley	Robertson
R2	250	Breede River Valley	Robertson
R3	180	Breede River Valley	Robertson
R4	170	Breede River Valley	Robertson
R5	110	Breede River Valley	Robertson
R6	140	Breede River Valley	Robertson
R7	180	Breede River Valley	Robertson
R8	120	Breede River Valley	Robertson
R9	180	Breede River Valley	Robertson
R10	160	Breede River Valley	Robertson
R11	340	Breede River Valley	Robertson
R12	115	Breede River Valley	Robertson
U1	690	Central Orange River Region	Upington
U2	793	Central Orange River Region	Upington
U3	881	Central Orange River Region	Upington
U4	650	Central Orange River Region	Upington

of 25°C to 30°C, adapted from Kriedemann (1968, 1977), wind speed of <4 m/s (Freeman *et al*., 1982; Hamilton, 1989) and relative humidity of 60% to 70% (Champagnol, 1984) requirements for optimal grapevine photosynthetic activity were superimposed onto the respective hourly mean climatic profiles. The percentage of time, during the study period and within the diurnal window, with temperature, wind speed and relative humidity falling inside and outside (below and above) the range for maximum photosynthetic activity, was also calculated for both periods. For the time falling inside the range, and therefore suitable for maximum photosynthetic activity, interpretation also included the difference between the morning (before 12:00) and the afternoon (after 12:00) occurrences and whether the remaining time within the time window was above or below the optimum range.

A mean cumulated time suitable (optimum climatic conditions) and unsuitable (extreme climatic conditions) for maximum photosynthetic activity was calculated. In this calculation, a coefficient of 3 was given to temperature, 2 to relative humidity and 1 to wind speed, due to temperature being assumed the most important climatic variable (Coombe, 1987), followed by relative humidity and then wind speed, to emphasise the proximity of the Ocean and the effect of local air circulations such as sea-breezes (Bonnardot, 2002). It was also assumed that the extremes (below and above optimum ranges) were equal, although low temperature should actually be more detrimental than high temperature, the latter being more bearable (less stressful) when water is available (Kriedemann, 1968). Light intensity was accepted as being sufficient.

In addition to photosynthesis, optimum temperature requirements for other physiological parameters were also investigated (based on Kliewer, 1971, 1977; Lakso & Kliewer, 1978; Pirie, 1979; Coombe, 1987; Iland, 1989; Marais *et al*., 1999; Yamane *et al*., 2006; Mori *et al*., 2007). A diurnal temperature range of 20°C to 25°C between 06:00 and 18:00 and a night temperature range of 10°C to 15°C between 18:00 and 06:00 for both colour and flavour were used. The temperature range of 25°C to 30°C, as used for photosynthesis, was also applied to sugar and potassium accumulation, organic acid formation and respiration. For photosynthesis, sugar, potassium and organic acid levels, a diurnal minimum/maximum temperature range of 20°C/35°C was used, below or above which levels in the leaves/berries would be seriously affected. For colour and flavour, a maximum night and maximum day temperature range of 20°C and 30°C were used, above which levels in the berries would decrease.

The stations were also classified (sorted) according to their potential for meeting the climatic requirements of each of the physiological parameters as well as of all the physiological parameters together, in order to assess the collective, spatial suitability variation within regions.

An ANNOVA procedure (Waller grouping) using the five seasons as replicates and performed with the Statistical Analysis System 8.2 version, was used to determine whether the differences between the stations were statistically significant.

RESULTS AND DISCUSSION

General regional climates

The three selected grape growing districts of South Africa, located between latitudes 28°4'S and 34°S, represent different macroclimatic conditions for vine growing (Bonnardot, 2005). The Stellenbosch district in the Western Cape (Coastal Region) experiences a warm temperate climate (Fig. 2 a) with warm summers (mean maximum February temperature of 28.1°C) and winter rainfall (740 mm annually). The mean annual temperature is 17.2°C and the annual thermal amplitude is reduced due to the maritime influence, which prevents high temperatures during summer and cold temperatures during winter as well as during the day and night. In the interior, the climate of the Robertson district (Breede River Valley Region) is semi-arid: hot and dry (Fig. 2b). The mean annual temperature is 17.8°C. It is situated at the eastern margin of the winter rainfall zone and it receives much less rain than the Stellenbosch district, i.e. 290 mm annually, mainly during winter. The annual amplitude is wider than in the Stellenbosch district, with a mean January maximum temperature of 31°C (the warmest month of the year) and a mean July minimum temperature of 5.1°C (the coldest month). The Upington district in the Northern Cape (Central Orange River Region) has a semi-arid climate (Fig. 2c) with very little rain (180 mm annually), convectional showers falling in summer (January-March) and a mean annual temperature of 19°C. The mean maximum temperature in January reaches 35°C, while the mean minimum temperature in July is 1.7°C. Vines in this part of the country experience frost during the change of seasons (winter to spring) and extreme high temperatures in summer (>40°C).

Using the mean seasonal climatic index of Winkler, the three districts varied from Region III to Region V and, using the Huglin index, the Stellenbosch district was classified as a "warm temperate", the Robertson district as a "hot" and the Upington district as a "very hot" climate for viticulture (Table 2). However, a variety of meso-climates exist within very short distances, especially in the Stellenbosch district, due to the complex topography in this district and the proximity of the sea (Bonnardot, 2000; Carey, 2001; Bonnardot *et al.*, 2002; Conradie *et al.*, 2002; Hunter & Bonnardot, 2004). Indeed, the stations in the Stellenbosch district mostly belong to Region III of the Winkler categories, although some fall at the lower limit of Region IV. According to the Huglin index, the type of climate varied from temperate at the stations located in vineyards nearest to the coast to hot at further inland stations, especially those located on northwest-facing slopes.

Site assessment according to climatic parameters meeting physiological requirements

Using the mean hourly climatic profiles of the three districts during pre- and post- véraison as well as the calculation of the duration within or outside optimum ranges for grapevine physiological processes, it clearly showed climatic details relevant to the physiological performance of the grapevine (Fig. 3).

Photosynthesis

Considering the optimum temperature range within the allocated diurnal time period (09:00 to 15:00), the climatic suitability for optimum photosynthesis differed markedly between the three districts (Fig. 3a). During pre-véraison (Fig. 3a left), temperatures in the Stellenbosch district were below the optimum range, with afternoon temperatures rising to just below the lower temperature limit. The Robertson district experienced climatic conditions inside the range for optimal photosynthesis in the afternoon, whereas the Upington district experienced climatic conditions inside the range for optimal photosynthesis in the morning, where after vines experienced high temperature stress during the whole afternoon. A similar situation occurred in the districts during post-véraison (Fig. 3a right), except for the Stellenbosch district where temperatures, albeit slightly lower than those in the Robertson district, were within the optimum temperature range in the afternoon. The distinction between the morning and afternoon values seemed relevant within a climate change context as it may have a significant impact on the physiological processes of the grapevine. It was recently shown that with increasing temperatures (deduced from long term records) in the Robertson district, the optimum temperature period for photosynthetic activity would shift to the morning and become noticeably shorter (Hunter *et al.,* 2010).

Considering only the duration with temperatures inside the optimal range for photosynthesis, thermal conditions in the Robertson and Upington districts are more often (28% to 35% of the time) suited for photosynthesis than those in the Stellenbosch district (18% to 26% of the time) during pre-véraison (Fig. 4a). The Waller grouping (p=0.005) resulted in 16 different groups. During post-véraison, as the temperature increased, the warmest sites of the Stellenbosch district (S11, S03, S14 and S10) met the temperature requirements for optimum photosynthesis as often (33% to 35% of the time) in comparison to the coolest sites of the Robertson district (Fig. 4b). Here, the Waller grouping resulted in 8 different groups only (2 in Upington, 3 in Robertson and 6 in Stellenbosch).

The Stellenbosch district, however, had more favourable relative humidity levels than the Robertson district (Figs 3b and 5). In the Upington district, photosynthesis would be reduced to lower levels, due to very low pre- and post-véraison relative humidity and low wind speeds (Figs 3c, 5 and 6), the latter which could reduce the transpiration efficiency and contribute to a rise in plant temperature.

In general, the Waller grouping performed on the durations

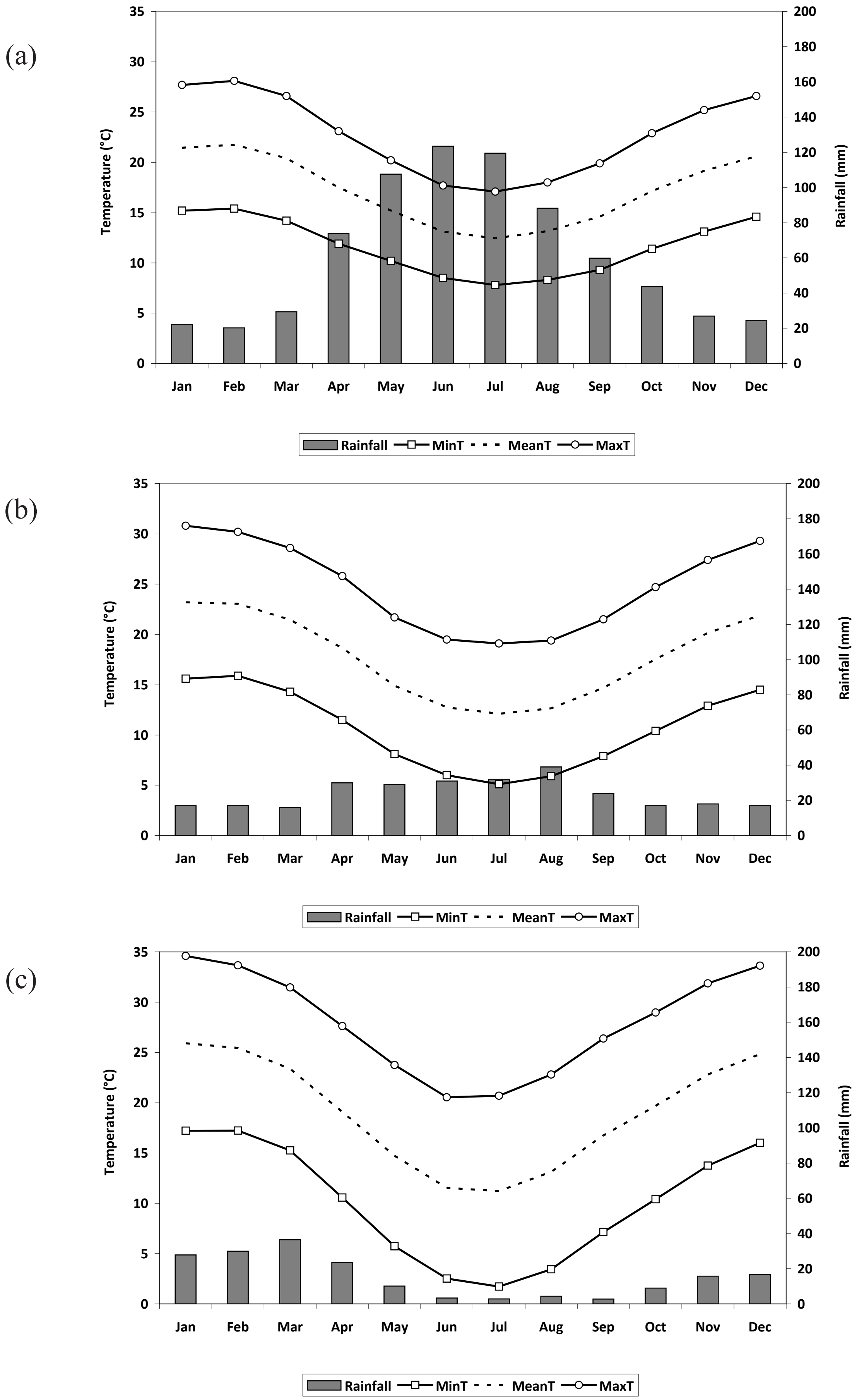

FIGURE 2
Mean monthly rainfall and temperature for (a) Stellenbosch (33°9'S/18°9'E) (Period 1967 to 2002), (b) Robertson (33°5'S/19°5'E) (Period 1961 to 1997) and (c) Upington (28°5'S/21°25'E) (Period 1949 to 1995). Source: ARC-ISCW, AgroMet Division, Pretoria.

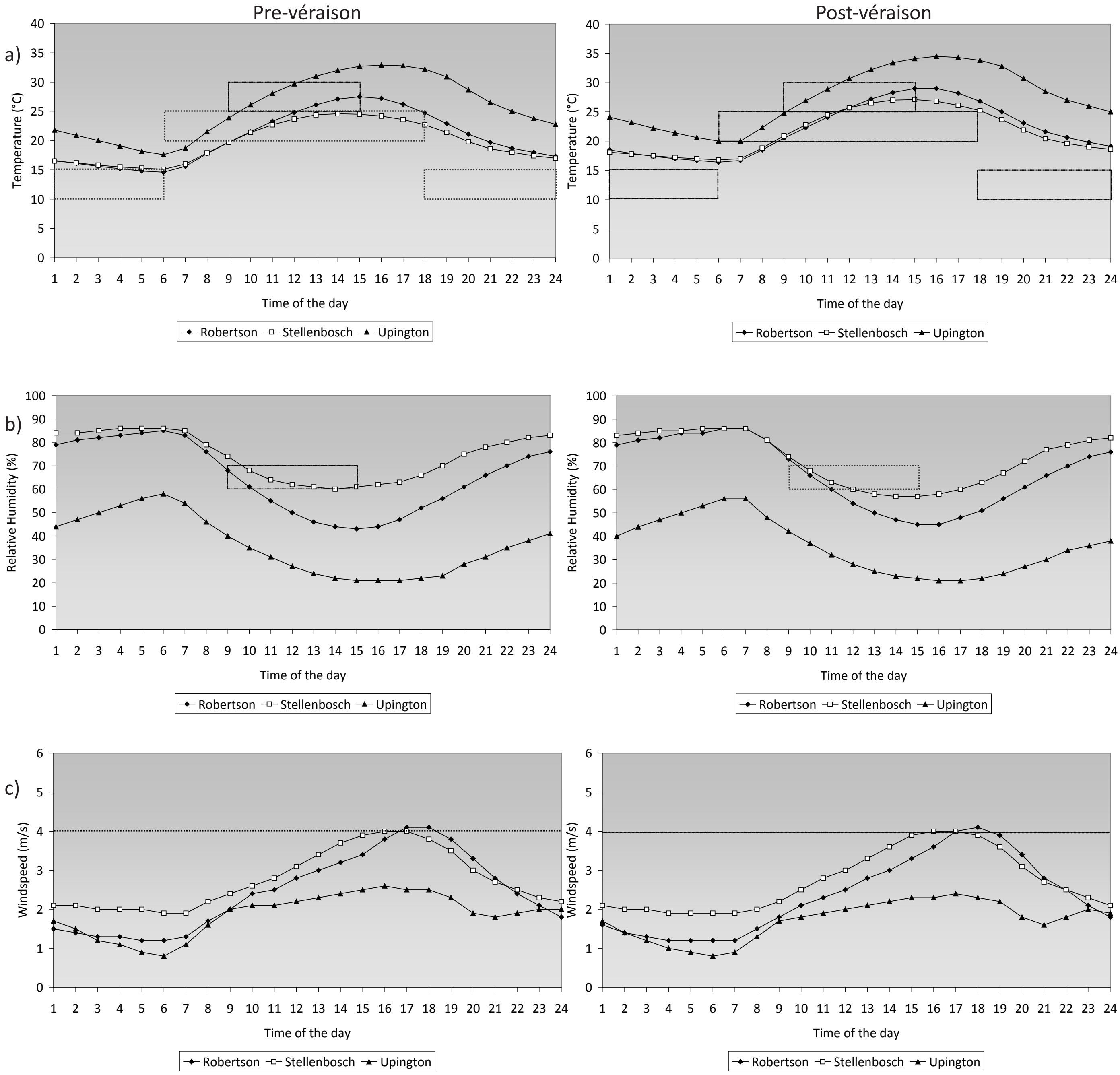

FIGURE 3
Hourly (a) mean temperature, (b) relative humidity and (c) windspeed during *pre-véraison* (Nov to Dec) and *post-véraison* (Jan to Feb) for Stellenbosch, Robertson and Upington wine-producing districts. Average for 5 seasons (1999 to 2004). The superimposed dotted frames represent the windows of temperature, wind speed and relative humidity requirements for optimal grapevine physiological activity.

with temperature, relative humidity and wind inside the optimal range for photosynthesis resulted in a higher occurrence of significant differences between locations during pre-véraison in comparison to those identified during post-véraison.

When the total duration within the optimum climatic (temperature, relative humidity and wind speed) ranges for photosynthesis was plotted *versus* the total duration outside the ranges (i.e. under climatic stress) (Fig. 7), the sites monitored in the Upington district showed that climatic stress was more often experienced by grapevines than favourable climatic conditions (right of the dashed line in Fig. 7) and this district was therefore the least suited for photosynthesis. Only one site in the Robertson district and two sites in the Stellenbosch district experienced more climatic stress than favourable conditions for photosynthesis during pre-véraison. On average, the Stellenbosch district had more often favourable climatic conditions than the Robertson and Upington districts, due to less time with stress. It is clear that climatic conditions for maximum photosynthetic activity in the Stellenbosch and Robertson districts were met more often during the post-véraison period than during the pre-véraison period. The percentage of time with optimum climatic values increased and

TABLE 2
Winkler and Huglin indices and their corresponding climatic region or climate type. Average of five seasons (1999 to 2004) for each of the Stellenbosch, Robertson and Upington districts. The stations are classified within their district by ascending Winkler index.

District	Station	Winkler Index	Winkler Region	Huglin Index	Climate type based on Huglin index as used by Tonietto & Carbonneau (2004)
Stellenbosch	S6	1701	III	2095	Temperate
Stellenbosch	S8	1737	III	2154	Warm Temperate
Stellenbosch	S5	1751	III	2179	Warm Temperate
Stellenbosch	S2	1791	III	2222	Warm Temperate
Stellenbosch	S7	1814	III	2155	Warm Temperate
Stellenbosch	S1	1943	III	2379	Warm Temperate
Stellenbosch	S12	1965	IV	2312	Warm Temperate
Stellenbosch	S14	1982	IV	2498	Hot
Stellenbosch	S10	1990	IV	2382	Warm Temperate
Stellenbosch	S4	2008	IV	2485	Hot
Stellenbosch	S3	2008	IV	2489	Hot
Stellenbosch	S11	2019	IV	2403	Hot
Stellenbosch	S9	2041	IV	2455	Hot
Stellenbosch	S13	2051	IV	2402	Hot
Average for Stellenbosch district		***1914***	***III***	***2329***	***Warm temperate***
Robertson	R11	1877	III	2447	Hot
Robertson	R2	1926	III	2401	Hot
Robertson	R9	1968	IV	2439	Hot
Robertson	R1	1997	IV	2478	Hot
Robertson	R5	2027	IV	2557	Hot
Robertson	R10	2030	IV	2590	Hot
Robertson	R8	2050	IV	2551	Hot
Robertson	R4	2053	IV	2592	Hot
Robertson	R7	2058	IV	2530	Hot
Robertson	R12	2061	IV	2608	Hot
Robertson	R3	2110	IV	2640	Hot
Robertson	R6	2120	IV	2650	Hot
Average for Robertson district		***2023***	***IV***	***2540***	***Hot***
Upington	U2	2901	V	3402	Very Hot
Upington	U3	2968	V	3459	Very Hot
Upington	U1	3114	V	3529	Very Hot
Upington	U4	3273	V	3755	Very Hot
Average for Upington district		***3064***	***V***	***3536***	***Very hot***

the percentage of time with climatic stress decreased during post-véraison (Fig. 7).

A well-photosynthesising, sucrose-producing canopy during the pre-véraison period is important for the supply of precursors for various compounds such as organic acids, amino acids and secondary compounds (De Freitas *et al*., 2000; Pastor del Rio & Kennedy, 2006; Rodriquez Montealegre *et al*., 2006). The latter include terpenoids (e.g. monoterpene flavour compounds and carotenoids), flavonoids and non-flavonoids [e.g. phenolic acids, polymeric flavan-3-ols (condensed tannins), flavonols and colour (anthocyanin) compounds]. During the post-véraison period conditions should be suited to maintenance and further formation of compounds. High photosynthetic activity during the post-véraison period would largely buffer a decrease in organic acid content and an increase in pH (Hunter & Ruffner, 2001).

Colour and flavour

The calculation for colour expression and flavour development and maintenance showed a clear distinction between sites in the three districts. Indeed, the Waller grouping resulted in 10 to 12 different groups during daytime (Fig. 8) and 17 to 18 different groups during night time (Fig. 9). The Stellenbosch district was the most suited. Considering the day temperature thresholds, at least 30% to 46% of the time during pre-véraison (Fig. 8a) and 33% to 43% of the time during post-véraison (Fig. 8b) were suitable for colour and flavour requirements in the Stellenbosch district. While daytime temperature stress was relatively limited during pre-véraison in the Stellenbosch (7% of the time) and Robertson (11% of the time) districts (Fig. 8a), the stations in the Upington district displayed highly limiting temperatures for colour and flavour requirements during both pre- and post-véraison (45% and 53% of the time, respectively; Figs 8a and 8b). Considering the night temperature thresholds,

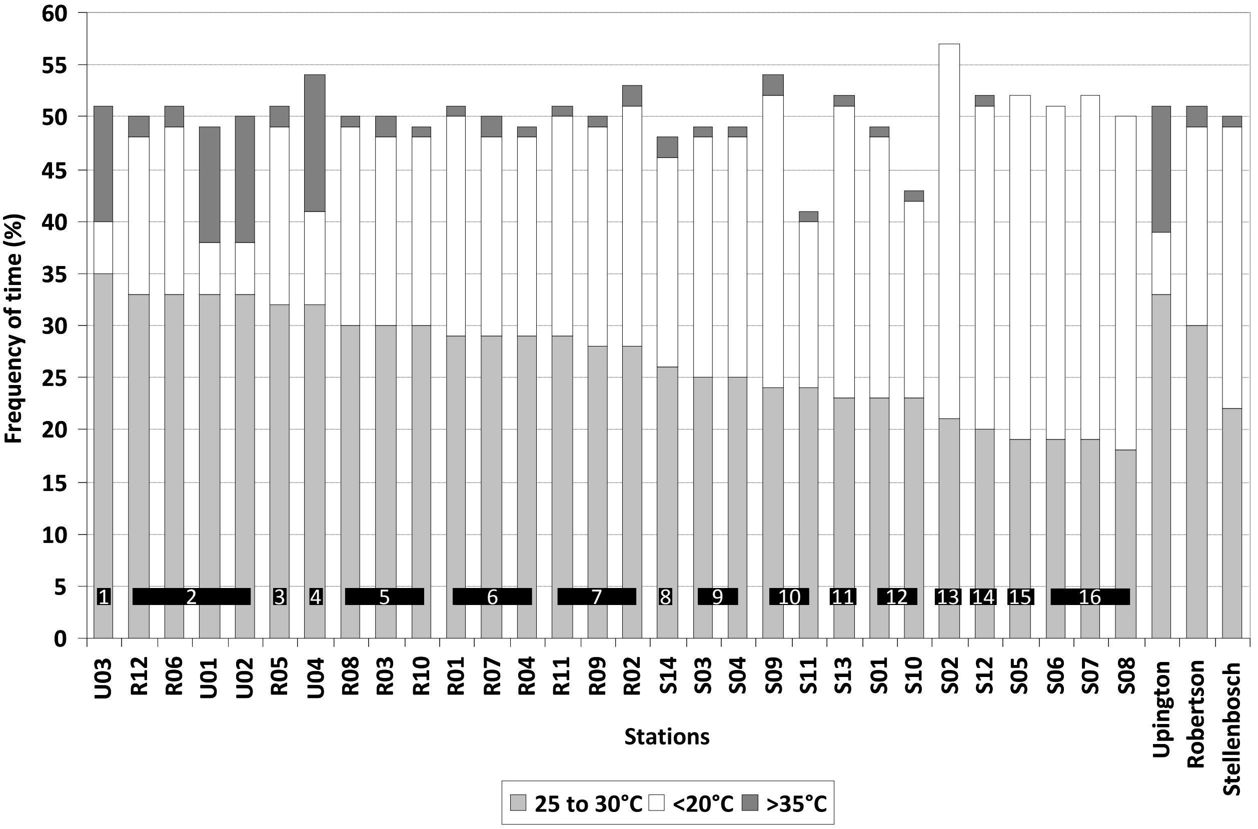

FIGURE 4A

Time between 09:00 and 15:00 (in %) with temperature below 20°C, between 25°C and 30°C, and above 35°C, during *pre-véraison* for the 30 stations and average for the three districts (1999 to 2004). Stations are grouped (Waller grouping p=0.005) and classified according to descending (25°C to 30°C) frequency.

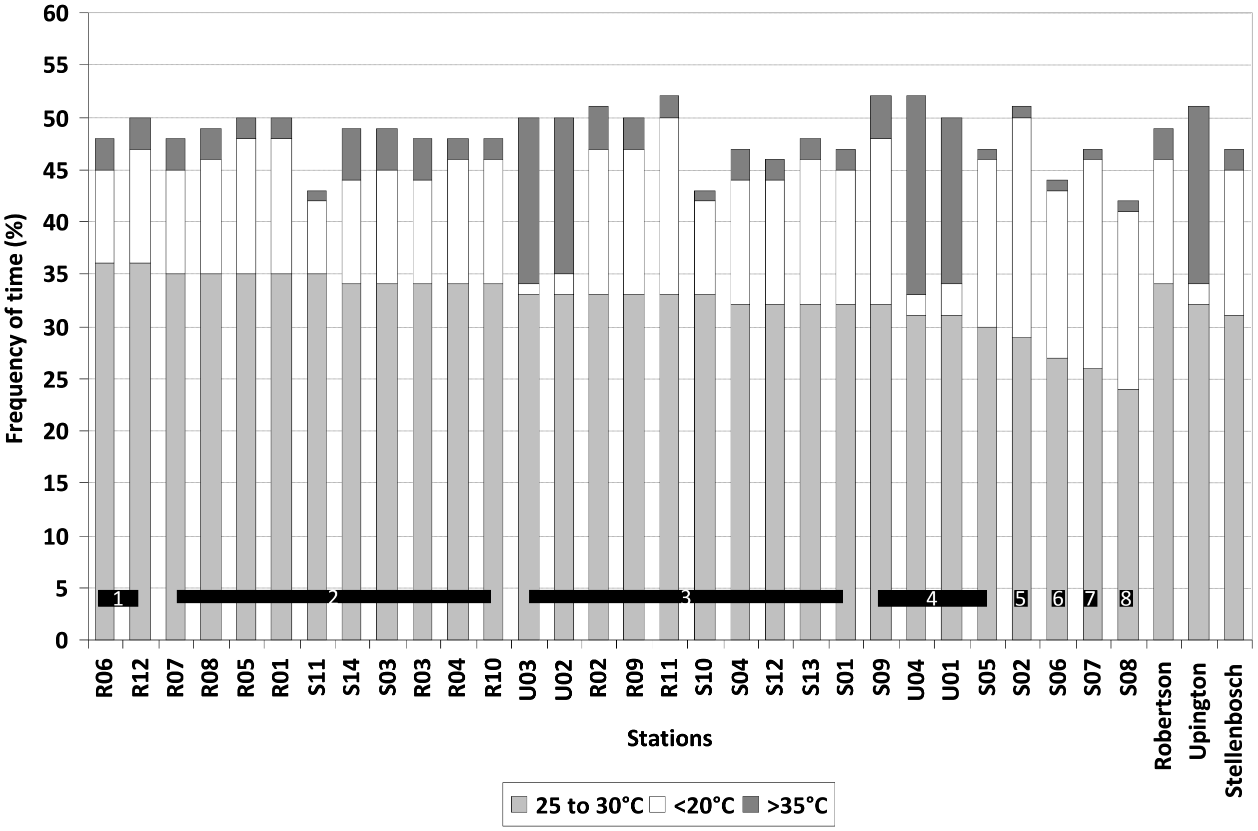

FIGURE 4B

Time between 09:00 and 15:00 (in %) with temperature below 20°C, between 25°C and 30°C, and above 35°C, during *post-véraison* for the 30 stations and average for the three districts (1999 to 2004). Stations are grouped (Waller grouping p=0.005) and classified according to descending (25°C to 30°C) frequency.

stressful thermal conditions for colour and flavour development and maintenance seemed to be a rule at night (Fig. 9), except for the Stellenbosch district during pre-véraison (Fig. 9a).

In the Upington district, temperatures increased to above maximum levels for optimum sugar accumulation during both pre- and post-véraison periods, with locations experiencing stressful thermal conditions during day and night for 53% to 73% of the time in total (Fig. 10). The negative effect of this on organic acid formation and colour expression would be accentuated by the very favourable temperature conditions in this region for excessive respiration of malic acid during the afternoons of both the pre- and post-véraison periods (Kliewer, 1971; Lakso & Kliewer, 1978). In addition, tartaric acid salt formation in particular would most likely be favoured in the berries during the whole season because of high temperatures restricting photosynthesis and therefore sugar production, and stimulating increased potassium distribution in order to maintain osmotic potential (as explained by Hunter & Ruffner, 2001). All of these would eventually lead to an unbalanced grape composition and a high pH, the latter further increasing during crushing in the winery (Iland, 1987). In the case of the Robertson district, temperature conditions were better suited for sugar and organic acid formation compared to the Upington district, with locations experiencing stressful thermal conditions for 28% to 37% of the time only during post-véraison and more often optimum thermal conditions (25% to 30%) than thermal stress (18% to 25%) during pre-véraison (Fig. 10). In the Stellenbosch district, cool pre-véraison temperatures may limit photosynthesis, sugar production and organic acid formation, but on the other hand, respiration of organic acid would probably be more restricted compared to the other regions. It is, however, still likely that the berries under such circumstances may enter the ripening period at lower organic acid concentrations than required for high grape quality. As a result, an unbalanced grape composition with a dominant sugar concentration (leading to wines high in alcohol) and lacking other oenologically important components, is also likely to be found at harvesting. This situation may be worse if the water requirements of the vine and canopy management to control vigour and canopy microclimate (from the beginning of the growth period) are neglected (Hunter, 2000; Hunter & Myburgh, 2001; Ojeda *et al*., 2002; Hunter *et al*., 2004). The temperature conditions in the Stellenbosch district nevertheless seemed best suited for colour and flavour development, having the largest part of the temperature profile inside the optimal range, particularly during pre-véraison (28% to 38% of the time - Fig. 10), the latter period being important for the formation of precursors in either case. The temperature profile of the Robertson district is similar to this (25% to 28% of the time within the optimum thermal range). During post-véraison, temperatures in both Stellenbosch and Robertson districts were inside the optimum range during the morning (Fig. 3a right), thereby favouring colour development and flavour maintenance. In the Upington district, colour development and the maintenance of flavour may, in addition to the climatic temperature restrictions, be negatively affected by potentially high pH levels (Iland, 1987; Hunter & Ruffner, 2001).

Higher and more favourable temperatures in the Stellenbosch district during the post-véraison period may result in a continuation/re-start of vegetative growth, especially when vineyards are over-irrigated or when rain falls during this period. This is not feasible for obtaining high grape quality. In the semi-arid Robertson and Upington districts vineyards may react similarly; and with vineyards being intensively monitored in these districts, variation in growth is probably less likely to occur because of potentially better control (albeit at high risk of error) over the water status of soils (growth uniformity is also largely dependent on, e.g. soil variation, soil preparation, plant material quality, planting practices, plant spacing, rootstock selection and the accommodation of growth on a suitable trellis system).

Naturally, in either of the districts, variation in climate conditions would occur, depending mainly on altitude, slope, aspect and prevailing wind. Vine performance would be affected by the way in which growth is accommodated, the soil water holding capacity, water deficit management, canopy management, and fertilization programs. Under any circumstances, management neglect or injudicious execution of practices at any time (winter and summer) may lead to an under-exploitation of the regional and site potential for grape growing and grape and wine quality.

Although the climatic requirements employed in this study for optimum photosynthesis would seem to indicate that conditions are, on average, best suited in the Robertson and Stellenbosch districts, followed by the Upington district, vines in the winter-rainfall Stellenbosch district (Schulze, 1997) are moderately vigorous and trained onto smaller trellises, whereas those in the semi-arid inland districts, such as Robertson and Upington, are more vigorous and generally trained onto larger trellises for growth accommodation (Hunter & Archer, 2001a). Vines in the Coastal Region are also mostly low intensity irrigated or grown under dry land conditions, whereas those in the inland regions are intensively irrigated, mostly because of a combination of high temperature and low soil water availability for the latter regions. This has a critical impact on growth and may enhance or repress physiological factors impacting on growth and grape composition, and finally wine quality. In addition to climatic differences, application of the aforementioned regional viticulture practices (as well as soil type/fertility, plant spacing, and row orientation), may also have a significant bearing on microclimate conditions that are experienced by the grapevine, and thus on canopy photosynthesis (and eventual grape and wine quality) (Hunter & Visser, 1988; Hunter *et al*., 1995; Riou, 1998; Hunter & Archer, 2001a,b). Moreover, the extent and timing of seasonal canopy management are critical for interior-canopy photosynthetic active radiation, temperature, humidity, wind velocity and eventual photosynthetic efficiency of the leaves (Hunter, 2000; Hunter *et al*., 2004). A lack of preventative measures in the Robertson and Upington districts may therefore result in vigorous growth and most probably dense canopies with only a small portion of photosynthetic efficient leaf area and unfavourable conditions for bunch health, development and composition. This would largely nullify the potentially favourable effects of the temperature profiles for photosynthetic activity and growth in these districts. It would also further impact on colour and flavour development and maintenance.

Photosynthesis, colour and flavour combined

Considering the mean total percentage of time inside the

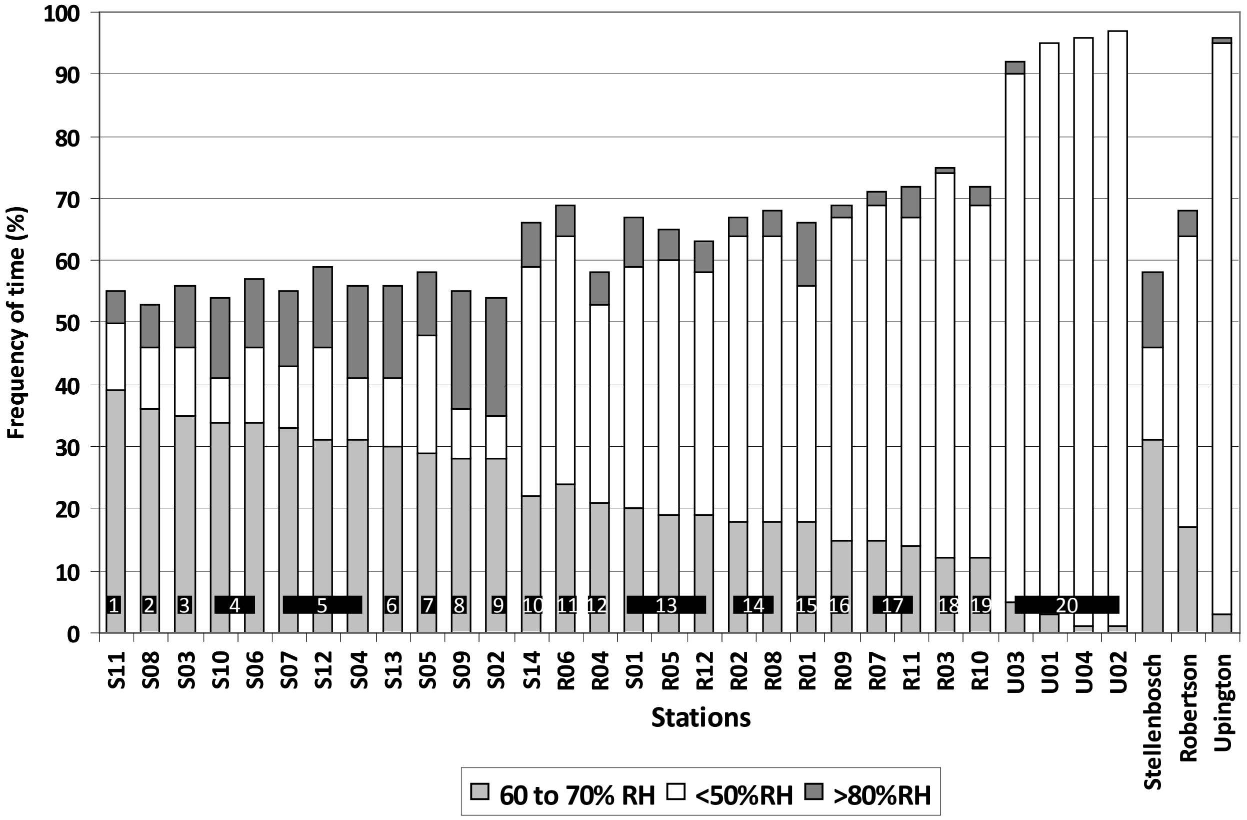

FIGURE 5A

Time between 09:00 and 15:00 (in %) with relative humidity below 50%, between 60% and 70% and above 80%, during *pre-véraison* for the 30 stations and average for the three districts (1999 to 2004). Stations are grouped (Waller grouping p=0.005) and classified according to descending (60% to 70%) frequency.

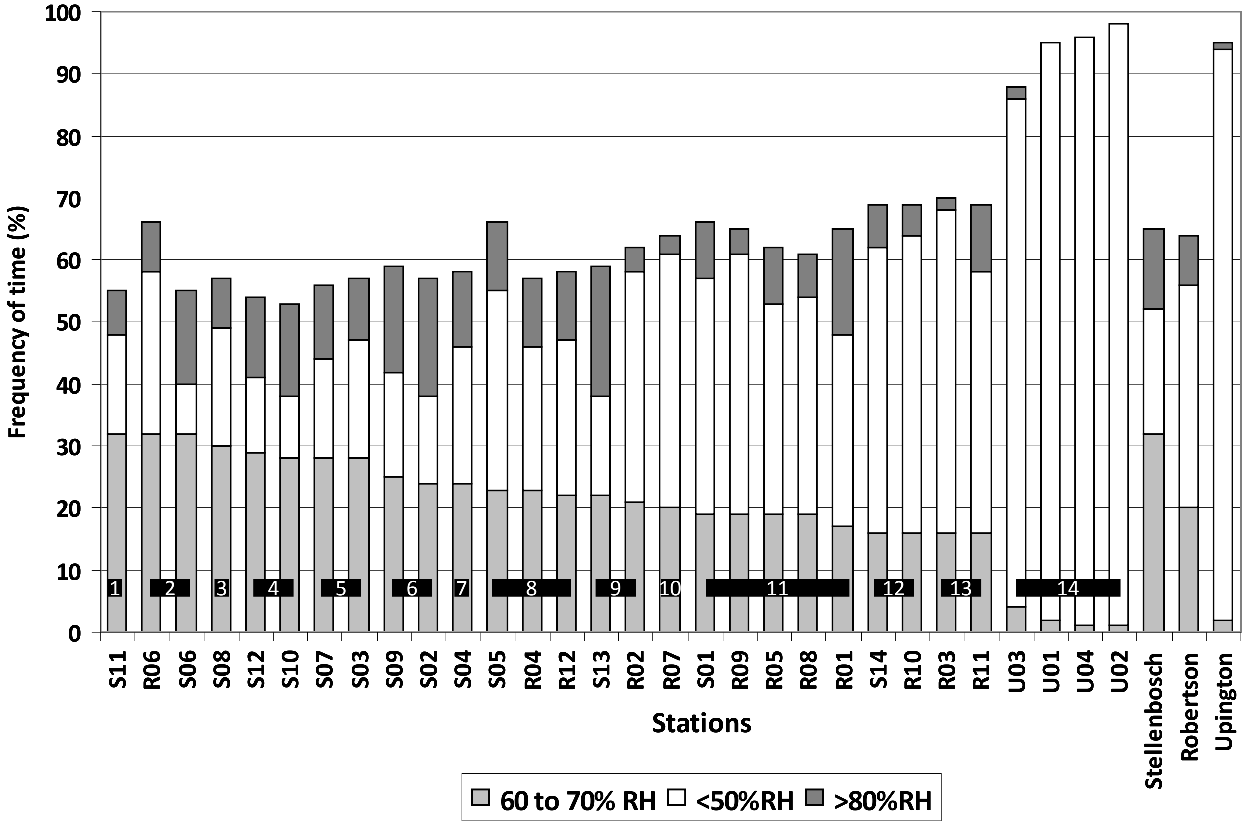

FIGURE 5B

Time between 09:00 and 15:00 (in %) with relative humidity below 50%, between 60% and 70% and above 80%, during *post-véraison* for the 30 stations and average for the three districts (1999 to 2004). Stations are grouped (Waller grouping p=0.005) and classified according to descending (60% to 70%) frequency.

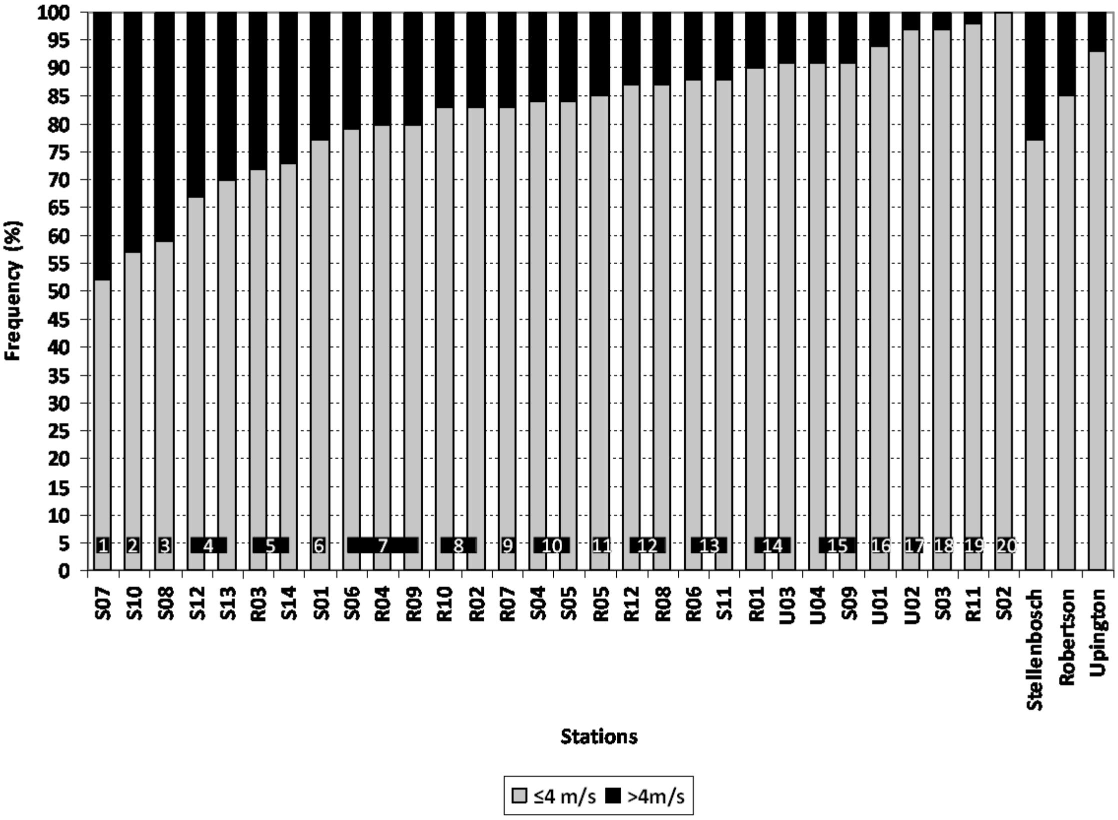

FIGURE 6A

Time between 09:00 and 15:00 (in %) with wind speed above and below 4m/s, during *pre-véraison* for the 30 stations and average for the three districts (1999 to 2004). Stations are grouped (Waller grouping p=0.005) and classified according to ascending (≤4m/s) frequency.

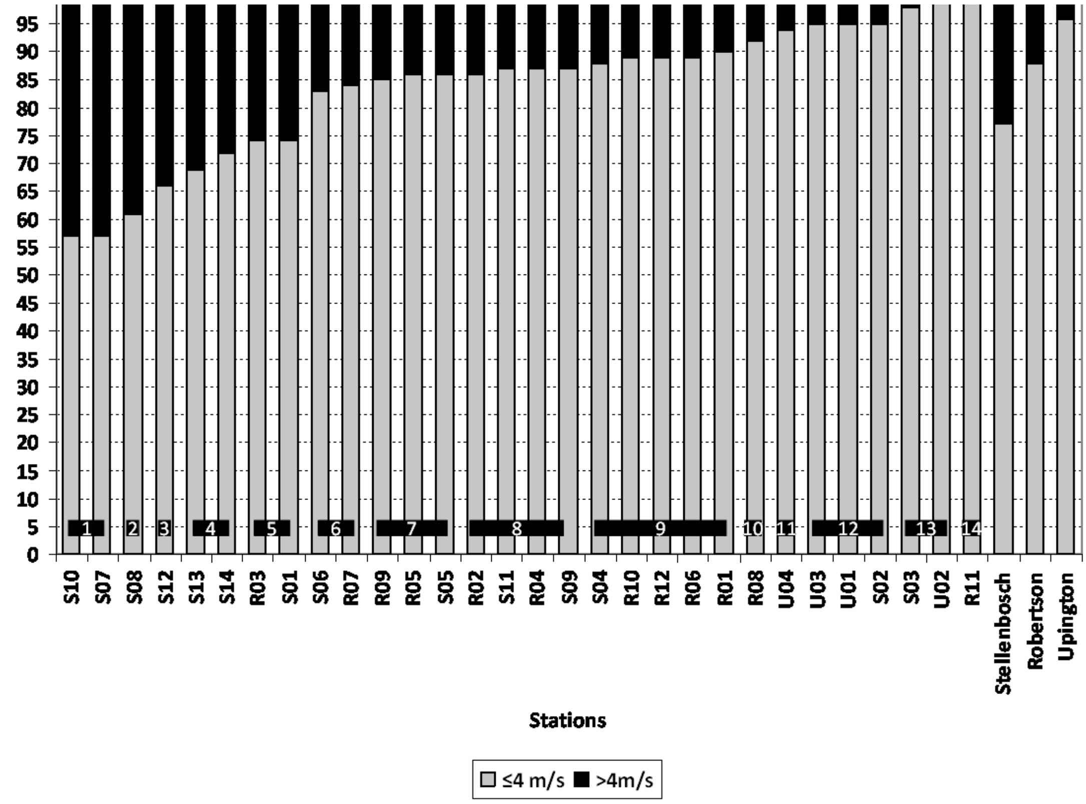

FIGURE 6B

Time between 09:00 and 15:00 (in %) with wind speed above and below 4m/s, during *post-véraison* for the 30 stations and average for the three districts (1999 to 2004). Stations are grouped (Waller grouping p=0.005) and classified according to ascending (≤4m/s) frequency.

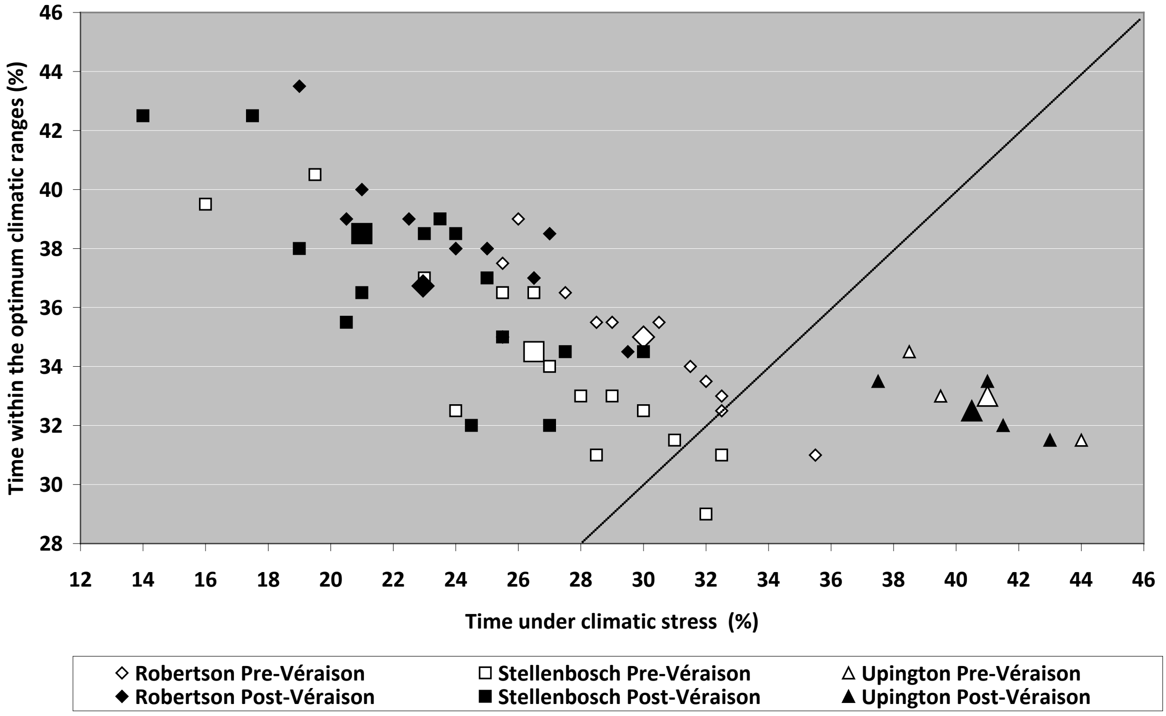

FIGURE 7
Cumulated time (%) within the optimum climatic ranges *vs* cumulated time (%) under climatic stress for photosynthesis during *pre-* (open symbols) and *post-véraison* (closed symbols) using a coefficient of 3 for temperature, 2 for relative humidity and 1 for wind. Average for the 30 stations and per district (larger symbols) over the 1999 to 2004 study period. A dashed line, below which stations experienced more often climatic stress than favourable climatic conditions, is superimposed.

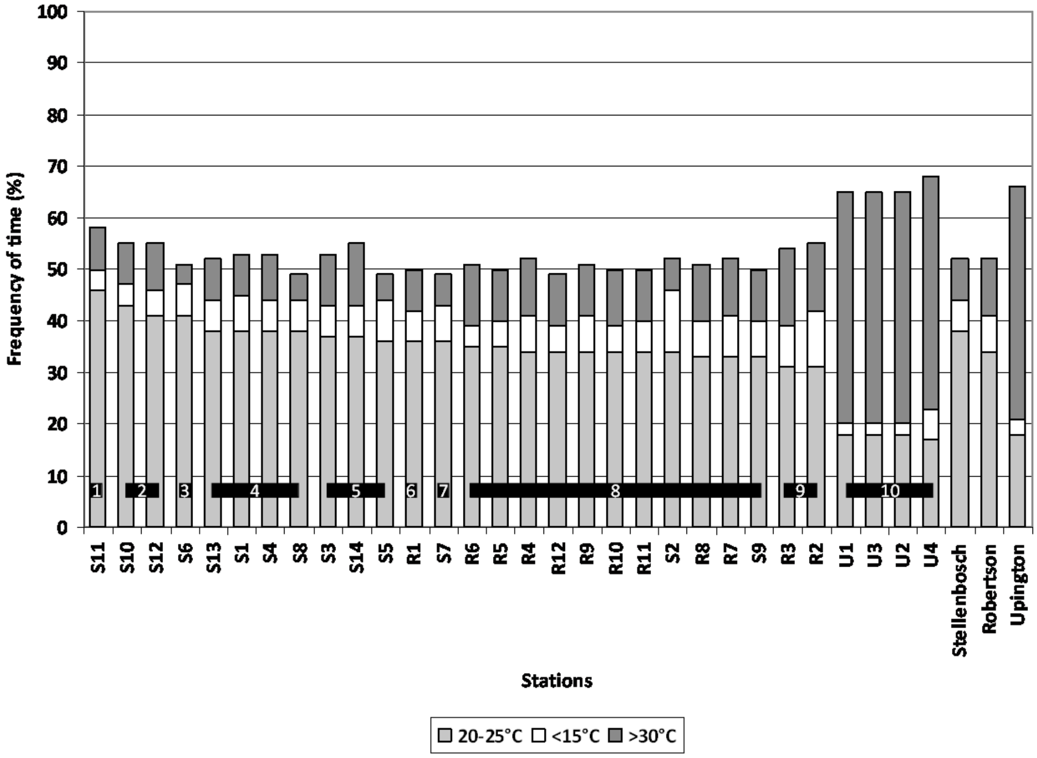

FIGURE 8A
Daytime (in %) with temperature below 15°C, between 20°C and 25°C and above 30°C for colour and flavour during *pre-véraison* for the 30 stations and average for the three districts (1999 to 2004). Stations are grouped (Waller grouping p=0.005) and sorted by descending % of time inside the optimum range (20°C to 25°C).

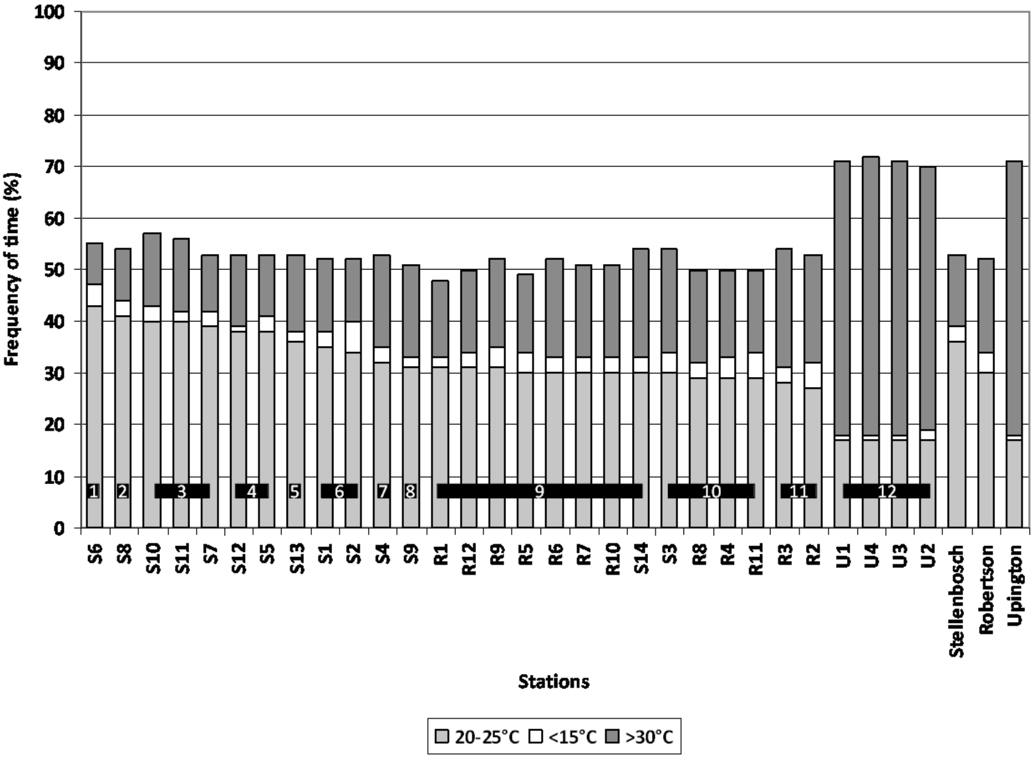

FIGURE 8B
Daytime (in %) with temperature below 15°C, between 20°C and 25°C and above 30°C for colour and flavour during *post-véraison* for the 30 stations and average for the three districts (1999 to 2004). Stations are grouped (Waller grouping p=0.005) and sorted by descending % of time inside the optimum range (20°C to 25°C).

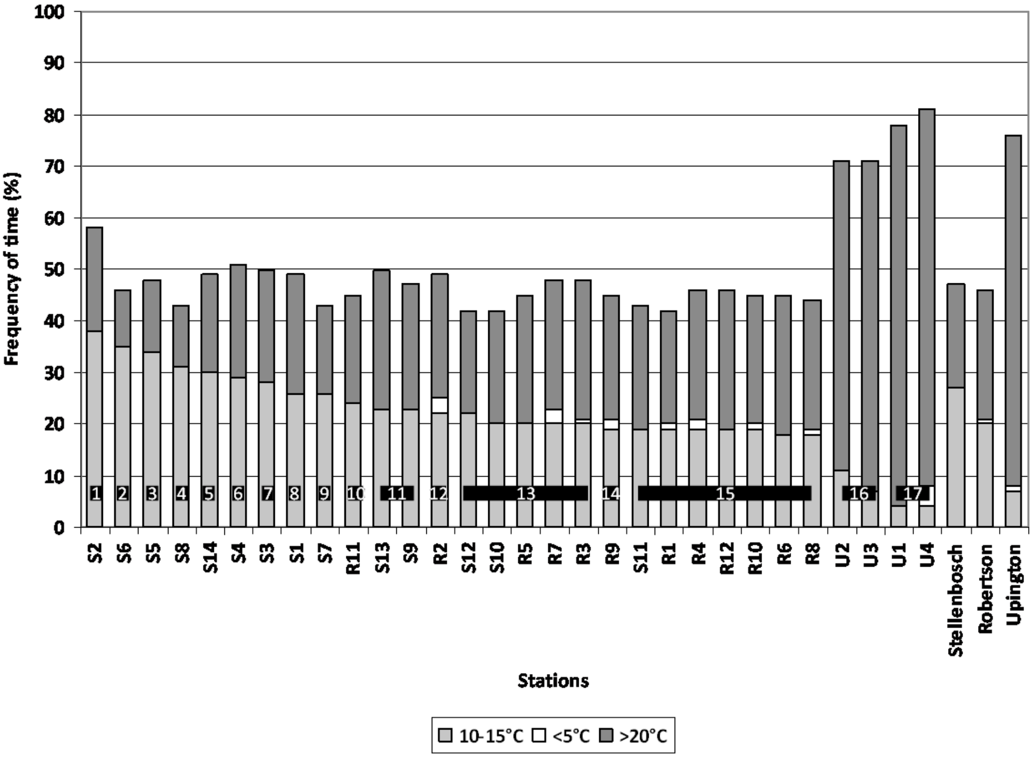

FIGURE 9A
Night time (in %) with temperature below 5°C, between 10°C and 15°C and above 20°C for colour and flavour during *pre-véraison* for the 30 stations and average for the three districts (1999 to 2004). Stations are grouped (Waller grouping p=0.005) and sorted by descending % of time inside the optimum range (10°C to 15°C).

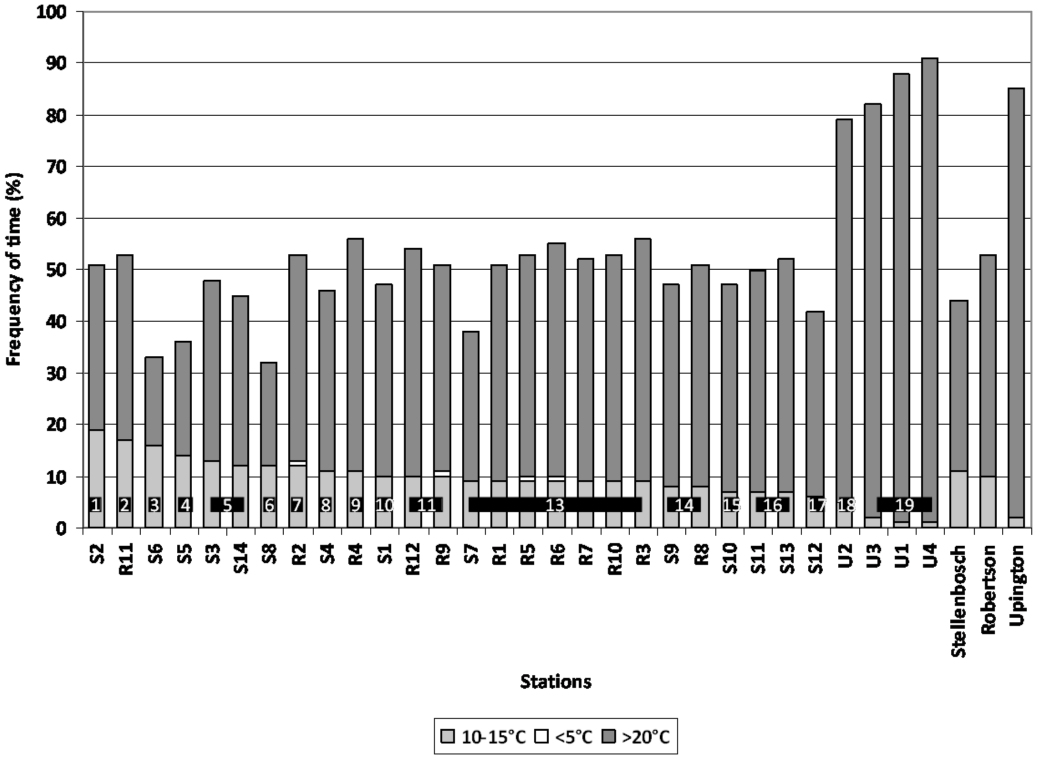

FIGURE 9B

Night time (in %) with temperature below 5°C, between 10°C and 15°C and above 20°C for colour and flavour during *post-véraison* for the 30 stations and average for the three districts (1999 to 2004). Stations are grouped (Waller grouping p=0.005) and sorted out by descending % of time inside the optimum range (10°C to 15°C).

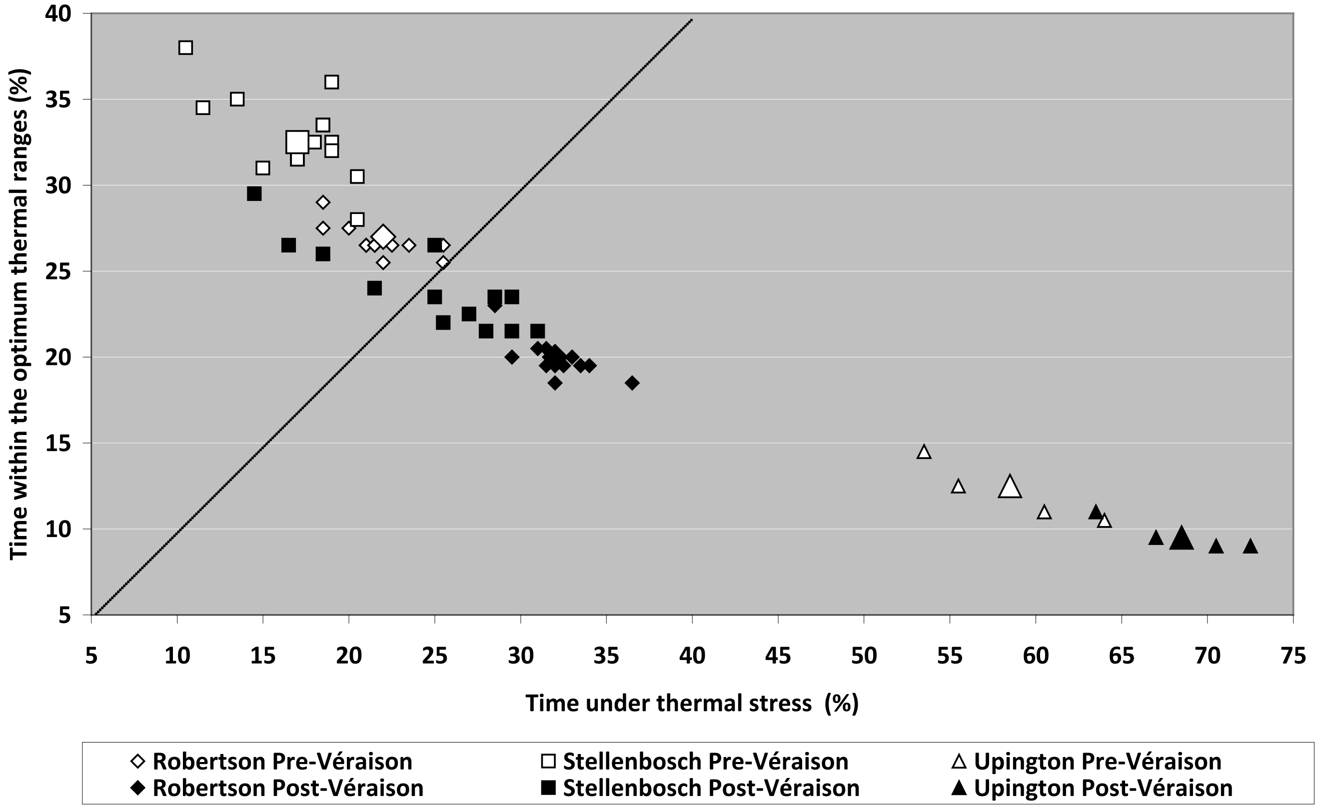

FIGURE 10

Mean cumulated time (%) within the day and night optimum temperature ranges *vs* mean cumulated time (%) under thermal stress for colour and flavour during *pre-* (open symbols) and *post-véraison* (closed symbols). Average for the 30 stations and per district (larger symbols) over the 1999 to 2004 study period. A dashed line, below which stations experienced more often climatic stress than favourable climatic conditions, is superimposed.

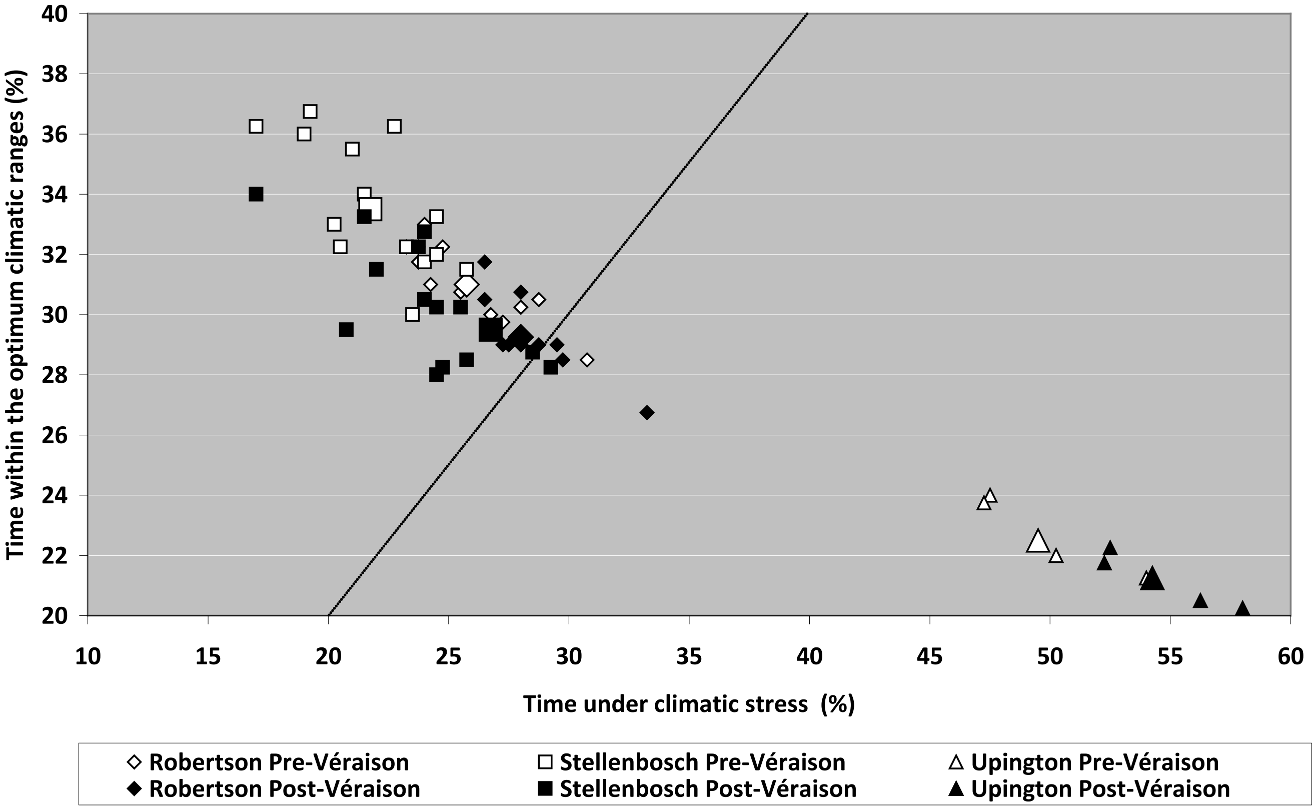

FIGURE 11
Mean cumulated time (%) within optimum climatic ranges *vs* mean cumulated time (%) under climatic stress for photosynthesis, colour and flavour during pre- (open symbols) and post-véraison (closed symbols). Average for the 30 stations and per district (larger symbols) over the 1999 to 2004 study period. A dashed line, below which stations experienced more often climatic stress than favourable climatic conditions, is superimposed.

optimal climatic ranges *versus* the mean total percentage of time under climatic stress for photosynthesis, colour and flavour parameters in combination, pre- and post-véraison (Fig. 11) and for the whole season (Fig. 12), the Stellenbosch district featured more sites in the top range and should be considered the best of the three districts in satisfying the requirements of the grapevine for expression of the measured parameters for 32% of the time on average (Fig. 12). The Stellenbosch district has a more complex topography and a cooler climate due to a moderating effect of the sea along the coast compared to the interior (SAWB, 1996). The occurrence of the sea breeze in the Stellenbosch district (Bonnardot *et al.*, 2002, 2004), which results in increasing wind velocity, intake of humidity and decreasing temperature, explains the earlier and lower maximum temperature, higher minimum relative humidity and earlier and stronger winds in this district compared to the other two districts (Fig. 3c). Along with the topographical variation, this also explains the larger site climatic heterogeneity in this district. The sea breeze in the Stellenbosch district seems to be a restrictive factor for optimal photosynthesis as far as wind is concerned, but the moderate temperature seems positive regarding colour development and the maintenance of flavour in this district. The Robertson district experienced almost as much climatic stress than favourable conditions (27% and 30% of the time, respectively), while vines in the Upington district clearly experienced excessive climatic stress (52%) (Fig. 12).

Special care should be taken to ensure that other biotic and abiotic impact factors on the grapevines are accommodated in such a way that the climatic profiles of the regions and terroirs within are used to maximum advantage in terms of growth, grape composition and wine quality/style.

CONCLUSIONS

The results showed different climatic profiles available for key grapevine physiological processes in South Africa and a significant spatial variation of these profiles within the regions investigated. Considering the relationships between climate and grapevine physiological behaviour, these climatic differences may have serious implications for the physiological functioning of grapevines. Mean climatic data and indices are seemingly not sufficient to properly understand variation in climatic conditions and, consequently, to quantify the impact on grapevine physiological behaviour at a particular location. This may lead to the selection and zoning of only apparently homogeneous terroirs, resulting in heterogeneous grapevine response. In this regard, the duration inside and outside an optimum range, and including extreme climatic conditions, would add value to climatic profile quantification aimed at grapevine physiological requirements and behaviour. The impact of potential climatic stress (direct and indirect) on grapevine physiological processes, growth, and grape development and quality should be further quantified.

On a macro-scale, climatic indices used to classify different

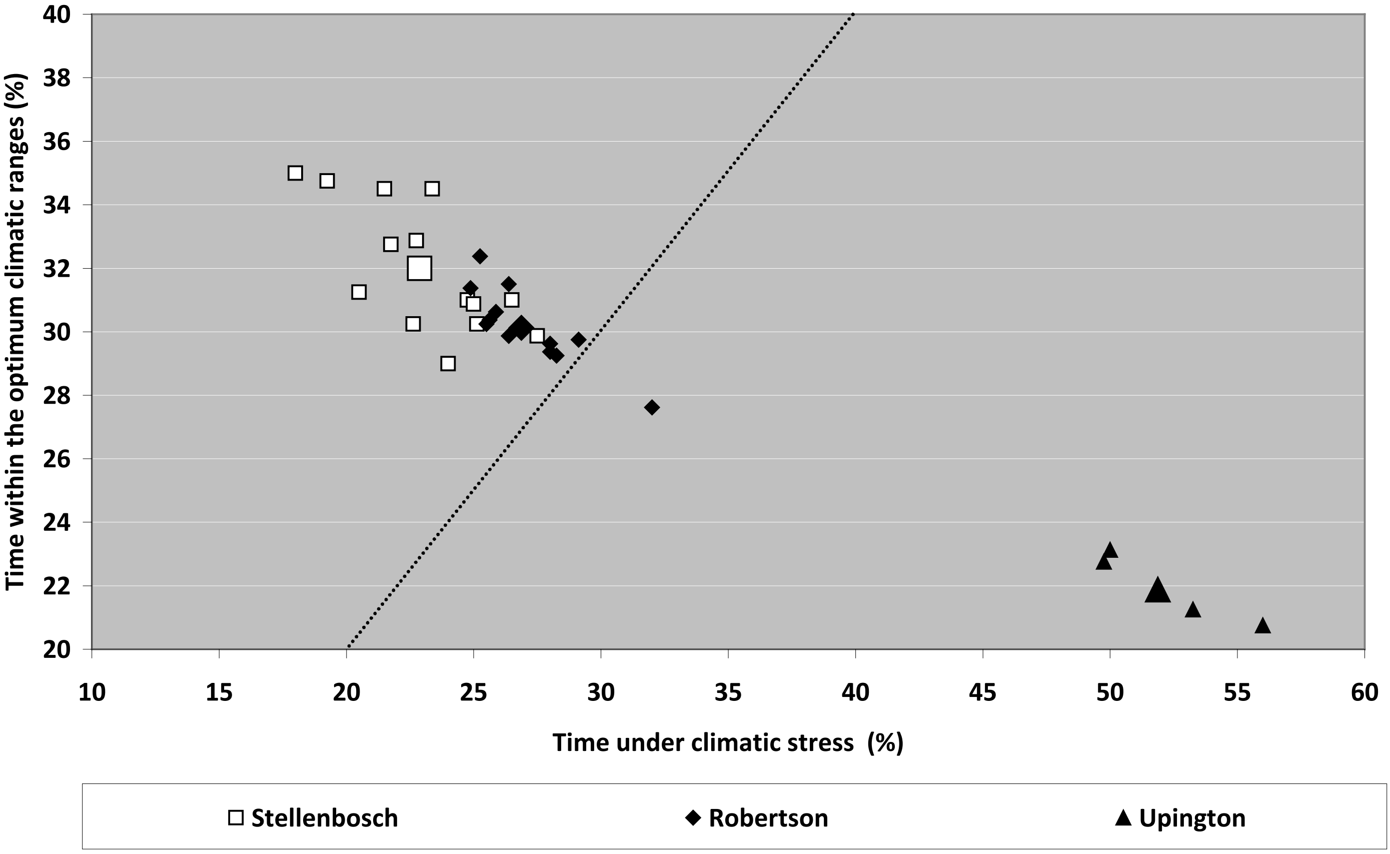

FIGURE 12

Averaged (*pre-* and *post-véraison*) cumulated time (%) within optimum climatic ranges *vs* averaged cumulated time (%) under climatic stress for photosynthesis, colour and flavour. Average for the 30 stations and per district (larger symbols) over the 1999 to 2004 study period. A dashed line, below which stations experienced more often climatic stress than favourable climatic conditions, is superimposed.

terroirs and which are applied for zoning, seem to be only an indication of what in reality is experienced between vine rows and by the root system and canopy in particular. The more macro-, meso-, micro- and even nano- (e.g. inside the bunches and at soil-root interface level) climate conditions and cultivating conditions in a particular region and at a particular site favour physiological requirements of the cultivar-rootstock combination to the benefit of grapevine functioning and grape development/composition, the better expression of site potential and the less seasonal variation in grape and wine quality would be obtained. Conversely, failure to successfully marry these concepts would result in an under-exploitation of the real potential of the chosen grapevine cultivar and site and would only result in an apparent zoning. In order to understand the behaviour of the grapevine within a particular terroir and to facilitate future terroir selection and zoning, these concepts must be studied in concert.

The novel methodology in linking climatic profiles and physiological processes, as explained in this paper, can be adapted and applied at any scale between and within wine regions. Further research that includes correlation between annual/seasonal variability of climatic profiles and wine quality (e.g. colour and flavour in particular) should be done to add further value.

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