SPATIAL VARIABILITY OF NIGHT TEMPERATURES AT A FINE SCALE OVER THE STELLENBOSCH WINE DISTRICT, SOUTH AFRICA

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Abstract

Aim : To improve knowledge of spatial climatic variability in viticultural region at fine scale

Methods and results : Night temperatures recorded at 40 data loggers that were located in the vineyards of the Stellenbosch Wine of Origin District were monitored during different weather conditions during the 2009 grape ripening period (January-March). The daily maximum difference in minimum temperature between the coolest and warmest sites was, on average, 3.2 °C for the three-month period while it reached a difference of 14 °C under radiative conditions (a difference of 1 °C to 2 °C per km and 3 °C per 100 m elevation approximately). Numerical simulations of night temperatures, using a mesoscale atmospheric model, were performed for two weather events over this period. Night temperature fields at 200 m resolution were generated, taking large scale weather conditions into account. Data from 16 automatic weather stations were used for validation. Temperature data from the data loggers that were located in the vineyards were used to produce maps of spatial distribution of the daily minimum temperature at a 90 m scale by means of multicriteria statistical modelling, which concomitantly took environmental factors into account. Locations with optimum thermal conditions for color and flavor development and maintenance were identified based on average values for the three-month period and for specific weather conditions.

Conclusion : The range of minimum temperatures varied as a function of geographical factors and synoptic weather conditions, which resulted in significant differences in night-time thermal conditions over the wine district, with possible implications for grape metabolism. The great spatial variability within short distances emphasized the difficulty of validating outputs of atmospheric modelling with accuracy. The study showed the importance and relevance of increasing resolution to refine studies on climate spatial variability and to perform climate modelling based on distinguished weather types.

Significance and impact of the study : In the context of climate change, it is crucial to improve knowledge of current climatic conditions at fine scale during periods of grapevine growth and berry ripening in order to have a baseline from which to work when discussing and considering future local adaptations to accommodate to a warmer environnement.

Key words : modelling, local climate, minimum temperature, wine-producing region, South Africa

Résumé

Objectif : Améliorer les connaissances sur la variabilité climatique spatiale en milieu viticole à échelle fine

Méthodes et résultats : Les températures minimales enregistrées par 40 capteurs situés dans les vignes du district de Stellenbosch sont étudiées, sous différentes conditions météorologiques, au cours de la période 2009 de maturation du raisin (janvier-mars). La différence maximale (en termes de température minimale) entre les sites est de 3,2 °C en moyenne pour la période étudiée, alors qu'elle atteint 14 °C par conditions radiatives (une différence de 1 °C à 2 °C par km et 3 °C par élévation de 100 m environ). Des simulations numériques utilisant un modèle atmosphérique méso-échelle ont été effectuées pour deux événements au cours de cette période afin de générer des champs de température minimale à 200 m de résolution prenant en compte la circulation atmosphérique de grande échelle. Les données de 16 stations météorologiques automatiques ont été utilisées pour valider les résultats. Les données de température des capteurs ont servi à produire les champs de température minimale à une échelle de 90 m grâce à une modélisation statistique multicritère prenant en compte les facteurs environnementaux. Les endroits avec des conditions optimales pour le développement et la maintenance de la couleur et des arômes sont identifiés en moyenne pour la période de trois mois et pour des conditions météorologiques particulières.

Conclusion : La fourchette des températures minimales qui varient en fonction des facteurs géographiques, mais aussi des conditions synoptiques, aboutit à des conditions thermiques nocturnes très différentes dans le district viticole avec un impact possible sur le métabolisme de la vigne. La grande variabilité spatiale enregistrée sur de très courtes distances souligne la difficulté de valider de façon précise les résultats de modélisation atmosphérique. L'étude a montré l'importance d'augmenter la résolution pour affiner les études sur les variations climatiques spatiales et de modéliser en fonction des types de temps.

Signification et impact de l'étude : Dans le contexte du changement climatique, il est capital d'améliorer les connaissances sur les conditions climatiques actuelles à échelle fine pendant les périodes de croissance de la vigne et de maturation des raisins dans les régions viticoles pour bénéficier d'une référence à partir de laquelle travailler lorsqu'il s'agira d'envisager les futures adaptations locales pour accommoder la vigne dans un environnement plus chaud.

Mots clés : modélisation du climat local, température minimale, région viticole, Afrique du Sud

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INTRODUCTION

Identification and characterisation of diverse environments for viticulture at different scales are of importance for the South African Wine Industry and a focal point of the South African viticultural research (Carey *et al.*, 2008). Among environmental factors contributing to viticulture, climate, and especially temperature, has an important effect on grapevine growth, wine quality and character (Coombe, 1987). Various environmental studies that have been undertaken in the Stellenbosch Wine of Origin District have shown significant mesoclimatic differences over short distances (Carey, 2001 ; Carey *et al.*, 2003a ; Conradie *et al.*, 2002 ; Hunter and Bonnardot, 2002). The proximity of the Atlantic Ocean and the complex topography, which includes coastal dunes, a coastal plain, inland hills and steep mountain ranges, cause the development and the interaction of interesting meso- and local scale air circulations, resulting in significant climatic variations for viticulture. Analysis of climatic surface data from the mesoscale network of weather stations showed that local air circulation (sea breeze) in this coastal region played a significant role in maximum temperature differences (Bonnardot, 1999 ; Carey *et al.*, 2003b ; Bonnardot, 2005). The sea breeze-induced patterns and the contributing effects of topography to local air circulation were ascertained at 5 km and 1 km scales with numerical simulations performed over this wine-producing region using a mesoscale atmospheric modelling system (Bonnardot *et al.*, 2002, 2005). More recent simulations (Bonnardot and Cautenet, 2009) have shown that, for local circulations forced by topography and surface contrasts, the use of a higher horizontal resolution (200 m) was of greater value in the characterisation of climatic potential of viticultural environments. Increasing resolution is therefore necessary to fully represent the vineyard-site climate.

In order to reproduce climatic fields at these fine scales, other approaches based on spatial interpolation methods are often used (Laughlin and Kalma, 1987 ; Carrega, 1995 ; Blennow and Persson, 1998 ; Wackernagel, 1998 ; Kurtzman and Kadmon, 1999 ; Bradley *et al.*, 2002 ; Chapman and Thornes, 2003 ; Madelin and Beltrando, 2005 ; Hijmans *et al.*, 2005 ; Stahl *et al.*, 2006 ; Daly, 2006 ; Bonnardot *et al.*, 2010), in particular applied to Southern Africa (Schulze, 1997 ; De Villiers, 1997 ; Joubert, 2007). For the Western Cape, Joubert (2007) estimated temperature and precipitation grids from observed points, using the ANUSPLIN software (thin plate smoothing splines and digital elevation model).

Research in this wine region has mainly concentrated on diurnal maximum temperatures as a result of the focus of studies on the sea breeze development and penetration. However, nocturnal temperatures are also of importance for the description of vineyard-site climates due to their effect, inter alia, on grapevine ripening, anthocyanin synthesis, and wine aroma potential (Coombe, 1987 ; Mori *et al.*, 2005 ab ; Hunter and Bonnardot, 2011), although effect of temperature varies depending on cultivars (Kliewer and Torres, 1972).

This paper focuses on the analysis of spatial variability of night temperatures within the Stellenbosch Wine of Origin District during the period of grape ripening. This research makes use of a temperature sensor / data logger network in order to observe vineyard-site climate and assess temperature variability at fine scales.

A mesoscale atmospheric modelling system is used so as to understand the local physical atmospheric processes that cause climate variability in the wine district. Previous generations of atmospheric models have been used to successfully predict the nocturnal cooling in an agricultural environment (Heinemann and Martsolf, 1988) and in a basin (Kondo and Okusa, 1990). In this case, the atmospheric modelling was used to create a high resolution grid of night temperatures under different weather conditions and thus to investigate the different degrees of nocturnal cooling, which may impact on grape berry metabolism.

Finally, statistical modelling is also used to map spatial distribution of night temperatures at fine scale. The aim is to identify, at increased spatial resolution, locations with optimum thermal conditions for color and flavor development and maintenance based both on average data for the three-month period and on data for specific weather conditions.

MATERIALS AND METHODS

1. Study domain

The study domain is located within the Stellenbosch Wine of Origin District in the Western Cape Province of South Africa (Figure 1).

2. Night temperature analysis : data loggers

Night temperature conditions over the 2009 grape ripening period (January-March) were analyzed using data from a fine scale network consisting of 40 data loggers (Gemini Tinytag Ultra 2 TGU-4500 or Gemini Tinytag Talk 2 TK-4023) (Table 1 and Figure 2). The Tinytag data loggers are situated in grapevine rows at 1.5 m above the ground at a similar height to the grapevine canopy in a ACS-5050 Stevenson type screen (Photo 1). Standardization between loggers was ensured as best as possible (e.g., removal of canopy around loggers) to reduce any data alteration (Craparo, 2009).

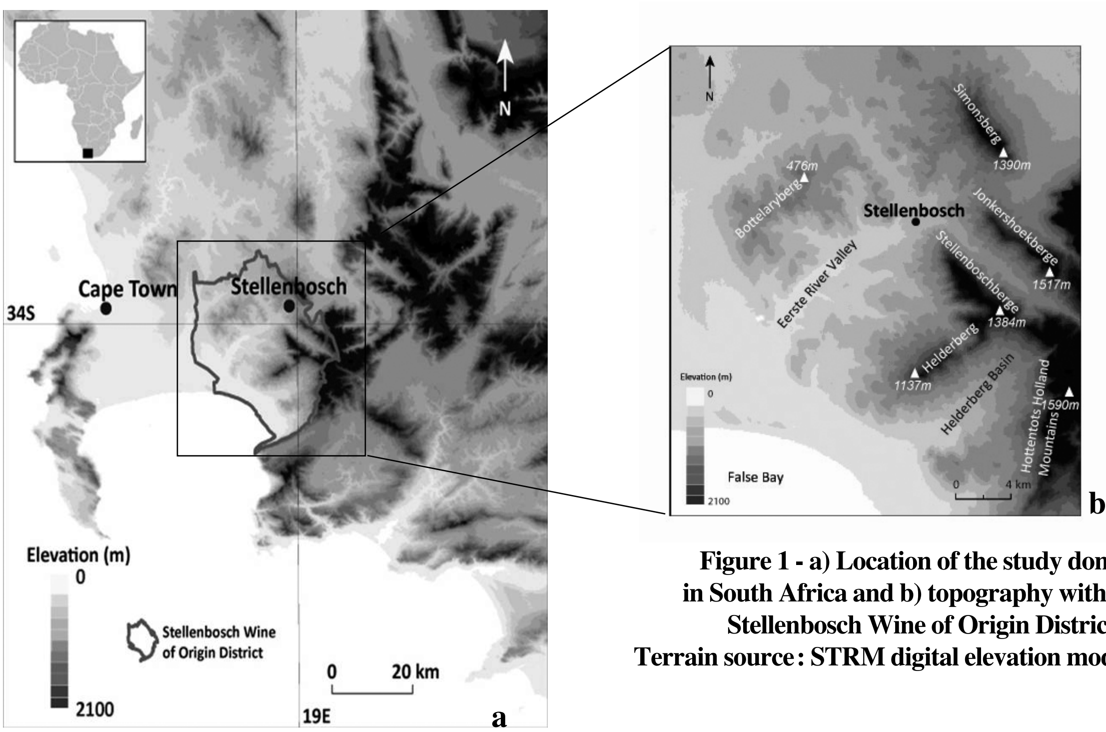


Figure 1 - a) Location of the study domain in South Africa and b) topography within the Stellenbosch Wine of Origin District. Terrain source: STRM digital elevation model (~90m)

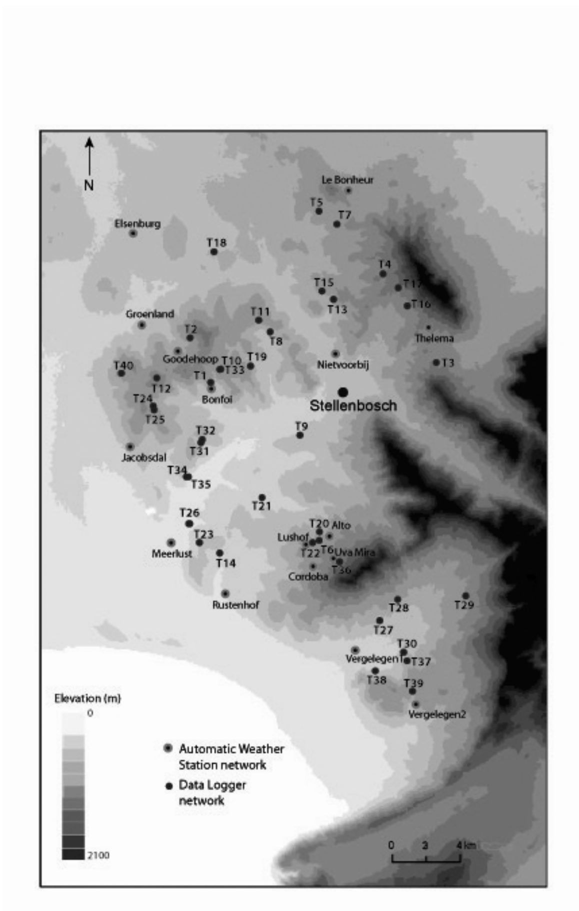


Figure 2 - Climatic networks (automatic weather station and Tinytag data loggers) within the Stellenbosch Wine of Origin District. Terrain source: SRTM digital elevation model (~90 m).

3. Modelling of temperature

Atmospheric modelling: RAMS numerical simulations were used in parallel to map mesoscale and local physical processes causing temperature variability, similarly to previous research in South Africa (Bonnardot *et al.*, 2002, 2005; Bonnardot and Cautenet, 2009). Version 6.0 of the Regional Atmospheric Modelling System (RAMS) (http://www.atmet.com; Pielke *et al.*, 1992) was used to perform the numerical simulations. RAMS is a numerical model based on the basic physical equations that govern the processes operating in the atmosphere. It takes surface data (landcover, topography and soil texture) and large scale atmospheric data into account. RAMS uses nested grids to provide high spatial resolution while covering a large domain at lower resolution. In this study, four grids were used (Figure 3a). The 25 km coarse resolution grid is the computational domain for simulations (29°S to 38°S and 13°E to 24°E), devoted to synoptic circulations. The second and third grids represent intermediate scales with horizontal resolutions of 5 km and 1 km (Figure 3b). Grid 4 is the high resolution grid (200 m) and the investigated domain for local air circulations over the Stellenbosch wine district (Figure 3c).

Simulations were performed for the 27th, 28th and 29th January 2009 and the 5th and 6th March 2009 in order to study the cooling potential of the terroirs under different weather conditions. Results are shown for the 28th January 2009 and the 5th March 2009 using horizontal cross sections for the 200 m grid resolution as

Table 1 - List of the Tinytag data loggers with their geographical coordinates and topographical attributes. Source: SRTM digital elevation (~90 m)

	Location	Latitude (South)	Longitude (East)	Elevation (m)	Slope (degree)	Aspect (degree)
T1	Aan den Weg	33.932	18.780	197	9.2	170
T2	Amperbo	33.908	18.767	267	14.3	202
T3	Clouds	33.922	18.925	401	11.1	55
T4	Delheim	33.874	18.890	413	11.1	252
T5	Delvera	33.841	18.850	247	6.4	213
T6	Helderkruin	34.018	18.845	237	3.1	336
T7	Laibach	33.848	18.861	245	10.3	309
T8	Leiberg	33.905	18.818	145	6.4	224
T9	Libertas	33.960	18.837	117	4.7	343
T10	L'Olivier	33.925	18.786	256	7.8	223
T11	Martin Meinert	33.899	18.811	224	12.7	195
T12	Mooiplaas	33.930	18.746	350	5.0	323
T13	Morgenhof	33.888	18.859	225	13.3	254
T14	Nuwerus	34.023	18.786	88	4.8	178
T15	Remhoogte	33.884	18.851	205	6.8	166
T16	Rustenberg CS	33.892	18.906	386	5.3	260
T17	Rustenberg SB	33.882	18.900	467	16.3	197
T18	Swartrivier	33.862	18.782	157	1.4	360
T19	Waterkloof	33.923	18.806	175	8.5	28
T20	Webersburg	34.011	18.850	177	4.8	333
T21	Blue Mountain	33.994	18.813	88	0.8	281
T22	Ernie Els	34.017	18.850	250	7.0	288
T23	Faure	34.018	18.773	109	7.5	273
T24	Jordan Top	33.947	18.744	257	10.2	17
T25	Jordan Mid	33.946	18.744	219	11.0	27
T26	Klein Welmoed	34.008	18.766	27	3.2	323
T27	Lourensford Bot	34.059	18.888	135	1.5	108
T28	Lourensford Mid	34.048	18.900	217	7.2	130
T29	Lourensford Top	34.046	18.943	320	6.5	219
T30	Morgenster	34.085	18.887	90	6.1	346
T31	Olives North	33.964	18.774	112	6.9	106
T32	Olives South East	33.963	18.775	111	8.1	194
T33	L'Olivier	33.925	18.786	256	7.8	223
T34	Uitsig Bot	33.983	18.766	49	8.2	121
T35	Uitsig Mid	33.980	18.765	84	7.9	135
T36	Uva Mira	34.028	18.862	445	9.3	283
T37	Vergelegen Bot	34.076	18.903	137	5.5	252
T38	Vergelegen Mid	34.080	18.905	183	3.9	303
T39	Vergelegen Top	34.097	18.909	262	5.7	191
T40	Zevenwacht	33.927	18.723	245	9.1	233

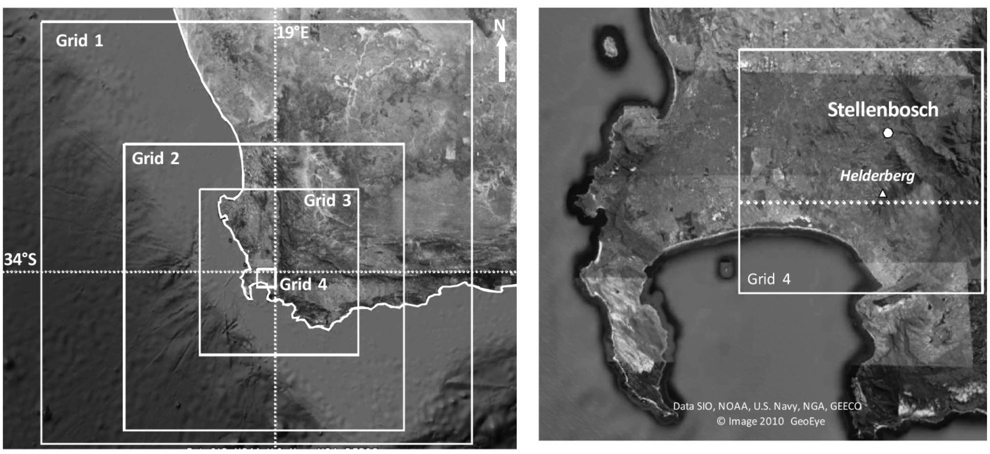
well as a West-East cross section going from the Eerste River Valley, over the Helderberg Mountain and Basin through to the Hottentots Holland Mountains (Figure 3d). Temperature data from the automatic weather station network of the ARC-ISCW (Institute for Soil, Climate and Water of the Agricultural Research Council) situated in proximity to studied vineyards (Figure 2) were used to validate the modelled output data.

Large-scale data, averaged over 00h00 UTC to 06h00 UTC for the South Atlantic Ocean and Southern Africa, from the NCEP Reanalysis (Kalnay *et al.*, 1996; http://www.esrl.noaa.gov/psd) were used to describe the synoptic weather conditions during the two study cases.

Multicriteria statistical modelling: In order to construct a fine-scale spatial temperature field, a second approach was used. This approach was based on multicriteria statistical modelling, taking environmental factors into account. Indeed, the role of topographic factors in the spatial variability of temperatures at fine scales, in addition to the influence of geographical location (latitude/longitude) at larger scale, has already been demonstrated (Geiger, 1966). In the present study, we used a multivariate (stepwise) linear regression to explain the variability of minimum temperature values of the 40 Tinytag data loggers located in vineyard rows (Figure 2), retaining as relevant a priori factors: position (determined by GPS), elevation, provided by the SRTM 90 m Digital Elevation Model (Shuttle Radar Topography Mission - http://srtm.usgs.gov), slope and aspect (2 components) computed from this dataset using a GIS software. Three different models were computed by taking into account 1) the minimum temperature on the 28th January 2009, 2) the minimum temperature on the 5th March 2009 and 3) the mean minimum temperature for the January-March 2009 period. The robustness of the models obtained from this analysis was then tested using a simple cross-validation technique. We computed 40 models for each dataset. For each model, observations from 10 % of sensors, i. e., 4 locations (changed iteratively), were discarded. The variations of the selected factors and the model's coefficients were examined for each run. Finally, the obtained models were used to estimate and map night temperature for the whole studied area. The spatial output had a resolution of 90 m x 90 m.

Photo 1 - Tinytag data logger (Gemini Tinytag Talk 2 TK-4023) inside a ACS-5050 Stevenson type screen mounted on a trellis pole in a grapevine row in the Stellenbosch Wine of Origin District

a) c)



b)

	Dimensions (km)	Horizontal resolution	Nb of cells	Grid points
Grid 1	1025 x 1025	25 km	41 x 41	1681
Grid 2	505 x 505	5 km	101 x 101	10201
Grid 3	281 x 301	1 km	281 x 301	84581
Grid 4	40,2 x 40,2	200 m	201 x 201	40401

d)

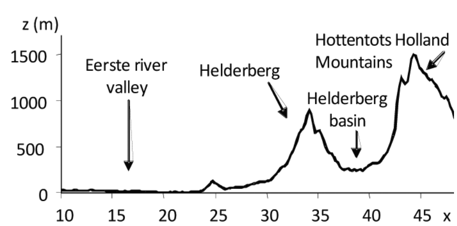


Figure 3 - a) Computational domain and nested grids for numerical simulations over South Africa using the Regional Atmospheric Modelling System (RAMS); b) Dimensions of the nested grids for RAMS numerical simulations over the study domain; c) Locations of Grid 4 and cross section at 34°01'43''S (dotted line) used to display results at a 200 m resolution over the Stellenbosch Wine of Origin District; and d) Topography along the cross section (source: RAMS 200 m resolution outputs).

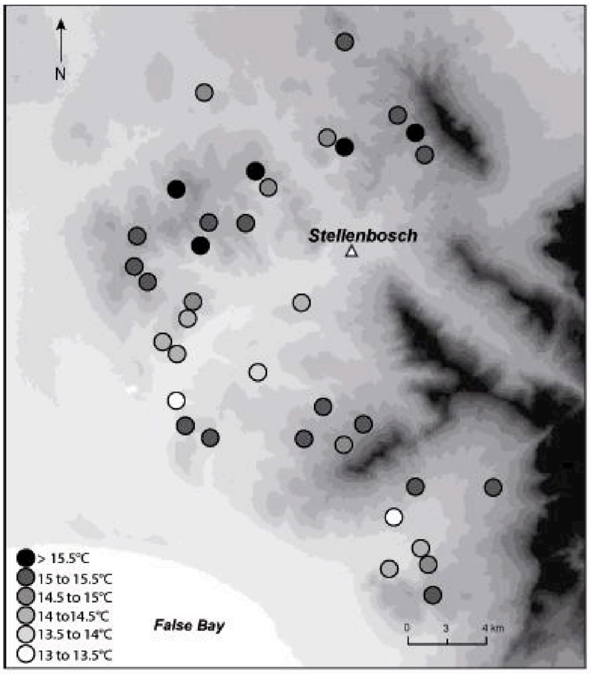


Figure 4 - Mean minimum temperature in the Stellenbosch Wine of Origin District recorded for the January to March 2009 period by 36 data loggers.
Circles represent measurement points and gradations of grey within each circle represent temperature ranges. Terrain source: SRTM digital elevation model (~90 m).

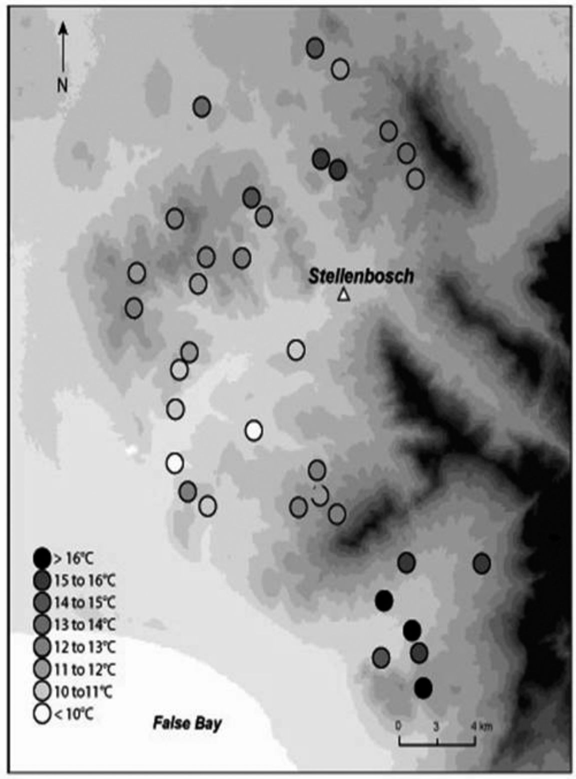


Figure 5 - Minimum temperature in the Stellenbosch Wine of Origin District recorded a) on 5/03/2009 (radiative weather conditions) by 31 data loggers and b) on 28/01/2009 (advective weather conditions) by 35 data loggers.
Circles represent measurement points and gradations of grey within each circle represent temperature ranges. Terrain source: SRTM digital elevation model (~90 m).

RESULTS AND DISCUSSION

1. Observed data

The night-time temperature variability during the 2009 grape ripening period (January to March) and then two study cases representative of radiative (5th March 2009) and advective weather conditions (28th January 2009) are presented and discussed.

The mean difference between minimum temperatures recorded at the different measurement points was 3.2 °C for the three-month period of January to March 2009. The coolest site (T27 at 13 °C) was situated on a lower slope of the Helderberg Basin and the warmest site (T30 at 16.2 °C) was situated inland to the north of Stellenbosch on the foot slopes of Simonsberg (Figure 4).

The greatest difference in minimum temperature between the different sites was 14 °C on 5th March 2009. For this night, a significant correlation was observed between elevation and minimum temperature recorded in vineyards ($R^2 = 0.89$), with warmer conditions at higher altitudes and cooler conditions at lower altitudes (Table 2). The highest minimum temperatures (23.8 °C and 23.4 °C) were recorded in vineyards situated at 467 m above sea level (asl) on the south-western slopes of Simonsberg and at 445 m asl on the north-western slopes of Helderberg, respectively (Figure 5a). The lowest minimum temperature (11.8 °C) during this night was recorded in a vineyard situated at 27 m asl in the Eerste River Valley. This represented a difference of 11.6 °C over a 12 km distance between the Eerste River Valley and the Helderberg slopes with a corresponding difference in elevation of 418 m. A temperature difference of 10.6 °C over a distance of 6 km and one of 12.2 °C over a distance of 12 km were observed on the western slopes of Simonsberg. In the Helderberg Basin, the greatest temperature difference reached 8.2 °C over a 185 m difference in elevation, between the highest (320 m) and the lowest (135 m) locations, recording 22.1° C (T29) and 13.9 °C (T27), respectively. These observations represented a difference of 1 °C to 2 °C per km in distance and 3 °C to 4 °C per 100 m in elevation. These values approximate those that have been observed in other, non-agricultural environments (Gustavsson, 1995).

On the 28th January 2009, the difference between the coolest and the warmest site was reduced to nearly 8 °C (Figure 5b). The lowest minimum temperatures (9.2 °C

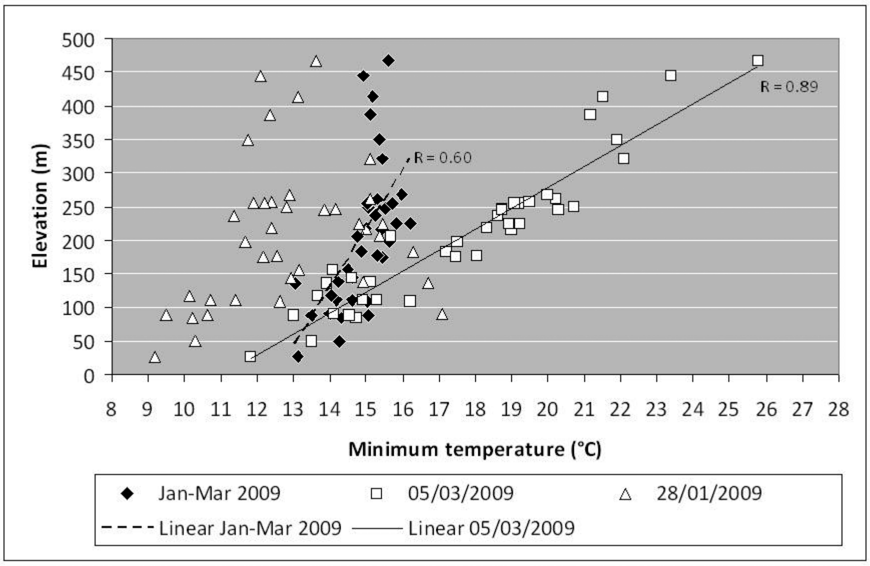


Figure 6 - Minimum temperature (°C) in the vineyards of the Stellenbosch Wine of Origin District (mean value for the 01/01/2009 to 31/03/2009 period, and values measured on 05/03/2009 and on 28/01/2009) vs elevation (m).

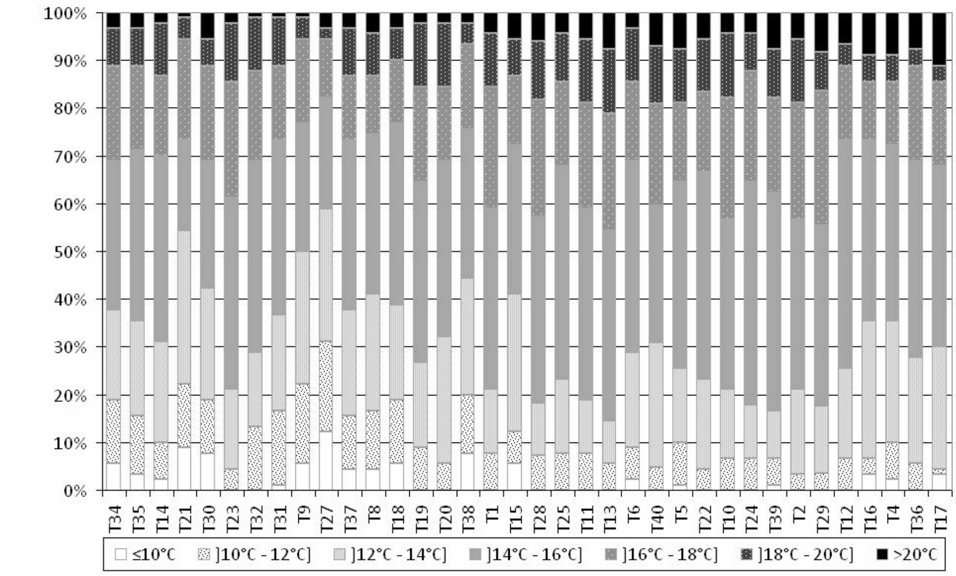


Figure 7- Frequency of daily minimum temperature ranges, using 2 °C thresholds, expressed as a percentage (%) of the total January-March 2009 period for 36 available sites. Sites are sorted by ascending elevation above sea level.

and 9.5 °C) were again recorded in the Eerste River Valley. The highest values were recorded inland on the slopes of Simonsberg (17.1 °C) or in the vineyards of the Helderberg Basin (between 15 °C and 16 °C).

As a result of steep temperature gradients along the slopes, vineyards experienced varying nocturnal conditions despite short distances, which may have been of significance for grape ripening (Tonietto and Carbonneau, 2004 ; Hunter and Bonnardot, 2011). The temperature gradient limits varied as a function of elevation as well as atmospheric conditions (Table 2). Temperature differential with change in elevation was greater during radiative weather conditions (Figure 6) and showed well-known inversion phenomena and downslope cold air drainage (Geiger, 1966 ; Madelin and Beltrando, 2005 ; Quenol *et al.*, 2007 ; Quenol and Beltrando, 2008). However, it was found in a study over the vineyards of Hérault, South of France (Tondut *et al.*, 2006) that the cool night index (March minimum temperature as described by Tonietto and Carbonneau, 2004) was not always well correlated

Table 2 - Minimum temperature values and elevation of corresponding vineyards; mean values for 01/01/2009 to 31/03/2009 and values during radiative (05/03/2009) and advective (28/01/2009) weather conditions in the Stellenbosch Wine of Origin District.

Minimum temperature ranges (°C)	Elevation of corresponding vineyards (m asl)		
	Mean calculated for 01/01/2009 to 31/03/2009	Recorded on 05/03/2009	Recorded on 28/01/2009
≤ 12	/	< 50 m	< 120 m
]12-14]	< 150 m	> 50 m and < 150 m	> 100 m and < 450 m
]14-16]	> 80 m and < 450 m	> 80 m and < 200 m	> 200 m and < 350 m
]16-18]	/	> 110 m and < 200 m	> 120 m and < 200 m
]18-20]	/	> 200 m and < 260 m	/
> 20	/	> 250 m	/

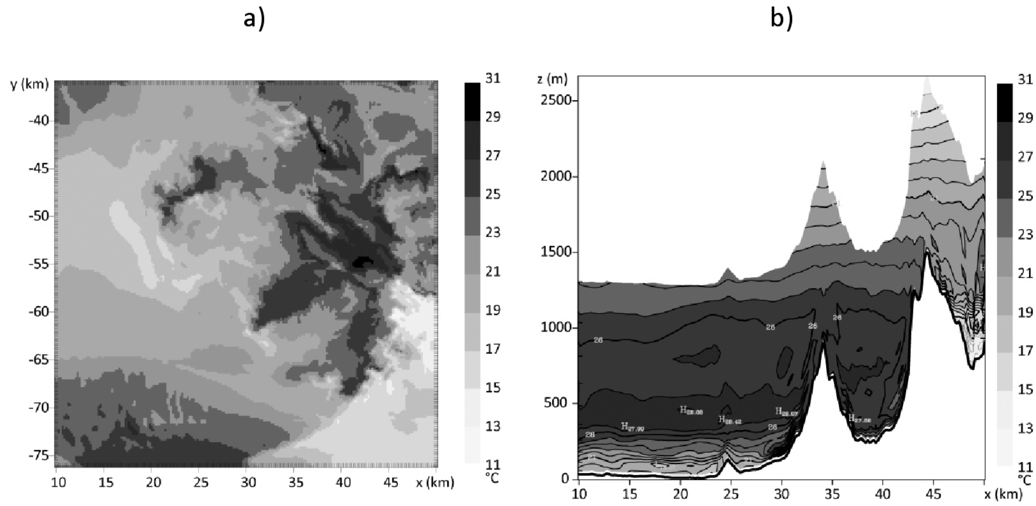


Figure 8 - RAMS modelled temperature (°C) at 200 m resolution over the Stellenbosch Wine of Origin District on 5/03/2009 at 04h00 UTC (06h00 South African time). a) Horizontal cross section at z = 24 m and b) West-East cross section at 34°01'43''S.

to elevation. Slope aspect and soil surface condition are also factors that affect this index.

This thermal inversion phenomenon (positive temperature difference between the highest -T17- and lowest -T26- sensors in the vineyards) occurred frequently at night during the January-March 2009 ripening period (71 % of the time), out of which 63 % and 3 % of occurrences had a temperature difference greater than 2 °C and 8 °C respectively. However, as shown in Figure 7, the frequency of daily minimum temperature ranges, using 2 °C thresholds, and expressed as a percentage over the January-March 2009 period, displays night-time temperatures that vary spatially. According to literature the optimum night temperature requirements for color and flavor development lie between 10 °C and 15 °C (Hunter and Bonnardot, 2011), and using these thresholds, the percentage of night-time with optimum thermal conditions (here between 10 °C and 16 °C) can be estimated as varying from 55 % (at T13 & T30) to 82 % (at T28) (Figure 7). Time with high night temperature stress for color and flavor (>20 °C) varied from 1 % (at T9 & T21) to 12 % (at T17). Many sites did not experience time with low night temperature stress but some of them, such as T27, experienced up to 12 % of time with minimum temperature values below 10 °C. Within the district, the spatial variability of nocturnal cooling of grapes is significant over short distances.

2. Atmospheric modelling

Analysis of the synoptic weather conditions for the 5th March 2009 showed that the Western Cape experienced winds with a northerly component, corresponding to winds to the west of a high pressure system over the interior (from NOAA, results not shown). The air at surface, averaged between 00h00 UTC and 06h00 UTC, was warm (between 21 °C and 23 °C) and

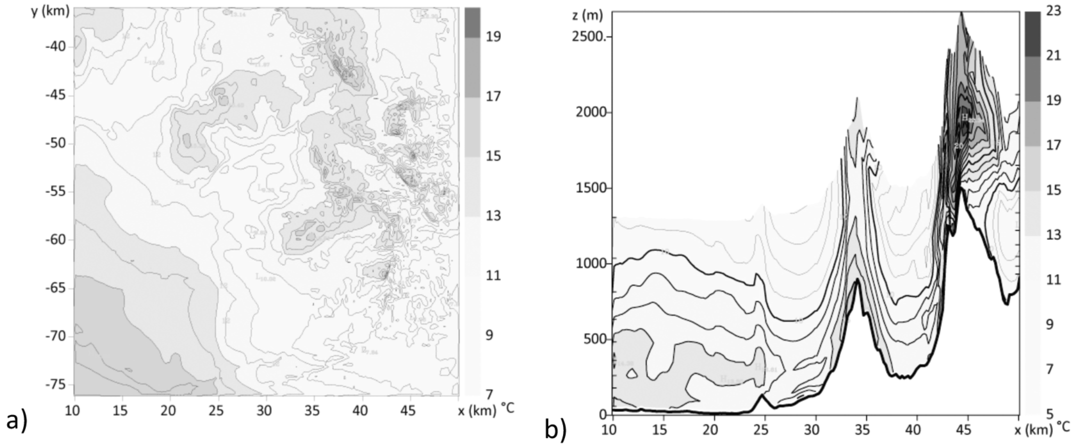


Figure 9 - RAMS modelled temperature (°C) at 200 m resolution over the Stellenbosch Wine of Origin District on 28/01/2009 at 04h00 UTC (06h00 South African time). a) Horizontal cross section at z = 24 m and b) West-East cross section at 34°01'43"S.

dry (less than 60 % of relative humidity) over the South Western Cape.

Physical processes in the lower atmosphere causing the temperature variation in the vineyards described in the previous paragraphs were investigated using mesoscale atmospheric modelling high resolution outputs. The West-East cross section of wind over the study domain at 06h00 South African local time, the time at which minimum temperature is usually recorded, showed light (< 2 m/s) land and downslope air circulations on the western slope of Helderberg and stable air (0 m/s) in the Helderberg Basin and Valleys to the east (Bonnardot *et al*., 2010). This favored cool air accumulation in the lowest positions in valleys and on lower slopes in the early morning. As shown in Figure 8a, modelled temperature values in the Eerste River Valley were the lowest of the district and those on mid western slopes of Helderberg and Hottentots Holland Mountains were the highest, similarly to what was recorded in the vineyards. The thermal inversion represented an approximately 500 m layer above the flat terrain of the Eerste River Valley (Figure 8b), explaining the significant positive correlation between elevation and observed minimum temperature up to an altitude of 500 m.

Using the large scale data from NOAA (results not shown), a high pressure system was located to the South West of Cape Agulhas with lower pressure over the interior on the 28th January 2009, resulting in winds with a easterly component. The air at surface (averaged between 00h00 UTC and 06h00 UTC) over the South Western Cape was cooler (16 °C to 17 °C) and more humid (between 75 % and 80 % relative humidity) than that of the previous case study. Consequently, results from the mesoscale atmospheric modelling at 200 m resolution showed that

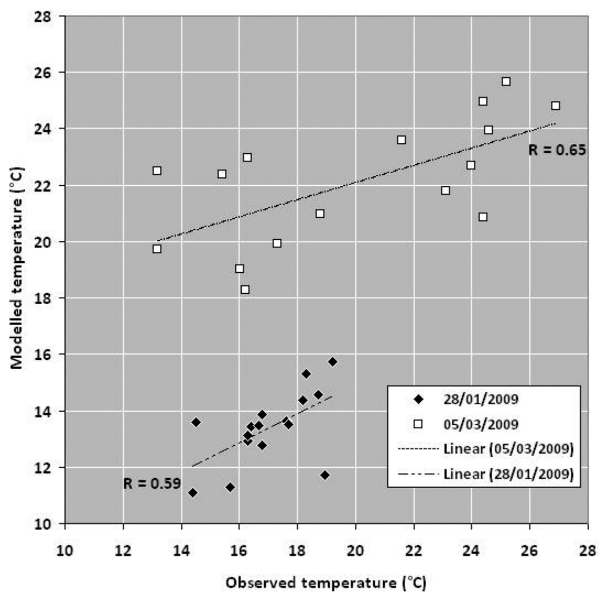


Figure 10 - Observed temperature at 06h00 South African local time for the 16 automatic weather stations located in the Stellenbosch Wine of Origin District vs modelled temperature by RAMS (obtained from the surrounding RAMS grid points for the 200 m resolution grid) for 28/01/2009 and 05/03/2009.

a thermal inversion occurred, yet not as important as the one that occurred for the previous case study, resulting in a reduced temperature range over the vineyards (Figure 9).

The comparison between modelled temperature (at z = 24 m asl) and observed temperature as recorded by

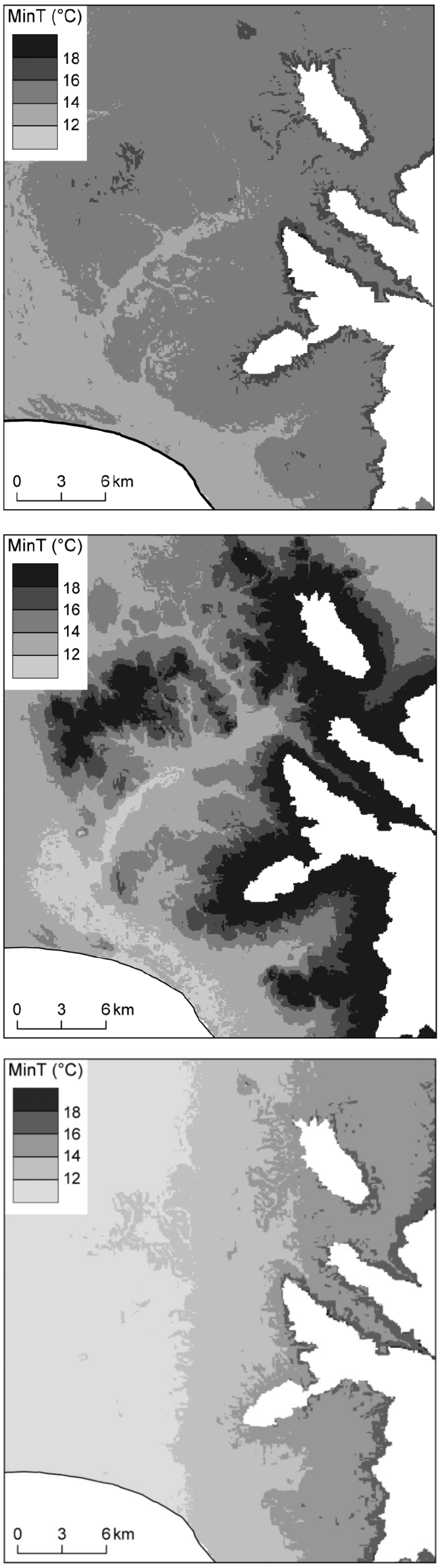


Figure 11 - Modelled minimum temperature in the Stellenbosch Wine of Origin District using multicriteria statistical modelling and displayed with 2 °C thresholds for a) mean for January-March 2009; b) 5/03/2009; and c) 28/01/2009.

the 16 automatic weather stations located in proximity to vineyards showed that the model over-estimated the values by 2 °C on average for the 5th March 2009 and under-estimated the values by 3 °C on the 28th January 2009 (Figure 10). The differences are probably due to the fact that comparison is made between data obtained from the surrounding RAMS grid point for the 200 m resolution grid at z = 24 m and data recorded by automatic weather stations located at specific points and with sensors located at 1.2 m above soil surface. Considering the significant differences in observed temperatures over very short distances, especially for the 5th March (Figure 5), it was expected that the mesoscale atmospheric model had some difficulties to reproduce the spatial temperature variation accurately.

3. Statistical spatial modelling of minimum temperatures

In addition, we used a different approach based on the minimum temperature values from the 40 Tinytag loggers and multicriteria statistical modelling (taking into account geographical and topographical factors, yet excluding other environmental factors such as soil surface condition).

Thus, the final model used to map the minimum temperature of the 2009 grapevine ripening period (mean for January-March) made use of the elevation and slope factors with a stepwise linear multiple regression (R^2 = 0.52; 50 % of residuals between -0.35 °C and 0.41 °C). The partial correlation coefficients of these two factors (0.38 and 0.46, respectively) showed relatively similar contribution. The following relationships were found: the steeper the slope, the higher the recorded value for minimum temperature (or, conversely, the flatter the terrain, the lower the recorded value for minimum temperature) and the lower the elevation at which the sensor was located, the lower the recorded minimum temperature value. This result showed again the importance of the thermal inversion phenomena and the downslope cold air drainage (Geiger, 1966; Mahrt, 1986). However, almost half of the variability of the mean minimum temperature for the three-month period was not explained by our model. This may be related to (i) differences resulting from comparison of data at different spatial resolutions (i. e., a 90 m grid point with data recorded by data loggers at specific points), (ii) variety variation in night-time weather conditions from January to March and thus in factors that explain the spatial distribution, and (iii) other factors not considered here (such as nature of the soil surface, soil moisture, wind, etc.).

Using this model, the mean minimum temperature during ripening was estimated for each point of the DEM grid at a 90 m scale. Due to elevation being the most significant factor, spatial distribution of minimum temperatures reflects the altitude variation. The estimation of minimum temperature was restricted to areas situated below 500 m asl for two reasons: there are few, if any, vineyards above this elevation (and in our case no data loggers) and the atmospheric model showed that the thermal inversion existed within the first 500 m above ground level. Using a 2 °C threshold as shown in Figure 11a, it can be concluded that night-time thermal conditions were optimum for color and flavor development and maintenance over the entire Stellenbosch wine district, on average, during the 2009 ripening period.

For the 5th March 2009, the main factor explaining the variability of minimum temperature is elevation (as seen above), and to a lesser extent slope, latitude and longitude. The model explained 94 % of the variance with the majority of residual values ranging between -0,55 °C and 0,56 °C. The statistical and atmospheric model outputs displayed similar information, showing the physics of topographic effects on air temperature with lower areas cooler than upper areas due to downslope cold air drainage (Figure 11b). Using the 2 °C threshold, the locations under thermal stress for color and flavor development and maintenance can be identified (Figure 11b).

Conversely, for the 28th January 2009, our model was much less satisfactory ($R^2 = 0.43$) and was mainly based on the longitude factor (mentioned previously) and slightly downhill. Residues lie between -2.7 °C and 3 °C (50 % between -1.2 °C and 1 °C) whereas the range of temperature variation was 8 °C and large biases were thus shown. The model's weakness in reproducing the temperature field for this specific day can be explained by the advective weather conditions, which reduced or moderated the influence of local factors, such as topography, on the spatial temperature distribution. The resulting estimated temperature map (Figure 11c) is probably far from reality if compared to that estimated by the atmospheric modelling, whose strength lies in reproducing high resolution temperature fields taking large-scale weather conditions into account.

CONCLUSION

Results are based on spatial minimum temperature variability for one season with a focus on two particular days and are thus not necessarily representative of all aspects of minimum temperature variability and nocturnal cooling potential during the ripening period. However, as the temperature gradient varies, not only as a function of geographical factors (mainly elevation and slope in these case studies), but also as a function of atmospheric conditions, results showed that fine-scale measurements in vineyards as well as atmospheric modelling and statistical modelling represent powerful tools to improve the understanding of local climatic factors.

Due to the high computational costs of the mesoscale atmospheric modelling, the numerical simulations were limited to selected single-night events. These provided a minimum temperature map at a resolution of 200 m resolution over the Stellenbosch wine district as well as emphasizing the influence of the weather conditions on the spatial distribution of temperature. The statistical modelling using a 90 m digital elevation model provided maps at increased resolution. For the radiative nights, the high resolution Tinytag data logger network seemed to provide a better spatial resolution and a clearer picture of the minimum temperature patterns than was previously obtained by means of similar statistical modelling methods over the region (Schulze, 1997; Joubert, 2007).

Further atmospheric and statistical modelling investigations are in progress. Observed soil and land cover characteristics for the high resolution grid (200 m) are being assimilated into the mesoscale atmospheric model in order to better adjust the model state towards observations, which in turn will contribute to improving the accuracy of the results. However, it will be a challenge for a regional atmospheric model to reproduce such an observed spatial variability with accuracy.

As it is necessary to assess climate at fine scales in order to optimize the understanding of grapevine functioning so as to improve grape and wine quality in a specific environment, this methodology can aid in characterising the climatic potential of locations for viticulture, providing valuable information for the search of the ideal cultivar x terroir combination.

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