Sensor technology to assess grape bunch temperature variability in V*itis vinifera* L. cv. Shiraz

by

TF Moffat

Thesis presented in partial fulfilment of the requirements for the degree of
Master of Agricultural Science
at
Stellenbosch University
Department of Viticulture and Oenology, Faculty of AgriSciences

Supervisor: Dr AE Strever
Co-supervisors: Prof JJ Hunter and Dr R Zorer

March 2013

DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: 26 December 2012

SUMMARY

The microclimate environment around the bunch is complex. The spatial distribution of leaves as well as bunch position and morphology impact on the path of direct radiation received by the berries. Canopy microclimate is largely determined by the meteorological conditions (air temperature, solar radiation, wind speed and direction, relative humidity, and precipitation) as well as management practices (trellis/training system, canopy height, vine spacing, row orientation, canopy management practices, irrigation and soil variability and management). The fact that the grapevine continuously responds to its environment, adds to the complexity and dynamic nature of the microclimate that the bunches experience. Field studies involving the effect of the natural bunch environment (i.e. light and temperature conditions) on berry composition, are therefore a challenge, due to the difficulties in quantifying meteorological elements such as temperature and light, which can be hugely variable.

There are different sensors available to assess bunch and berry temperature and it can be deployed in different ways within the grapevine canopy, but the difficulty remains in studying the variability that exists within a bunch. This study investigated the value of available sensor technology to measure bunch/berry temperature as well as the spatial and temporal variability on a bunch. Differences in temperature on an intra-berry level were assessed whereas the impact of canopy configuration and bunch orientation on the different sensor levels was also investigated. The contribution of macro- and mesoclimate on bunch and berry temperature was addressed by measuring at two locations (Robertson and Stellenbosch). The potential long term differences in temperature within a bunch with regard to thermal accumulation are discussed. Issues around sensor placement and some technical difficulties related to the sensors are discussed.

The results indicated how the effects of mesoclimate were transferred through to the different sensors. A dominating effect of the sea breeze in Stellenbosch was found. Canopy configuration/architecture affected the light regime in the canopy, consequently impacting on bunch temperature variability, specifically in Stellenbosch where a “Ballerina" trellising system was used. Bunch orientation resulted in differences in the temporal variability of bunch/berry temperature and little variability was observed in temperature within the berry. Temperatures of berries situated at the back of the bunch were judged more optimal compared to exposed berries. Direct radiation caused extreme temperatures in exposed berries, which may be detrimental to berry composition and wine quality. This emphasized the importance of the canopy (trellis/training system and management practices) in protecting the bunch from extreme conditions. The large on-bunch spatial variability, observed from measurements with the thermal imager, demonstrated the importance of sensor placement in quantifying the bunch temperature regime; this is also relevant for the future development of berry temperature modelling. Thermal accumulation through the season also illustrated the variability that existed within a bunch, suggesting a potential long term effect on the berry composition. This study proved, in conditions similar to those that may prevail in the South African wine industry, that sensor type and positioning need to be carefully considered in any viticultural/oenological study where bunch microclimate and grape temperatures are assessed.

OPSOMMING

Die mikroklimaat omgewing rondom die tros is kompleks. Die ruimtelike verspreiding van blare sowel as trosposisie en -morfologie het ‘n impak op die pad waarlangs direkte straling ontvang word deur die korrels. Lowermikroklimaat word grootliks bepaal deur die meteorologiese kondisies (lugtemperatuur, sonstraling, windspoed en -rigting, relatiewe humiditeit en reënval) sowel as bestuurspraktyke (prieel/opleistelsel, lowerhoogte, wingerdstokspasiëring, ry-oriëntasie, lowerbestuurspraktyke, besproeiing asook grondvariasie en bestuur). Die feit dat die wingerdstok voortdurend reageer op sy omgewing dra by tot die kompleksiteit en dinamiese aard van die mikroklimaat wat die trosse ervaar. Veldstudies gemoeid met die effek van die natuurlike trosomgewing (d.w.s. lig- en temperatuurkondisies) op korrelsamestelling is daarom ‘n uitdaging. Die rede hiervoor is dat dit problematies is om meteorologiese elemente soos temperatuur en lig, wat baie veranderlik kan wees, te kwantifiseer.

Verskillende sensors is beskikbaar waarmee tros- en korreltemperatuur bepaal kan word en dit kan op verskillende wyses binne die wingerdstoklower aangewend word. Die bestudering van die variasie wat bestaan binne ‘n tros is egter steeds problematies. Hierdie studie het die waarde ondersoek van die beskikbare sensortegnologie vir die meting van tros/korreltemperatuur en die ruimtelike en tydsvariasie op ‘n tros. Verskille in temperatuur op ‘n intra-korrelvlak is bepaal terwyl die impak van lowerkonfigurasie en trosoriëntasie op die verskillende sensorvlakke ook ondersoek is. Die bydrae van makro- en mesoklimaat tot tros- en korreltemperatuur is ondersoek deur te meet by twee verskillende liggings (Robertson en Stellenbosch). Die potensiële langtermyn verskille in temperatuur binne-in ‘n tros met betrekking tot temperatuur akkumulasie word bespreek. Kwessies rakende sensorplasing en sommige tegniese probleme wat verband hou met sensors word bespreek.

Die resultate het aangedui hoedat die effekte van mesoklimaat oorgedra is na die verskillende sensors. ‘n Dominerende effek van die seebries is waargeneem in Stellenbosch. Lowerkonfigurasie/argitektuur het die ligregime in die lower beïnvloed en gevolglik ‘n invloed gehad op die trostemperatuur veranderlikheid. Dit was veral die geval in Stellenbosch waar ‘n “Ballerina” opleistelsel gebruik is. Trosoriëntasie het gelei tot verskille in tydsvariasie van tros/ korreltemperatuur en min variasie is waargeneem in temperatuur binne die korrel. Temperature van korrels wat voorkom aan die agterkant van die tros is beoordeel as meer optimaal vergeleke met blootgestelde korrels. Direkte straling het uiterste temperature in blootgestelde korrels veroorsaak wat nadelig kan wees vir korrelsamestelling en wynkwaliteit. Hierdeur is die belang van die lower (prieel/opleistelsel en bestuurspraktyke) om die tros te beskerm teen uiterste kondisies beklemtoon. Die groot ruimtelike variasie op ‘n tros, soos waargeneem in metings met die termiese kamera, het die belangrikheid van sensorplasing in die kwantifisering van die trostemperatuur regime beklemtoon. Dit is ook relevant vir die toekomstige ontwikkeling van korreltemperatuur modellering. Termiese akkumulasie gedurende die seisoen is ook geïllustreer deur die veranderlikheid wat voorkom binne ‘n tros, wat dui op ‘n potensiële langtermyn effek op die korrelsamestelling. Hierdie studie het bewys, in kondisies wat algemeen voorkom in die Suid-Afrikaanse wynbedryf, dat sensortipe en -plasing sorgvuldig in ag geneem moet word in enige wingerd/wynkundige studie waar trosmikroklimaat en druiftemperature bepaal word.

This thesis is dedicated to my family for their support and encouragement

BIOGRAPHICAL SKETCH

Tessa Moffat was born in Cape Town on 28 July 1988. She matriculated at Herschel Girls' High School in 2006. Tessa enrolled at Stellenbosch University in 2007 and obtained the degree BScAgric in Viticulture and Oenology in December 2010. She then enrolled for the MScAgric in Viticulture degree in 2011 at Stellenbosch University.

ACKNOWLEDGEMENTS

I wish to express my sincere gratitude and appreciation to the following persons and institutions:

- **Dr AE Strever,** Department of Viticulture and Oenology, Stellenbosch University, for his invaluable guidance, encouragement and motivation during my study, without whom this would not have been possible.

- **Prof K Hunter,** Agricultural Research Council (ARC) Infruitec-Nietvoorbij, Stellenbosch, for his invaluable advice and assistance in conducting my study and writing up my thesis.

- **Dr R Zorer,** GIS and Remote Sensing Unit, Fondazione Edmund Mach, Italy, for his input, enthusiasm and absolute encouragement as a co-supervisor for my project.

- **Mr D Jacobson,** Institute for Wine Biotechnology, Stellenbosch University, for his assistance on the statistical analysis.

- **Ms T Mehmel,** Department of Viticulture and Oenology, Stellenbosch University, for her support, contribution and invaluable assistance throughout this study.

- **Mr N Volschenk and Mr S Fouche,** Agricultural Research Council (ARC) Infruitec-Nietvoorbij, Stellenbosch, for their assistance in the Robertson trial.

- **My family Mrs Anne-Janene Moffat, Mr Richard Moffat and Ms Emma Moffat,** for their encouragement and support throughout this process.

- **Ms Letizia Rocchi,** Milano University, for her assistance in the field.

- **Mr Nino Pisciotta,** Palermo**,** for his assistance in the field.

- **Winetech,** for their financial support of the project.

- The **National Research Foundation** for their financial support of the project.

PREFACE

This thesis is presented as a compilation of four chapters. Each chapter is introduced separately and is written according to the style of the South African Journal of Enology and Viticulture.

Chapter I	**General introduction and project aims**
Chapter II	**Literature review** Bunch and berry temperature variability in *Vitis vinifera*
Chapter III	**Research results** An assessment of temperature variability in *Vitis vinifera* L. cv. Shiraz
Chapter IV	**General discussion and conclusions**

CONTENTS

Chapter 1

Introduction and project aims

CHAPTER I: INTRODUCTION AND PROJECT AIMS

1.1 Introduction

Variability exists at many levels in viticulture, such as variable climatic regions within an area (Blanco-Ward *et al.*, 2007) and variability within a vineyard (Hunter *et al.*, 2010).This can be as a result of environmental factors, such as the meteorological conditions (i.e. rainfall, temperature and radiation) and soil composition. Management practices, such as irrigation and canopy management, may also contribute to variable conditions in the vineyard. Variability may also exist at a bunch level (Melo, 2011) and may be further affected by the microclimate surrounding it. Bunch variability can occur in the size and density of the berries as well as the distribution of temperature and light around it. Variability in bunch composition can affect sampling practices and accurate harvest dates which are crucial in winemaking. Variability can thus not be ignored and there is a need for a better understanding.

The importance of light and temperature has been widely investigated with regard to the effect on chemical bunch composition (Spayd *et al.*, 2002), such as the effect of threshold temperatures on enzymes involved with malic acid metabolism (Lakso & Kliewer, 1975; Lakso & Kliewer, 1978). Yamane *et al.* (2006) explored the stages at which berry coloration was sensitive to temperature. Kliewer (1970) found anthocyanin accumulation was much higher at a lower night temperature. Few articles however, state whether the effect is a result of the duration of thresholds, the threshold itself or the rate of change in temperature. These studies regarding light and temperature are predominantly performed under controlled conditions, such as in the potted Cabernet Sauvignon and Pinot noir experiment of Dokoozlian & Kliewer (1996) where the vines were grown in a phytotron in which humidity and temperature were controlled. Controlled conditions may not be a true reflection of the vineyard environment, which may be more complex due to aspects such as slope and orientation of the terrain, row orientation, soil cover and reflectivity, training system used as well as specific management practices. There is a need therefore to quantify the environment around the bunch in a state as found in a commercial vineyard.

When it comes to understanding the physiological mechanisms that occur as a result of temperature, the importance of the method used to define temperature could not be more emphasized. There are different techniques used to measure bunch temperature which may also have certain limitations. The environment which the sensor describes may also be limited to the area of placement, which may lead to inaccurate/inappropriate descriptions when trying to make general assumptions of the bunch environment. The placement of a sensor may depend largely on the aim of the investigation or the physiological question to be answered.

The variability in light and temperature regime around and inside a bunch is a product of the different levels of microclimate. The exposure and shading pattern of the canopy, which may influence light and temperature experienced by the bunch, are a result of both the architecture of the grapevine and of the vineyard. This is influenced by the trellising system as well as environmental factors mentioned previously. The mesoclimate, which is described as the prevailing meteorological conditions at vineyard level, will also affect the bunch microclimate and is a product of factors such as the aspect, slope and elevation. Due to the complexities that may arise as a result of all of the above, it may be important to investigate the finer levels of climate. Bonnardot *et al.* (2012) and Bonnardot & Cautenet (2009) emphasized the importance of higher resolution in accurately describing the vineyard.

This study investigates the temperature and light microclimate experienced by the bunch in comparison to the temperature and light regime at the different levels (at meso and macro levels) and in two different sites. A further level of temperature is investigated at the intra-berry level. In this study, this involved temperature measurements within the different sections of a single berry, i.e. the skin, under the skin and in the pulp, which may be physiologically relevant.

Considering all of these aspects, there is a need to further investigate the effect of canopy architecture on the temperature and light regime within the canopies and bunch zones of differently managed vineyards in different areas such as the Robertson and Stellenbosch vineyards that were part of this study.

Research involved in defining the bunch microclimate as well as berry skin and pulp temperature is usually limited to few temperature canopy sensors spread throughout a vineyard as well as a few thermocouples inserted into the pulp of random berries.

Little research has zoomed in on the level of a single bunch or berry and investigated what it experiences in terms of light and temperature, throughout the day, and at regular intervals. There is a need for a reliable method(s) which aids in defining temperature experienced by the bunch in order to be able to relate it to physiological reaction. Therefore, the overall objective of this study is characterising the bunch environment in terms of temperature and light and at the same time comparing available technology as a means for finding a method/s which may aid in defining the appropriate conditions which can then be linked to berry physiology and composition.

1.2 Project Aims

The aims of this study were:

1.2.1 Comparing existing technology used to measure bunch/berry temperature and discuss the impacts of:

1.2.1.1 Spatial (on the bunch/berry) and temporal (diurnal or seasonal) variability
1.2.1.2 Bunch exposure/orientation and training system (canopy architecture)
1.2.1.3 Intra-berry temperature differences

1.2.2 Assessing potential long-term (seasonal) differences in temperature related to thermal time accumulation.

The significance of this study for the research community is to assess and optimise current measurement strategies related to canopy, bunch and berry temperature in order to characterise bunch microclimate. This study may also be of value in future modelling of berry/bunch temperature. The grape/wine industry will benefit from these models, providing that it could account for the highly diverse conditions in which vineyards can be found.

1.3 References

Blanco-Ward, D., Queijeiro, J.M.G. & Jones, G., 2007. Spatial climate variability and viticulture in the Miño River Valley of Spain. VITIS 46 (2), 63.

Bonnardot, V., Carey, V.A., Madelin, M., Cautenet, S., Coetzee, Z. & Quénol, H., 2012. Spatial variability of night temperatures at a fine scale over the Stellenbosch wine district, South Africa. J Int Sci Vigne Vin 46 (1), 1-13.

Bonnardot, V. & Cautenet, S., 2009. Mesoscale atmospheric modeling using a high horizontal grid resolution over a complex coastal terrain and a wine region of South Africa. J Appl Meteorol 48 (2), 330-348.

Dokoozlian, N.K. & Kliewer, W.M., 1996. Influence of light on grape berry growth and composition varies during fruit development. J Am Soc Hortic Sci 121 (5), 869-874.

Hunter, J., Archer, E. & Volschenk, C.G., 2010. Vineyard management for environment valorisation. In: Proc. Eighth International Terrior Conference, Soave, Italy. pp. 3-15.

Kliewer, W., 1970. Effect of day temperature and light intensity on coloration of Vitis vinifera L. grapes. J Am Soc Hortic Sci 95, 693-7.

Lakso, A. & Kliewer, W.M., 1978. The influence of temperature on malic acid metabolism in grape berries. II. Temperature responses of net dark CO2 fixation and malic acid pools. Am J Enol Vitic 29 (3), 145-149.

Lakso, A.N. & Kliewer, W.M., 1975. The Influence of Temperature on Malic Acid Metabolism in Grape Berries: I. Enzyme Responses 1. Plant Physiology 56 (3), 370.

Melo, M.S., 2011. Berry size implications for phenolic composition and wine quality of Vitis vinifera L. cv. Syrah. thesis, University of Applied Sciences, Geisenheim, Germany.

Spayd, S.E., Tarara, J.M., Mee, D.L. & Ferguson, J., 2002. Separation of sunlight and temperature effects on the composition of Vitis vinifera cv. Merlot berries. Am J Enol Vitic 53 (3), 171-182.

Yamane, T., Jeong, S.T., Goto-Yamamoto, N., Koshita, Y. & Kobayashi, S., 2006. Effects of temperature on anthocyanin biosynthesis in grape berry skins. Am J Enol Vitic 57 (1), 54-59.

Chapter 2

Literature review

Bunch and berry temperature variability in *Vitis vinifera*

CHAPTER II: BUNCH AND BERRY TEMPERATURE VARIABILITY IN *VITIS VINIFERA*

2.1 Introduction

Climate can be divided into three scale levels, namely macro-, meso- and microclimate (Smart & Robinson, 1991). Both temperature and light can be measured at these different levels, but also other parameters such as relative humidity, wind speed and wind direction. Temperature is said to be the most important factor affecting grape quality (Coombe, 1986). Temperature on a macro scale can aid in denominating areas for specific crops, i.e. during determination of land suitability. The Winkler index is a method used to classify wine growing regions into areas based on heat summation (Amerine & Winkler, 1944b). Temperature on such a scale directly impacts temperature on a meso- and micro- scale, which can be affected by other climatic factors such as wind speed, cloud cover, humidity and precipitation. Thus temperature on a meso- and micro- scale largely depends on the regional climatic conditions specific to the area. Mesoclimate refers to a smaller denomination, such as a vineyard, and is governed by factors such as aspect, slope and distance to the sea (Bonnardot *et al.*, 2002). Canopy microclimate is the degree of foliar and bunch exposure and is dependent on the grapevine architecture, which is dictated by the vigour and trellis system (Smart *et al.*, 1985). Moving down the climatic levels from a macro scale to a micro scale, there is an increase in the spatial resolution as a result of the increasing variability and furthermore a need for an increase in the temporal resolution as a result of fast changing conditions, specifically on a microclimatic level. Based on the increasing variability down the scale (spatially and temporally), methods and sensors differ accordingly.

The importance of understanding climate, specifically temperature, on a finer scale level lies in the complexity of the microclimate, which may be overlooked when examining temperature on the larger scales. Delimiting areas into similar climates or terroirs based on regional scale measurements can create apparent homogeneous/similar zones. Heterogeneity may occur in these zones as a result of the variability existing within vineyards and even single grapevines (Hunter & Bonnardot, 2011). The reaction of the bunch, in terms of temperature, to its dynamic climatic environment may be physiologically important. Temperature variability in space and time should thus be addressed for a better understanding of grapevine reaction. This may also aid in more accurate zoning of temperature on the larger scales.

In light of the above, measurements performed on the basis of defining the bunch or canopy microclimate (light and temperature) are often limited to point measurements, which do not necessarily include quantification of bunch spatial distribution - an important aspect when investigating bunch variability. There is a need for the use of instruments which measure temperature spatially and temporally for a more accurate understanding of the diurnal bunch/berry temperature regime.

The importance of light and temperature in viticulture is a widely studied topic with regard to its potential effect on grape composition (Buttrose *et al.*, 1971; Kliewer & Torres, 1972; Kliewer, 1977; Haselgrove *et al.*, 2000). Quantifying the exact effects of environmental factors on the metabolic processes of the grape berry is difficult due to the complexity of the metabolic pathways and the combined effect of environmental factors which are a challenge to separate, specifically at vineyard level. Many studies investigating the effects of temperature on metabolites are thus performed under controlled conditions in order to eliminate the contribution of other external factors (Buttrose *et al.*, 1971). This review touches on some potential effects of temperature (and light) on the synthesis and accumulation of important grape compounds. The main focus, however, is that of the temperature measurements performed in defining bunch microclimate under conditions as experienced in a commercial vineyard as well as some technical aspects which may determine the success of such measurements.

2.2 Temperature measurements

2.2.1 Macro/meso scale measurements

Macroclimate refers to the climate on a regional scale extending over a large area (hundreds of kilometres) and is described from long term data, usually over 30 years. Bioclimatic indices, such as the Huglin and Winkler indices, have been developed for the allocation of grape varieties into areas that meet their minimal thermal requirement (Amerine & Winkler, 1944a; Huglin, 1978). The limitation of many climatic models, however, is the use of the mean values as well as the use of independent temperature values without consideration of the other climatic factors (Tonietto & Carbonneau, 2004; Blanco-Ward *et al.*, 2007) These include wind, humidity and cloud cover, which can be spatially and temporally quite variable. The use of daily averages also fails to account for the variability in temperature as a result of conditions such as an increase in wind speed or cloud cover. Temperature variability through the day may be important with regard to grapevine physiological processes. Averages exclude detail with regard to duration at specific thresholds as well as rate of change in temperature.

The mesoclimate describes a smaller area that can be a vineyard or vineyards and is affected by the surrounding topography, such as slope, aspect, elevation and ocean proximity (Vaudour, 2003; Deloire, 2005). Temperature measurements performed on a meso-scale refer to remote sensing and weather stations, investigating temperature on farms or between vineyards (Strever *et al.*, 2012). Weather stations measure meteorological elements, which are usually limited to a small area; there is therefore a need for a sufficient number of standardised weather stations and adequate statistical methods for the spatial interpolation of the data to cover a region. The placement of a weather station is also essential as it can be affected by external factors such as buildings blocking wind, trees affecting radiation as well as the proximity to the area being investigated. If placed in a hollow area, night temperatures may read lower values due to the inversion effect of downslope cold air movement mentioned by Bonnardot *et al.* (2012). A weather station placed too far from the vineyard may also not be a good representation of the mesoclimate. Zorer *et al.* (2011) mention the difficulty in the use of meteorological stations in a multifarious topography, such as the European Alps, due to their sparse and irregular distribution. This study uses the MODerate resolution Imaging Spectroradiometer-Land Surface Temperature (MODIS-LST) satellite product as an alternative in defining areas meeting the thermal requirements for different cultivars based on the Winkler index. Land surface temperature has potential to incorporate the spatial element critical to define temperatures in complex terrains and also increases the resolution of temperature measurements. The expected variability refers to inter-annual and seasonal changes.

2.2.2 Micro scale

At higher spatial and temporal resolution, the microclimate (Smart, 1985), describes the environment within a canopy, which may include variability within a single bunch and with a time scale of less than one hour. The final behaviour largely depends on the macro- and mesoclimates, but the fluctuations are due to the immediate surroundings created by the vineyard layout and architecture. The irregular distribution of leaves, in addition to the vertical structure of most canopies, creates a dynamic and complex environment which can often be unaccounted for when working with temperature on the meso- and macro-scales. Other aspects which can potentially affect bunch microclimate include row orientation, canopy height and width as well as certain characteristics specific to cultivars such as leaf size and shape. Row direction dictates (along with the trellis system and row spacing) the time and intensity at which the bunch zone is exposed to direct radiation during the day. Canopy height and width may also determine the diurnal light regime of the microclimate. A higher canopy may result in bunches being exposed for shorter periods of time. A thicker/wider canopy may result in a west facing bunch (in a north-south row direction) receiving direct light at a later time during the day compared to a thinner canopy. Certain cultivars may create differing microclimates as a result of their leaf characteristics. Cabernet Sauvignon, with five sinuses, creating the impression of a leaf with five holes, may let more light through compared to a Chardonnay leaf with one sinus (petiole position). There is a need for a better understanding and quantification of the temperature at a microclimatic level by using sensors that focus on the climate around the bunch. This will aid in the development of bunch temperature models that can be applicable, globally.

2.2.2.1 Contact measurements (canopy sensors and thermocouples)

Contact measurements apply to a sensor that comes into direct contact with the medium/object being measured. Temperature sensors in this regard, involving microclimatic measurements, refer to thermocouples and canopy sensors. A canopy sensor is described as being in direct contact with the climate surrounding it and within the canopy.

Canopy sensors

Sensors measuring canopy air temperature and humidity are placed in the canopy in the area of interest such as the bunch zone, depending on the topic of investigation. The sensors most commonly used in viticulture are ambient temperature (sometimes also incorporating relative humidity) data loggers such as the Tinytag® logger (Gemini Data Loggers) which can measure a range of temperatures depending on the model. These can withstand most environmental conditions due to their robustness and waterproof casing. The disadvantage of using these sensors may be the fact that the temperature readings may be higher than the actual air temperature due to the sensor heating up when in direct sunlight. A Stevenson screen or a radiation shield, as illustrated by Bonnardot *et al.* (2004) and Bonnardot *et al.* (2012), usually prevents this direct radiation exposure. Despite the air vents on the radiation as well as the Stevenson screens, the sensor inside the screen (such as a Tinytag® sensor) may be somewhat protected from fast changing environmental conditions induced by warm or cool winds for instance.

Thermocouples

Thermocouples are used in viticulture to measure berry pulp and bunch temperatures. In terms of the technical operation of these sensors, measurements are based on the temperature difference between two junctions connected by two wires of dissimilar metal composition. The two junctions being: the measuring junction and the reference temperature junction. This is known as the Seebeck effect, named after the discoverer, T.J. Seebeck in 1831. The measured voltage potential across the two wires is directly proportional to the temperature difference and by multiplying the voltage by a coefficient (Seebeck’s coefficient) determined by the metal type of the wires, the temperature difference between the two junctions can be calculated. In order to measure/calculate the temperature of interest, the reference temperature junction must be measured along with the voltage potential created by the differing junctions (Anonymous, 2012b).

The necessity of such measurements lies in the deviation of the pulp from the ambient temperature under certain conditions. It was observed by Bergqvist *et al.* (2001) that berry temperature for Cabernet Sauvignon, under exposed conditions, was 7°C above ambient temperature during midday. A weather station, although very important to quantify ambient conditions, can therefore not give an accurate indication of temperature inside the berry, due to these localised heating effects, especially under direct exposure of the grapes. According to Smart & Sinclair (1976) the two most important environmental factors which contribute to the heating of fruits are the flux density of solar radiation (i.e. the photon flow tempo for a specific surface area measured for a specific duration) air temperature and wind velocity. The flux density of solar radiation or the exposure of the berries to the sun depends on the architecture of the canopy which creates a variable light environment for the bunch, temporally and spatially. Temporal variation in the light regime refers to the movement of the sun path through the canopy, through the day. Spatial light variation refers to the direct and diffuse light received by bunches as a result of the spatial orientation of the leaves and the three-dimensional structure of bunches. Obtaining a correct description of bunch temperature is a challenge as a result of the varying light conditions that may occur on/around it. The use of a single thermocouple may inaccurately characterize what the entire bunch is experiencing. Possible differences over a bunch could be observed between the interior and exterior as well as between exposed and shaded portions, as a result of light variability within a canopy and the bunch positioning within it. Bunches in shaded conditions, receiving diffuse light, are said to match the ambient temperature whereas bunches exposed to direct sunlight can reach temperatures of up to 13°C above ambient temperatures (Spayd *et al*., 2002), highlighting an inseparable interaction between light and temperature. Other factors possibly affecting berry temperature, which are relatively less important, include bunch compactness and roughness as well as berry size and albedo (Smart and Sinclair, 1976; Cola *et al.* 2009). Albedo describes the reflective capacity of a surface. It is the ratio of radiation reflected from a surface to the incident radiation. In a compact bunch, the sensor will more likely come into contact with a berry's surface, possibly giving a different reading to that of a loose bunch where the probe may be more likely in contact with the surrounding air.

In light of the above the importance of sensor positioning cannot be over emphasized. The placement of sensor probes within a single berry may also affect readings. A portion of the berry may be exposed, whereas the sensor may be placed in a sun spot rendering a higher reading. Certain metabolites responsible for berry quality are limited to specific zones in the berry, such as anthocyanins which are synthesised and stored in the epidermal layer of the skin (Holton & Cornish, 1995; Jeong *et al.*, 2004). A further investigation into the temperature variability of the different zones within a berry may therefore be relevant.

The disadvantage of the thermocouple, apart from it being a point measurement, is that it is destructive as a result of the puncturing action of the probe in the skin. Depending on the period of measurement (how long the sensor is kept inside the berry), this may result in deterioration of the berry and a concomitant decrease in berry size as a result of water loss. Pulp temperature observations of a single berry thus usually last for a few days. However, thinner probes are available which allow for the observation of berry temperature for a longer time period. A further disadvantage of thermocouples is the cost of data loggers as well as the expertise required for setup of the probes and loggers.

2.2.2.2 Non-contact measurements (thermal imaging)

The thermal imager captures infrared radiation emitted by the object of interest. All objects above 0° Kelvin (-273.15°C) have the ability to emit this radiation (Vadivambal & Jayas, 2011). Infrared radiation is divided into four categories based on wavelength or energy content (Table 1) (Meola & Carlomagno, 2004).

Table 1 Categories of infrared radiation with corresponding wavelengths.

Infrared radiation	**Wavelength**
Near Infrared (NIR)	0.75-3 µm
Mid Infrared (MIR)	3-6 µm
Far Infrared (FIR)	6-15 µm
Extreme Infrared (EIR)	15-1000 µm

Thermal imagers generally measure the light within the wavelength range 8-14 µm (FIR), as this is described by Jones (2004) as being one of the 'atmospheric windows' where radiation is not absorbed to a great extent by the atmosphere. Detectors, which are divided into thermal and photon detectors, identify infrared radiation and convert it to electrical signals which are processed and transformed into temperature units in for instance a thermal image (Vadivambal & Jayas, 2011).

Thermal imaging was first applied in the military in World War II and since then it has been applied widely. According to Meola & Carlomagno (2004) thermal imaging has advanced to:

- Medicine, for example, in the diagnosis of nerve irritation or nerve compression such as Carpal Tunnel Syndrome or Vibration-white-finger Syndrome (Anbar, 1998).
- Agriculture, for example, in the detection of stress responses in grapevines under different irrigation strategies (Grant *et al.*, 2007).
- Environment, for example, in the nucleation of ice (Fuller & Wisniewski, 1998), i.e. where the ice nucleates and how it spreads, which is a notorious phenomenon that can destroy crops.
- Disease, for example, detection of pre-symptomatic increase or decrease in temperature of grapevines infected with *Plasmopara viticola* (Stoll *et al.*, 2008). A relationship between the pathogen and transpiration was suggested as a result of the penetration of the pathogen through the stomata which controls leaf temperature. Reduced functioning of the stomatal aperture would be expected to result in an increase in leaf temperature.

The above examples are only a few of the applications. Thermal imaging is particularly attractive for agriculture due to its non-destructive nature, efficiency and relative ease of use.

Surface temperature measured by thermal imaging can be done on a macro-, meso- and micro scale. From the late 1970's satellite thermal imagery of land surface temperature was used as an indication of evapotranspiration. This is as a result of the close relationship that temperature has with latent heat and sensible heat flux (Price, 1982; Seguin *et al.*, 1994). Latent heat is the heat released into the atmosphere when water is evaporated from the soil surface or transpired from a plant surface, incorporating phase change, whereas sensible heat refers to the heat energy transferred that affects the atmospheric temperature (Anonymous, 2012a).

Jackson *et al.* (1977) derived a formula known as the 'stress degree day' which is a summation of the surface temperature minus the air temperature over a period of time. This was formulated as an indicator for crop water use for wheat, which in turn could aid in determining irrigation amounts and scheduling. Seguin *et al.* (1991) further investigated the use of thermal infrared data for assessing crop water conditions on a regional scale, which divulged spatial differences in climate, as well as temporal differences over three years in France. A 'Crop Water Stress Index' (CWSI) was derived (Idso *et al.*, 1981; Idso, 1982) using canopy temperature as an indicator. This is based on the assumption that when water becomes limiting, transpiration decreases causing a subsequent increase in leaf temperature (Jackson *et al.*, 1988). Möller *et al.* (2007) describes this index as the difference between canopy temperature and temperature of a 'non-water stressed baseline' measured using infrared thermography. However, there is debate around the use of this index due to its sensitivity to climatic factors such as wind and humidity (Jackson *et al.*, 1988). Jones (1999) used an adapted 'CWSI' that addressed the effect of climate by using 'wet' and 'dry' reference leaves. It must be noted that grapevines have the ability to conserve water by decreasing transpiration, without being stressed, which is also cultivar dependent.

Grant *et al.* (2007) investigated the use of thermal imaging in the detection of plant water status (stress) of grapevines (*Vitis vinifera* L. cvs Castelão and Aragonês) in reaction to different irrigation techniques. The different treatments included regulated deficit irrigation (RDI), partial root zone drying (PRD), no irrigation (NI) and full irrigation (FI). A distinction was made between irrigated and non-irrigated grapevines as well as between the deficit irrigation techniques, using the thermal imager. Traditional methods, such as leaf and stem water potential for measuring plant water status, are often used for irrigation scheduling. These methods are laborious and destructive. Stomatal conductance is also an important measurement for timing of irrigation, but can be time consuming. Both these techniques are point measurements and together with the variability occurring in a vine, can result in inaccurate results. Thermal imaging is a spatial and temporal measurement of temperature, i.e. it gives a spatial distribution of temperature over an area which can be used to observe variability and it has the ability to measure temperature in sequential events over a period of time.

Leaf temperature is closely related to stomatal conductance, as a decrease in water content results in stomatal closure and a subsequent increase in temperature and can thus be an indicator of plant stress. An important observation in this study was the preferred use of average temperatures of areas rather than the use of individual leaves, which did not closely correlate with stomatal conductance. Grant & Chaves (2005) suggested this might be as a result of orientation and inclination angles of leaves. Leaves of similar temperatures varied in stomatal conductance depending on the angle of orientation of the leaf (e.g. facing north to south) and the angle of inclination. The authors suggested that this could prevent one from accurately distinguishing between stressed and non-water stressed canopies using temperature.

Stoll *et al.* (2008) studied the use of thermal imaging in the detection of pathogens in grapevines. The pathogen studied, *Plasmopara viticola*, penetrates *via* the stomatal aperture. This is based on the theory that the shrinking effect that this pathogen has on the stomata, causes a reduction in the conductance and consequent increase in temperature. However, in irrigated vines, a temperature increase was observed in contrast to the temperature decrease in non-irrigated vines at the point of infection. The method of analysis was the deviation of pixels from the mean and effectively differentiated between the infected and healthy parts of the leaves regardless of the plant water status. The thermal increments or decrements in the infected leaves under greenhouse conditions were observed prior to visible symptoms.

In the more recent years, hand-held thermal cameras focusing on temperature on a meso/micro scale with a higher resolution have become decreasingly expensive and increasingly popular in agriculture. In viticulture, the architecture of the canopy favours thermal imaging on a smaller scale, specifically trellising systems where the majority of the canopy exposure is vertical (Vertical Shoot Positioned trellising otherwise known as the VSP or hedge trellis). The advantages of the thermal imaging device lie in the spatial mapping of temperature, which is not practically very feasible or even possible with other indirect or contact point measurements, such as with a handheld infrared thermometer or thermocouples. Thermal imaging can also be used to demonstrate spatial variability over time, which is not accurately possible for point measurements. The resolution of the instrument determines the efficiency in distinguishing between two objects within an image, which thus determines the amount of temperature measurements over a given surface area. Such a device with high resolution is costly, and there is a requirement for personnel who are trained for proper analysis. A further problem encountered with the images is the difficulty in distinguishing the object from the background, particularly when it comes to gaps in the canopy. Inaccuracy in this regard can be avoided with the use of a uniform background such as a white sheet. More advanced software is also needed for accurate image analysis that aids in distinguishing between the object and the background (i.e. through threshold detection, edge detection or manual cropping of the object of interest).

The application of thermal imaging in monitoring the grapevine canopy is a relatively new concept and appears to be gaining more interest due to the higher accuracy as a result of its spatial and temporal advantages.

In order for contact temperature to be estimated, the emissivity of the object needs to be taken into account. Emissivity is the ability of an object to emit energy in the form of radiation. It is the ratio of the energy emitted by the object to the energy emitted by a black body at a specified temperature. A black body will radiate infrared radiation at its contact temperature (Anonymous, 2001). Thermograms or thermal images are thus an estimate of the contact temperature. A grape berry comprises of compounds such as organic acids which are intermediates of the metabolic pathways such as the Krebs cycle and are thus described as ‘metabolic entities’ (Ruffner, 1982). Organic compounds are thus believed to be synthesized *in situ* and in the leaves, but not transported to the berries. This possible independence may augment variability that may occur within a bunch. Variability in berry maturity within a bunch is particularly notable during the veraison period and was suggested by Coombe (1992) to be induced during the period of anthesis. Variability with regard to temperature and berry maturity, particularly around veraison, makes it difficult to calculate a set emissivity. In a study by Bulanon *et al.* (2008) the emissivity of citrus fruit was estimated using two methods. The first method adjusted the emissivity setting on the thermal camera so that it read the same temperature as the contact measurement of a Dew Point Meter or Hygrometer. This estimated emissivity of 0.89 had a large interval (0.82-0.96) with a standard deviation of 0.031. The range in estimated emissivity obtained with this method was said to be as a result of the fluctuations between ambient and fruit temperature. A higher fruit temperature compared to ambient temperature reduces this interval. The second method used a reference emitter (black electrical tape) with a known emissivity of 0.95, which was placed on the fruit. Images were taken every 20s for 10 minutes using the thermal camera and the temperatures of the tape and fruit read from the images. Emissivity of the fruit area was adjusted until the temperature was the same as the tape, giving an estimated emissivity of 0.9. The second method gave a better result with a smaller interval of 0.88-0.92 and a smaller standard deviation of 0.01. The better results obtained with this method was said to be due to the higher temperature of the fruit relative to the surroundings as well as the shorter intervals at which images were taken, limiting variation of external factors. No specific value has been allocated for berries, only a general value for spherical fruits seen in Table 2 (Thorpe, 1974; Smart & Sinclair, 1976). The berries are thus treated like any solid object.

Table 2 Examples of emissivity values for certain materials (Anonymous, 2007)

Material	**Emissivity**
Polished Aluminium	0.05
Aluminium, rough surface	0.07
Powdered Charcoal	0.9
Polished Copper	0.01
Glass	0.92
Oxidized Lead	0.63
Spherical fruits	0.9

Hand-held radiometer

An additional non-destructive or non-contact instrument for measuring temperature is the hand-held infrared thermometer. Its principle of operation is identical to the thermal camera, where infrared radiation emitted from the object is converted into a temperature value. The difference lies in the spatial element which is absent in most hand-held infrared thermometers. This is a manual instrument which relays a single average surface point measurement for a specific area depending on the distance of the thermometer to the object of interest, which may be a disadvantage, especially when monitoring sparse canopies where background reflectance may have a large effect on the temperature. The further the thermometer from the object, the more area is averaged, leading to this effect potentially being larger. There are many studies on the use of leaf temperature for indications of water stress and thus aid in irrigation management as mentioned above (Jones, 1999; Möller *et al.*, 2007; Intrigliolo *et al.*, 2009). This is due to the relationship between leaf temperature and the reaction of stomatal conductance to water stress. In a study by Van Zyl (1986) the infrared thermometer was used to measure canopy temperature as an indicator of water stressed grapevines with the advantage of measuring whole canopies accurately and in a relatively short space of time. Reduced transpiration rates measured by stomatal resistance resulted in canopy temperatures (1.16-1.26°C) above the non-stressed control. A significant and linear correlation between canopy temperature and soil water content was found.

2.3 Factors affecting bunch and berry temperature variability in the grapevine

2.3.1 Climatic factors

2.3.1.1 Ambient temperature

Ambient temperature, most commonly measured by automatic weather stations, can largely determine bunch or berry temperature, specifically when berries are shaded (Spayd *et al.*, 2002). The disadvantage in using weather stations to estimate bunch or berry temperature lies in their sparse distribution which may lead to inaccurate estimations if there is large variability in topography over short distances. Complex elements in and around the bunch which affect temperature or light exposure, can also be problematic when using ambient temperatures to describe the conditions experienced by a bunch or berry. Factors such as berry colour, bunch compaction/morphology, wind speed and most importantly direct and reflected radiation which is largely affected by the canopy configuration and row orientation. Cola *et al.* (2009) described ambient temperature as having ‘poor descriptive power’ of berry temperature, with a slight exception for days on which the sky was overcast. This applied to bunches under exposed conditions (leaf removal). Smart & Sinclair (1976) observed hotspot berry temperatures of 12.4°C and 11.1°C above ambient in tight and loose bunches which elucidates the above statement of Cola *et al.* (2009) with regard to the less accurate estimation of berry temperature by the weather station for exposed bunches.

2.3.1.2 Wind

Depending on the direction (wind and/or row), wind may have varying effects on temperature. Vineyards in the False Bay area of the Western Cape, close to the sea, may for instance be exposed to the cooling effect of the off-shore sea breezes from a southerly direction (Bonnardot *et al.*, 2002), which arise as a result of the land-water temperature differences in the lower atmospheric layer. The study of Bonnardot *et al.* (2002) used the Regional Atmospheric Modelling System, which takes into account the meteorological data at different levels in the atmosphere as well as the topography. A difference in ambient temperature was also observed between the northern and southern slopes. Northern slopes were warmer than southern slopes, with the difference being greater closer to the sea.

The temperature effect of wind on bunches in the canopy is also determined by the distance from the sea, the row orientation as well as the canopy density. Bonnardot *et al.* (2001) found a disintegration of the cooling sea breeze 10-15 km from False Bay, i.e. a temperature decreasing effect was not observed past Bottelaryberg. The row orientation in addition to wind direction may also play a role. A north-south row orientation may be more protected from a westerly wind than a south-westerly wind. Wind can therefore affect the temperature inside the canopy depending on the proximity to large bodies of water, the direction and speed of the wind, as well as the vineyard row orientation.

2.3.1.3 Relative humidity

The proximity to the ocean can also affect ambient humidity. Depending on the wind direction, wind coming from the sea can contain a high content of moisture, increasing the relative humidity. Transpiration by leaves can result in an increase in humidity in the centre of canopies (Smart, 1985). An increase in humidity results in a decrease in evapotranspiration and a possible rise in leaf temperature. There is little literature on the effects of transpiration on the energy budget of the berry. Transpirational cooling, according to Smart & Sinclair (1976), is a minor component of energy loss by the berry. Stomata present on the epidermis of the berry are said to be non-functional post véraison. A drastic decrease in berry transpiration (per unit of weight or skin area) was observed for the interval between the first growth period and ripening ((Blanke & Leyhe, 1987; Ollat *et al.*, 2002). This suggests that a young berry may be more susceptible to energy loss compared to a berry in the ripening phase.

2.3.1.4 Radiation (light quantity and quality)

When investigating plant responses to light, the light quantity or intensity and the light quality need to be addressed. Light quality refers to the different wavelengths that make up the light spectrum. Light intensity, which affects temperature, is the radiant energy emitted from shortwave radiation. Shortwave radiation comprises of visible (VIS), near-ultra violet (UV) and near infrared (NIR). Studying the separate effects of light and temperature in any aspect, especially when it comes to berry composition, is a major challenge. In the canopy of a grapevine the distribution of light is dictated by the spatial distribution of the leaves, which may create a variable light environment. This variable light environment creates temperature variability within the canopy, bunch or berry. Light can also be divided into direct and diffuse components. Direct radiation refers to the unscattered beam of light that reaches the bunch or berry, whereas as diffuse light refers to light that has been intercepted/reflected by any object before it reaches the bunch/berry. Diffuse light can be reflected from the opposite canopy (VSP trellising systems) and soil (Smart, 1985) as well as light received by the bunch on a cloudy day; it is therefore affected by macro and meso factors. Light and temperature are linearly related (Smart, 1986; Bergqvist *et al*., 2001). The energy balance of a spherical fruit such as a berry is determined by the shortwave radiation absorbed by the berry as well as energy lost by convection (movement of heat through a liquid) and conduction (transfer of heat between substances in direct contact) (Smart & Sinclair, 1976). The variable nature of the bunch as well as the microclimate in which it is situated creates a complex system for the flow/path of light, which further complicates quantifying the reaction in terms of fruit temperature.

2.3.1.5 Cloud cover

The presence of clouds can result in a decrease in the visible spectrum of radiation, i.e. 400-700 or photosynthetically active radiation (PAR). Smart *et al.* (1982) observed a 50% decrease in PAR received by leaves on the exterior portion of the canopy under cloudy conditions. Near-infrared radiation, however, is not affected by cloud cover, which gives the plant the ability to detect low light conditions as a result of cloud or shade (Smith, 1982; Smart, 1986). A reduction in the amount of energy (W/m^2) in the visible range that is received by the berries, as result of cloud cover, can thus have an effect on the temperature conditions in the canopy.

2.3.2 Viticultural factors

2.3.2.1 Row orientation

Most vineyards conform to the traditional north-south row orientations in order for both sides of the canopy to receive a ‘balanced’ amount of radiation through the day. Row orientation decisions are based on the sun-earth geometry in order to maximize radiation intercepted by the canopy. According to Tarara *et al.* (2005) a decision on row orientation should also be based on the prevailing wind direction. In areas with high radiation and consistent winds, wind-induced canopy asymmetry can result in irregular and possible over-exposure of the fruiting zone. This study specifically investigated the effect of a south-westerly wind on two row orientations: parallel and oblique to the prevailing wind. In the rows oblique to the wind, windward shoots were significantly shorter than shoots on the leeward side. Down row streamlining was observed in rows parallel to the wind with no differences between the two sides of the canopy. In this situation, wind-induced canopy asymmetry may be undesirable as west-facing bunches on the windward side of the canopy may experience maximum irradiance at the same time as maximum ambient temperatures. This may have potential detrimental effects on grape composition as the bunches may be exposed to more intense radiation for a longer period of time than without wind-induced canopy asymmetry

In the southern hemisphere, an east-west row orientation results in the south-facing side of the canopy mostly being shaded through the day whereas the north-facing side mostly being in the sun. The north-south and east-west row orientations would thus create different diurnal radiation regimes in the fruit zone and therefore a possible difference in the bunch and berry temperatures. Depending on the row orientation, fruiting zones will be exposed at specific times of the day and therefore may reach peak temperatures at different times as seen in the study by Tarara *et al.* (2005).

In a northern-hemisphere study in California (38°N), where the majority of vineyards are trained to vertical shoot positioning systems, the insolation was investigated using hemispherical photography for an east-west row orientation (Weiss *et al.*, 2003). Insolation is the solar radiation received by a body for a given time. North-south; north-east south-west and north-west south-east row orientations were simulated using software. Hemispherical photography describes the sun path through the day for the different months, based on the geometry of the open sky. It computes the canopy gap fraction as well as the percentage of direct and diffuse radiation received by the bunch (Zorer *et al.*, 2005). In the abovementioned study by Weiss *et al.* (2003) the south side of the east-west row orientation displayed a higher peak of irradiance (800-900 $W.m^{-2}$) for a longer time period whereas the north side was mostly shaded by the canopy with lower peaks of irradiance (300-500 $W.m^{-2}$) for shorter periods at sunrise and sunset. The south had a longer exposure time later in the season whereas direct light on the north side disappeared towards the end of the season. Balanced insolation was observed for the east and west sides of the north-south row orientation. Insolation on the east side occurred around 10:30 whereas on the west side, fruit exposure occurred from 13:00 to some point in time between 15:00 and 17:00. The north-east south-west row orientation simulated higher insolation (800-900 $W.m^{-2}$) for a longer period on the south-east side and lower insolation (600-900 $W.m^{-2}$) for a shorter period in the afternoon on the north-west side. The north-east side of the north-west south-east row orientation received direct radiation until 11:00 whereas the south-west side experienced intense insolation for a long period in the afternoon. In lower latitudes such as in Australia where the sun is nearly overhead, an east-west row orientation is preferred. Bunches are mostly shaded during the hottest time and bunches on the north side receiving high radiation are acclimatized as exposure occurs for a longer period through the day (Gladstones, 1992). The investigations of Weiss *et al.* (2003) and Gladstones (1992) however, are specific to the conditions in these studies, such as the trellis system, the latitude as well as the canopy and row dimensions. Closer row spacing as well as taller canopies may affect the radiation regime differently. In grapevines trained without trellising, such as the goblet or bush vine, row orientation becomes less important, but canopy structure probably more important. The limitations of using hemispherical images for computing insolation is that it assumes no transmittance of light through leaves as well as clouds. Reflection from the opposite canopy as well as soil is not taken into account which may be of importance with regard to bunch/berry temperature change. Only incident, direct radiation is calculated. The distance of the thresholded object (i.e. the canopy or leaf in question) from the bunch is also not accounted for, which can also determine the level of shielding around the bunch with regards to diffuse radiation.

2.3.2.2 Canopy composition/architecture

The dispersal of light in the canopy is determined by the canopy's structure, which is in turn a result of the trellis and training system. (Gladstones & Dokoozlian, 2003) examined the leaf area density (m^2 leaf area per m^3 of canopy volume) differences in positioned and non-positioned training systems. Non-positioned systems include the single curtain (or sprawl) and the double curtain trellising systems. Shoot positioning was applied to the lyre, hedge-type (VSP), Smart-Dyson and Smart-Henry systems. Differences in the localisation of leaf area density occurred. Non-positioned systems had a higher leaf area density layer on the outer section and a lower leaf area density in the interior. In positioned systems, leaf area density increased from the top of the vine towards the bunch zone which would probably be dependent on the vigour and time of topping. A well-exposed bunch zone at higher leaf area densities but lower leaf layer numbers was observed compared to the non-positioned systems which achieved high bunch exposure at lower leaf area densities but higher leaf layer numbers. These differences were ascribed to the direct effect shoot positioning has on restricting canopy volume. Only a gradual decrease in photosynthetic photon flux (PPF) was observed as leaf area index increased, whereas a sharp decrease in PPF occurred as leaf area index increased in the non-positioned systems. The sharper decrease in PPF in non-positioned systems may have been due to the higher leaf layer number, suggesting better light conditions in positioned systems as the vine develops. Differences in light intensity between systems as a result of the differences in leaf distribution and localisation may result in differences in bunch or berry temperatures. Significantly higher bunch temperatures in bush vines compared to the lengthened Perold and slanting trellis were observed by Van Zyl & Van Huyssteen (1980). These differences were markedly different around 12:00 and were as a result of the higher exposure of bunches to direct sunlight as well as the reflected heat from the soil. Canopy structure or architecture as well as the distance from the soil surface can contribute to the temperature in the canopy and bunch zone.

2.3.2.3 Surface management

Radiation reflection of soils depends on certain characteristics such as soil colour. This is often determined by the organic matter content. Darker soils have higher temperatures due to the higher absorption of radiation and thus a lower reflectance. Bowers & Hanks (1965) mentioned the influence of particle size, organic matter content and moisture content on the reflective ability of soils. This study observed a decrease in reflectance of radiation and an increase in absorbance with an increase in soil moisture. Reflectance increased with the oxidation of organic matter. For both Kaolinite and Bentonite soils, reflectance increased exponentially as particle size decreased. The radiation reflection is also determined by the presence of a cover crop and the row spacing. A larger distance between rows results in a greater area of soil that is exposed to radiation. According to Smart (1973) the light absorbed from the soil component is almost negligible relative to the other components mentioned, such as light absorbed by the top and sides of the vine. This applied to conditions including vigorous vines in Australia with a height of 2 m and row spacing of 4 m in a north-south row direction. The surface is assumed to be horizontal and flat.

Gladstones (1992) mentioned the traditional belief that stony, rocky soils are advantageous in cooler climates as heat is absorbed in the day and re-radiated to the vines during the night, also preventing frost. It is also mentioned that light- to reddish-coloured rocky soil increases the light reflection of useful light wavelengths into the canopy. The ability of specific soils to reflect radiation back to the vine creates a more complex radiation regime which may have the potential to affect bunch temperature and variability. In a study by Hunter (1998) higher soil temperatures were generally observed with wider spacing (between row x in row: 3 x 3 m, 3 x 1.5 m and 2 x 2 m) compared to narrower spacing (1 x 1 m and 1 x 0.5 m), which had almost continuous shading through the season. This resulted in more stable soil water content for the narrower spaced vines compared to large fluctuations in soil water content of the wider spaced vines. Row orientation can also impact soil-reflected radiation in the bunch zone (Hunter *et al.*, 2010). The highest PAR received by the bunch zone was observed in the north-south row orientation whereas the lowest was observed in the east-west row orientation.

2.3.3 Modelling temperature

The importance of temperature in the canopy and bunch/berry has created a developing interest in temperature prediction or modelling. Predicting berry temperature relies on the knowledge of the radiation flow through the canopy. The above mentioned viticultural and climatic factors play a role in determining light and temperature in the canopy and consequently in bunch/berry temperature and thus need to be taken into consideration when developing models.

Smart & Sinclair (1976) described the energy balance on the surface of spherical fruit to be composed of the radiation absorbed and the energy dissipated by convection and conduction into the fruit. Energy lost by long wave radiation or emission and transpiration are described as being insignificant in relation to the other components. Energy lost *via* forced convection is as a result of the air movement around the berry. This becomes more complex when observing berries in a bunch. In a loose bunch, there may be little berry-to-berry transfer of energy and each berry is more exposed to heat loss by forced convection. Tight berry clusters show higher berry temperatures as a result of the berry-to-berry heat conduction and only the sides of the berries exposed to wind will lose heat. A shortcoming of model developed by Smart & Sinclair (1976) is the assumption that the heat transfer coefficient is uniform over the sphere or grape berry. For berries in tight clusters this may not be true, due to the impaired movement of air. It also assumes constant boundary layer conditions which do not exist in the fluctuating microclimate of the plant canopy (Saudreau *et al.*, 2007). Saudreau *et al.* (2007) developed a model that simulates the spatial and temporal distribution of temperature for ellipsoidal fruits with boundary conditions that are not homogenous and experience unsteady heat fluxes as expected under normal conditions. Cola *et al.* (2009) developed a model simulating hourly berry surface temperature for an exposed bunch from véraison to harvest, based on the micrometeorological approach of energy balance. Calibration and validation were also performed to determine the success and application of the model. The only measured parameters driving the model were daily ambient minimum and maximum temperature values, which were easier to obtain. Daily and hourly values for parameters such as global solar radiation, cloud coverage, relative humidity and wind velocity were simulated from the measured parameters. The limitation of the model is that it included specific canopy parameters (for a hedge shaped canopy) with a set leaf area index and canopy height. For berries experiencing ‘exposed’ conditions, validation and calibration applied only to berries on the external middle part of the bunch. The leaves were also removed around the bunch so that shading only occurred when the sun moved over the canopy. Under normal canopy conditions, however, leaves often surround the bunch, creating sun flecks and variable shading patterns through the day. The model performed well under stable conditions, such as clear skies and consistent high incoming radiation, whereas cloud coverage, rainfall and fluctuations in wind speed and direction resulted in less accurate simulations.

2.4 The potential effects of light and temperature on grape composition

2.4.1 Interaction of light and temperature

Under natural conditions, separating the effects of light and temperature is a challenge, which complicates studies where components are affected due to the interaction between these two factors. Haselgrove *et al.* (2000) observed the response of anthocyanin metabolism in reaction to changes in both light and temperature. The first experiment studied artificial modification of light exposure. Leaf removal around bunches was conducted for the fully exposed treatment and aluminium wrapped around wired cages (with the interior painted black) covering bunches, represented the fully shaded treatment. This experiment showed light to be a limiting factor in anthocyanin accumulation during the early stages of ripening (15 and 35 days after veraison). In the second experiment, under natural conditions, bunches were chosen in exposed and shaded conditions. Bunches received adequate light but temperatures often exceeded 35°C. A decrease in anthocyanin content in the exposed bunches resulted, which was suggested to be either as a result of inhibition of anthocyanin synthesis or increased degradation. Bergqvist *et al.* (2001) agreed with this and stated that the effect of light on berry composition is dependent on the extent of temperature increase.

Spayd *et al.* (2002) attempted to separate light and temperature in the vineyard by using "sun and shade blowers". This was done by cooling exposed bunches (which reached temperatures of up to 13°C above ambient) to the temperature of shaded bunches and heating shaded bunches to the temperature of exposed bunches. Control treatments were conducted for the effects of forced convection. Exposure to sun was found to increase total skin monomeric anthocyanin (TSMA) concentrations regardless of temperature, showing the importance of light for coloration. Cooling sun exposed clusters increased TSMA and heating shaded clusters caused a decrease in TSMA. This change in TSMA can thus be ascribed to a temperature effect.

Light exposure of bunches during the pre-véraison period showed significant reductions in the levels of 2-methoxy-3-isobutylpyrazine (ibMP) which is responsible for the green pepper and vegetative characteristics, most notable in Sauvignon blanc and Cabernet Sauvignon (Ryona *et al.*, 2008; Koch *et al.*, 2012). Differentiating the effect of light and temperature as mentioned before is a challenge. Many studies surrounding these environmental elements and methoxypyrazine content suggest that temperature may well play a role. Marais *et al.* (1999) found that the temperature differences between the different regions and seasons played a more prominent role on the concentration of ibMP than the actual shading treatment. Koch *et al.* (2012) found that in the season in which there was no treatment effect, ibMP was lower than the sensory threshold. This coincided with the higher temperatures early in berry development and higher temperature accumulation of the season compared to the other cooler two seasons, which had a significant treatment effect.

2.4.2 Anthocyanins

Anthocyanins are part of a very important group known as flavonoids, which contribute to the quality of wine. Anthocyanins are pigments accountable for the coloration of grapes and subsequently the wine (Ribéreau-Gayon & Glories, 1986). These pigmented compounds are found in the vacuoles in the epidermal layer of the skin and are synthesized by the phenylpropanoid and flavonoid pathways (Holton & Cornish, 1995; Jeong *et al.*, 2004). The localisation of anthocyanins is an important point to consider when studying the effect of temperature. It is also important to know in what part of the metabolic process temperature can affect anthocyanin content and where it is located, i.e. the skin or the pulp, as different parts of the berry may have different thermal properties.

There are many studies that have investigated anthocyanin biosynthesis on a molecular level. Due to the cloning of anthocyanin biosynthetic genes and isogenes of enzymes such as phenylalanine ammonia lyase (PAL), chalcone synthase (CHS), chalcone isomerase (CHI), flavone-3-hydrolase (F3H), dihydroflavonol 4-reductase (DFR), leucoanthocyanidin dioxygenase (LDOX) and udp-glucose: flavonoid 3-o-glucosyltransferase (UFGT) (Sparvoli *et al.*, 1994), it is possible to study the effects of temperature on anthocyanin biosynthesis. In a study by Mori *et al.* (2005), the importance of elevated night temperatures on anthocyanin accumulation was investigated. Continuously high night temperatures (30°C) reduced anthocyanin accumulation as well as enzyme activity and gene expression of CHS, F3H, DFR, LDOX and UFGT at véraison. The reduction in anthocyanin accumulation was suggested by the authors to be a result of the adverse effect on the stability of the enzyme and substrate. There was a decrease in the expression of the biosynthetic genes and a decrease in the activity of the biosynthetic enzymes. In a further study by Mori *et al.* (2007) potted Cabernet Sauvignon vines were placed in a phytotron with two temperature regimes. The first was a control with a maximum of 25°C and the second had a maximum of 35°C. The experiment started one week before veraison, continuing to fruit maturation. The total anthocyanins from the experiment under high temperatures (35°C) were reduced to less than half of the total anthocyanins of the control. It was observed, however, that the anthocyanin biosynthetic genes were not strongly down regulated at high temperatures relative to the control. The authors performed a further experiment to investigate the possibility of anthocyanin degradation. Stable isotope-labelled trace elements were performed on excised, softened green berries which were sampled one week before véraison. These berries were exposed to one of three temperatures 15°C, 25°C and 35°C and examined at different stages over a week. Berries exposed to the highest temperatures showed a marked decrease in the content of total labelled anthocyanins compared to berries under 15°C and 25°C. It was thus suggested that the decrease in anthocyanins might be due to the degradation of anthocyanins (occurring at 35°C), in addition to the inhibition of mRNA transcription of the anthocyanin biosynthetic genes.

Thresholds

The general consensus of controlled studies is that lower day temperatures enhance pigmentation in grapes. Buttrose *et al.* (1971) did an experiment on pot grown vines (*Vitis vinifera*) using artificial light, which was kept constant. Grapevines were exposed either to 20°C or 30°C day temperatures. Night temperatures were kept constant at 15°C for both treatments. The outcome agreed with the above statement that lower day time temperatures are conducive to anthocyanin formation. It is not entirely clear how field-grown grapevines will respond. In a study by Cohen *et al.* (2012) treatment effects of differing temperature regimes on total proanthocyanidins showed inconsistent results through the three seasons. In the last two seasons no treatment effect was observed despite a 30% difference in the thermal time accumulation (degree days) and mean daily temperature differences of 4°C observed between treatments.

In a study done by Kliewer & Torres (1972) under controlled day and night temperatures (phytotron), a temperature of 35°C completely impeded coloration in ‘Tokay’ grapes, irrespective of the night temperature. This threshold for anthocyanin synthesis was also observed by Haselgrove *et al.* (2000) as well as Spayd *et al.* (2002). Kliewer & Torres (1972) observed the highest coloration at low day and night temperatures (both 15°C) for Cardinal, Pinot noir and Tokay. The difference between the day and night temperatures also had an effect, with a difference of less than 10°C benefitting coloration in contrast with a greater difference resulting in lower anthocyanin levels. The authors, however, could not explain the result.

Stage of accumulation

Specific physiological and biochemical events were monitored during different stages of berry development by Hrazdina *et al.* (1984). Anthocyanin content illustrated a sharp increase directly after véraison along with Brix, pH, K+ and sugars. This coincided with an increase in the activity of the anthocyanin biosynthetic enzymes. However, in De Chaunac grapes, small amounts of anthocyanins were visible shortly after fruit formation which was too low to measure. This study described a measurable amount of anthocyanins starting briefly after the commencement of sugar accumulation at véraison, which was confirmed later by Jeong *et al.* (2004).

Effect of temperature on stage of accumulation

Yamane *et al.* (2006) investigated the importance of threshold temperatures at different stages of berry development. This study exposed potted vines either to 20°C or 30°C for two weeks at four stages of berry development and ripening. The highest anthocyanin accumulation was observed at 20°C one to three weeks after the onset of colouring. This period also proved to be sensitive to high night temperatures with regard to expression levels of the enzyme UFGT, which plays an important role in anthocyanin synthesis (Mori *et al.*, 2005).

2.5 Conclusions

Climatic parameters have been measured at different levels, from macroclimate to microclimate. Climate studies on a meso-scale focuses on a smaller area and provides more detail on the topographical aspects such as the slope, aspect or altitude of the land, which is closely related to the influence of terroir. Here, the proximity to large bodies of water may also play a role as well as the wind speed and direction and relative humidity. Climatic measurements on this level also aid in the denomination of cultivars of *Vitis vinifera* into areas according to suitability for wine quality. The microclimate, at a more detailed scale level, refers to the climate inside and immediately surrounding the canopy, of which light and temperature are the main focus with regard to berry composition and thus berry quality. The canopy is a complex and dynamic system which creates a variable environment in terms of light and temperature. The apparent sun path, in addition to the spatial distribution of leaves, makes characterization of the bunch microclimate a difficult task. There are many sensors available for the quantification of temperature in the canopy and on the bunch. However, due to the cost of such tools and the limited knowledge available on the finer levels of climate, inaccurate or inappropriate assumptions can be made. Thus there is a need for a study that defines the techniques for measuring bunch/berry temperature accurately/appropriately. A better understanding of the response in temperature of the bunch/berry to its environment is required. This refers to the microclimatic parameters in the immediate environment (the canopy), as affected by the meso- or macroclimate. Parameters contributing to the immediate environment refer to the microclimate as well as the viticultural practices such as the trellis system and row orientation.

Temperature is known to contribute to grape quality in terms of the effect it has on certain physiological components. Little is known on the exact mechanisms of action. The inhibition of the transcription of certain enzymes as well as enzymes activity and the degradation of components as a result of temperature thresholds are suggested. The different metabolic activities involving the synthesis and storage of components occur in different sections of the berry. These different sections, such as the skin and pulp, may respond differently to temperature. More knowledge on the temperature gradients inside the berry and throughout the day may thus be important.

Characterising the temperature variability on a higher resolution such as the bunch/berry may give a better understanding of the contribution of the surrounding environment. This may provide insight on the parameters needed for the development of models predicting bunch/berry temperature.

2.6 Literature cited

Amerine, M.A. & Winkler, A.J., 1944a. Composition and quality of musts and wines of California grapes. Hilgardia 15, 493-675.

Amerine, M.A. & Winkler, A.J., 1944b. Composition and quality of musts and wines of California grapes. University of California.

Anbar, M., 1998. Clinical thermal imaging today. IEEE Engineering in Medicine and Biology Magazine 17 (4), 25-33.

Anonymous, 2001. Emissivity: Definition and Influence in Non-contact Temperature Measurement. Keller MSR infrared temperature solutions. URL: http://www.keller-msr.com/temperature-pyrometers/emissivity-definition-and-influence-in-non-contact-temperature-measurement.php.

Anonymous, 2007. Emissivity values of common materials. Fluke Corporation. URL: http://www.frigidn.com/resources/EmissivityTable.pdf.

Anonymous, 2012a. Climate education for K-12: latent and sensible heat. State climate office North Carolina. URL: http://www.nc-climate.ncsu.edu/edu/k12/.lsheat.

Anonymous, 2012b. Thermocouples. Data Track Technology. URL: http://www.datatrackpi.com/technical-papers/how-does-a-thermocouple-work.htm.

Bergqvist, J., Dokoozlian, N. & Ebisuda, N., 2001. Sunlight exposure and temperature effects on berry growth and composition of Cabernet Sauvignon and Grenache in the Central San Joaquin Valley of California. Am J Enol Vitic 52 (1), 1-7.

Blanco-Ward, D., Queijeiro, J.M.G. & Jones, G., 2007. Spatial climate variability and viticulture in the Miño River Valley of Spain. Vitis 46 (2), 63.

Blanke, M.M. & Leyhe, A., 1987. Stomatal activity of the grape berry cv. Riesling, Müller-Thurgau and Ehrenfelser. J Plant Physiol 127 (5), 451-460.

Bonnardot, V., Carey, V., Planchon, O. & Cautenet, S., 2001. Sea breeze mechanism and observations of its effects in the Stellenbosch wine producing area. Wineland 107-113.

Bonnardot, V., Carey, V.A., Madelin, M., Cautenet, S., Coetzee, Z. & Quénol, H., 2012. Spatial variability of night temperatures at a fine scale over the Stellenbosch wine district, South Africa. J Int Sci Vigne Vin 46 (1), 1-13.

Bonnardot, V., Carey, V.A. & Strydom, J., 2004. Weather stations: Applications for viticulture. Wineland.

Bonnardot, V., Planchon, O., Carey, V. & Cautenet, S., 2002. Diurnal wind, relative humidity and temperature variation in the Stellenbosch-Groot Drakenstein wine-growing area. S Afr J Enol Vitic 23 (2), 62-71.

Bowers, S. & Hanks, R., 1965. Reflection of radiant energy from soils. Soil Sci 100 (2), 130-138.

Bulanon, D., Burks, T. & Alchanatis, V., 2008. Study on temporal variation in citrus canopy using thermal imaging for citrus fruit detection. Biosyst Eng 101 (2), 161-171.

Buttrose, M., Hale, C. & Kliewer, W.M., 1971. Effect of temperature on the composition of'Cabernet Sauvignon'berries. Am J Enol Vitic 22 (2), 71-75.

Cohen, S.D., Tarara, J.M., Gambetta, G.A., Matthews, M.A. & Kennedy, J.A., 2012. Impact of diurnal temperature variation on grape berry development, proanthocyanidin accumulation, and the expression of flavonoid pathway genes. J Exp Bot 63 (7), 2655-2665.

Cola, G., Failla, O. & Mariani, L., 2009. BerryTone--A simulation model for the daily course of grape berry temperature. Agric For Meteorol 149 (8), 1215-1228.

Coombe, B., 1986. Influence of temperature on composition and quality of grapes. In: Proc. Acta Horticulturae, pp. 23-36.

Coombe, B., 1992. Research on development and ripening of the grape berry. Am J Enol Vitic 43 (1), 101-110.

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

Fuller, M. & Wisniewski, M., 1998. The use of infrared thermal imaging in the study of ice nucleation and freezing of plants1. J Therm Biol 23 (2), 81-89.

Gladstones, E. & Dokoozlian, N.K., 2003. Influence of leaf area density and trellis/training system on the light microclimate within grapevine canopies. VITIS 42 (3), 123-132.

Gladstones, J., 1992. Viticulture and environment. Winetitles, Adelaide.

Grant, O. & Chaves, M., 2005. Thermal imaging successfully identifies water stress in field-grown grapevines. In: Proc. 14th International GESCO Viticulture Congress, Geisenheim, Germany. pp. 219-224.

Grant, O.M., Tronina, Ł., Jones, H.G. & Chaves, M.M., 2007. Exploring thermal imaging variables for the detection of stress responses in grapevine under different irrigation regimes. J Exp Bot 58 (4), 815-825.

Haselgrove, L., Botting, D., Heeswijck, R., Høj, P., Dry, P., Ford, C. & Land, P., 2000. Canopy microclimate and berry composition: The effect of bunch exposure on the phenolic composition of Vitis vinifera L cv. Shiraz grape berries. Aust J Grape Wine Res 6 (2), 141-149.

Holton, T.A. & Cornish, E.C., 1995. Genetics and biochemistry of anthocyanin biosynthesis. Plant Cell 7 (7), 1071.

Hrazdina, G., Parsons, G.F. & Mattick, L.R., 1984. Physiological and biochemical events during development and maturation of grape berries. Am J Enol Vitic 35 (4), 220-227.

Huglin, P., 1978. Nouveau mode d'évaluation des possibilités héliothermiques d'un milieu viticole. C. R. Acad. Agr. France, 1117-1126.

Hunter, J., 1998. Plant spacing implications for grafted grapevine II. Soil water, plant water relations, canopy physiology, vegetative and reproductive characteristics, grape composition, wine quality and labour requirements. S Afr J Enol Vitic 19, 35-51.

Hunter, J., Archer, E. & Volschenk, C.G., 2010. Vineyard management for environment valorisation. In: Proc. Eighth International Terrior Conference, Soave, Italy. pp. 3-15.

Hunter, J. & Bonnardot, V., 2011. Suitability of some climatic parameters for grapevine cultivation in South Africa, with focus on key physiological processes. S. Afr. J. Enol. Vitic 32 (1).

Idso, S., Jackson, R., Pinter Jr, P., Reginato, R. & Hatfield, J., 1981. Normalizing the stress-degree-day parameter for environmental variability. Agr Meteorol 24, 45-55.

Idso, S.B., 1982. Non-water-stressed baselines: a key to measuring and interpreting plant water stress. Agr Meteor 27 (1-2), 59-70.

Intrigliolo, F., Stagno, F. & Giuffrida, A., 2009. Canopy Temperature as an Indicator of Water Status in Citrus Trees. In: Proc. 6th International Symposium on Irrigation of Horticultural Crops, Viña del Mar, Chile. pp. 347-353.

Jackson, R., Reginato, R. & Idso, S., 1977. Wheat canopy temperature: a practical tool for evaluating water requirements. Water Resour Res 13 (3), 651-656.

Jackson, R.D., Kustas, W.P. & Choudhury, B.J., 1988. A reexamination of the crop water stress index. Irrig Sci 9 (4), 309-317.

Jeong, S.T., Goto-Yamamoto, N., Kobayashi, S. & Esaka, M., 2004. Effects of plant hormones and shading on the accumulation of anthocyanins and the expression of anthocyanin biosynthetic genes in grape berry skins. Plant Sci 167 (2), 247-252.

Jones, H.G., 1999. Use of infrared thermometry for estimation of stomatal conductance as a possible aid to irrigation scheduling. Agric For Meteorol 95 (3), 139-149.

Jones, H.G., 2004. Application of thermal imaging and infrared sensing in plant physiology and ecophysiology. Adv Bot Res 41, 107-163.

Kliewer, W.M., 1977. Influence of temperature, solar radiation and nitrogen on coloration and composition of Emperor grapes. Am J Enol Vitic 28 (2), 96-103.

Kliewer, W.M. & Torres, R.E., 1972. Effect of controlled day and night temperatures on grape coloration. Am J Enol Vitic 23 (2), 71-77.

Koch, A., Ebeler, S.E., Williams, L.E. & Matthews, M.A., 2012. Fruit ripening in *Vitis vinifera*: light intensity before and not during ripening determines the concentration of 2-methoxy-3-isobutylpyrazine in Cabernet Sauvignon berries. Physiol Plant 145 (2), 275–285.

Marais, J., Hunter, J. & Haasbroek, P., 1999. Effect of canopy microclimate, season and region on Sauvignon blanc grape composition and wine quality. S Afr J Enol Vitic 20, 19-30.

Meola, C. & Carlomagno, G.M., 2004. Recent advances in the use of infrared thermography. Meas Sci and Technol 15, R27.

Möller, M., Alchanatis, V., Cohen, Y., Meron, M., Tsipris, J., Naor, A., Ostrovsky, V., Sprintsin, M. & Cohen, S., 2007. Use of thermal and visible imagery for estimating crop water status of irrigated grapevine. J Exp Bot 58 (4), 827-838.

Mori, K., Goto-Yamamoto, N., Kitayama, M. & Hashizume, K., 2007. Loss of anthocyanins in red-wine grape under high temperature. J Exp Bot 58 (8), 1935-1945.

Mori, K., Sugaya, S. & Gemma, H., 2005. Decreased anthocyanin biosynthesis in grape berries grown under elevated night temperature condition. Scientia Horticulturae 105 (3), 319-330.

Ollat, N., Diakou-Verdin, P., Carde, J., Barrieu, F., Gaudillere, J.P. & Moing, A., 2002. Grape berry development: a review. J Int Sci Vigne Vin 36.

Price, J.C., 1982. Estimation of regional scale evapotranspiration through analysis of satellite thermal-infrared data. Geoscience and Remote Sensing, IEEE Transactions on(3), 286-292.

Ribéreau-Gayon, P. & Glories, Y., 1986. Phenolics in grapes and wines. In: Proc. 6th Australian Wine Industry Technical Conference, Adelaide. pp. 247-256.

Ruffner, H.P., 1982. Metabolism of tartaric and malic acids in Vitis: a review - part A. Vitis 21 (3), 247-259.

Ryona, I., Pan, B.S., Intrigliolo, D.S., Lakso, A.N. & Sacks, G.L., 2008. Effects of cluster light exposure on 3-isobutyl-2-methoxypyrazine accumulation and degradation patterns in red wine grapes (Vitis vinifera L. cv. Cabernet Franc). J Agric Food Chem 56 (22), 10838-10846.

Saudreau, M., Sinoquet, H., Santin, O., Marquier, A., Adam, B., Longuenesse, J.J., Guilioni, L. & Chelle, M., 2007. A 3D model for simulating the spatial and temporal distribution of temperature within ellipsoidal fruit. Agric For Meteorol 147 (1-2), 1-15.

Seguin, B., Courault, D. & Guerif, M., 1994. Surface temperature and evapotranspiration: application of local scale methods to regional scales using satellite data. Remote Sens Environ 49 (3), 287-295.

Seguin, B., Lagouarde, J.P. & Savane, M., 1991. The assessment of regional crop water conditions from meteorological satellite thermal infrared data. Remote Sens Environ 35 (2-3), 141-148.

Smart, R., Robinson, J., Due, G. & Brien, C., 1985. Canopy microclimate modification for the cultivar Shiraz. I. Definition of canopy microclimate. Vitis 24, 17-31.

Smart, R. & Robinson, M., 1991. Sunlight into wine: a handbook for winegrape canopy management. Winetitles, Adelaide.

Smart, R., Shaulis, N. & Lemon, E., 1982. The effect of Concord vineyard microclimate on yield. I. The effects of pruning, training, and shoot positioning on radiation microclimate. Am J Enol Vitic 33 (2), 99-108.

Smart, R.E., 1973. Sunlight interception by vineyards. Am J Enol Vitic 24 (4), 141-147.

Smart, R.E., 1985. Principles of grapevine canopy microclimate manipulation with implications for yield and quality. A review. Am J Enol Vitic 36 (3), 230-239.

Smart, R.E., 1986. Influence of light on composition and quality of grapes. In, pp. 37-48.

Smart, R.E. & Sinclair, T.R., 1976. Solar heating of grape berries and other spherical fruits. Agric Meteorol 17 (4), 241-259.

Smith, H., 1982. Light quality, photoperception, and plant strategy. Annual review of plant physiology 33 (1), 481-518.

Sparvoli, F., Martin, C., Scienza, A., Gavazzi, G. & Tonelli, C., 1994. Cloning and molecular analysis of structural genes involved in flavonoid and stilbene biosynthesis in grape (Vitis vinifera L.). Plant Mol Biol 24 (5), 743-755.

Spayd, S.E., Tarara, J.M., Mee, D.L. & Ferguson, J., 2002. Separation of sunlight and temperature effects on the composition of Vitis vinifera cv. Merlot berries. Am J Enol Vitic 53 (3), 171-182.

Stoll, M., Schultz, H.R. & Berkelmann-Loehnertz, B., 2008. Exploring the sensitivity of thermal imaging for Plasmopara viticola pathogen detection in grapevines under different water status. Funct Plant Biol 35 (4), 281-288.

Strever, A., Bezuidenhout, D., Zorer, R., Moffat, T. & Hunter, J., 2012. Optical and thermal applications in grapevine (*Vitis vinifera* L.) research-an overview and some novel approaches. SAIEE Research Journal 103 (1), 55-60.

Tarara, J., Ferguson, J., Hoheisel, G.A. & Perez Peña, J., 2005. Asymmetrical canopy architecture due to prevailing wind direction and row orientation creates an imbalance in irradiance at the fruiting zone of grapevines. Agric For Meteorol 135 (1), 144-155.

Thorpe, M., 1974. Radiant heating of apples. J Appl Ecol, 755-760.

Tonietto, J. & Carbonneau, A., 2004. A multicriteria climatic classification system for grape-growing regions worldwide. Agric For Meteorol 124 (1), 81-97.

Vadivambal, R. & Jayas, D.S., 2011. Applications of thermal imaging in agriculture and food industry—a review. Food Bioprocess Tech 4 (2), 186-199.

Van Zyl, J., 1986. Canopy temperature as a water stress indicator in vines. S. Afr. J. Enol. Vitic 7 (2), 53-60.

Van Zyl, J. & Van Huyssteen, L., 1980. Comparative studies on wine grapes on different trellising systems: II. Microclimatic studies, grape composition, and wine quality. S. Afr. J. Enol. Vitic 1 (1), 15.

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

Weiss, S.B., Luth, D.C. & Guerra, B., 2003. Potential solar radiation in a vertical shoot positioned (VSP) trellis at 38° N latitude (May/June). Practical winery and vineyard.

Yamane, T., Jeong, S.T., Goto-Yamamoto, N., Koshita, Y. & Kobayashi, S., 2006. Effects of temperature on anthocyanin biosynthesis in grape berry skins. Am J Enol Vitic 57 (1), 54-59.

Zorer, R., Cobelli, T., Tomasi, T., Zulini, L. & Bertamini, M., 2005. Effect of temperature and light availability on ripening of Vitis vinifera L. cv. Chardonnay. In: Proc. 14th International GESCO Viticulture Congress, Geisenheim, Germany. pp. 319-325.

Zorer, R., Rocchini, D., Delucchi, L., Zottele, F., Meggio, F. & Neteler, M., 2011. Use of multi-annual modis land surface temperature data for the characterization of the heat requirements for grapevine varieties. In: Proc. 6th International Workshop on the Analysis of Multi-temporal Remote Sensing Images (Multi-Temp), pp. 225-228.

Chapter 3

Research results

An assessment of temperature variability in *Vitis vinifera* L. cv. Shiraz

CHAPTER III: AN ASSESSMENT OF TEMPERATURE VARIABILITY IN *VITIS VINIFERA* L. CV. SHIRAZ

3.1 Introduction

Aspects impacting variability include macroclimatic variables such as latitude, proximity to the ocean (Bonnardot et al., 2001) as well as mesoclimatic factors such as elevation, slope, aspect and sun hours. However, variability on a vineyard level can be reduced to a certain extent with the proper execution of vineyard practices (Hunter et al., 2010). Variability in temperature on a bunch and/or berry level is a reality when it comes to the cultivation of the grapevine under commercial conditions. Variability on a bunch level is important as it may affect the berry composition, which in turn determines the wine quality. In addition, the sampling techniques with regard to scientific studies on grape composition can be largely affected by the variability existing in a bunch, as well as variability between bunches and vines (Barbagallo *et al.*, 2011; Melo, 2011). The canopy architecture which is dictated by the trellis or training system, the row orientation as well as external or environmental factors, will also contribute to the variability in microclimate. A further understanding of the conditions or microclimate in which the bunch is situated is required due to the complexity of the above mentioned.

There is a need for focus on what a specific bunch or berry is experiencing under certain conditions which will aid in future studies on berry temperature modelling. Little research has focussed on temperature on such a high resolution under ‘natural’ conditions as studies involved in defining the bunch microclimate usually consist of the random placement of sensors with little or no quantification of the light environment. Furthermore, little research has investigated the distribution of temperature within a berry throughout the day at regular intervals. There is a need for a method and guideline which aids in defining temperature experienced by the bunch in order to be able to relate it to physiological reaction.

This chapter discusses the use of different temperature sensors as well as the impacts of spatial and temporal variability observed on a bunch. Temperature sensors on this scale included the Thermal Camera which registered temperature images of the whole bunch and thus aided in the quantification of spatial variability. Thermal imaging is also used on a large scale with devices on board satellites, such as the MODerate resolution Imaging Spectroradiometer (MODIS), which provide land surface temperatures used in the determination of cultivar suitability in different regions (Zorer *et al.*, 2011) as well as on a smaller scale in irrigation scheduling as a result of the close relationship between stomatal control and leaf temperature (Jones, 1999). Other sensors included thermocouples with dimensions that allowed for the different positioning on and within the berry, as well as temperature monitoring of the same berry throughout the ripening period.

3.2 Materials and Methods

3.2.1 Vineyards

3.2.1.1 Robertson and Stellenbosch

Diurnal light and temperature measurements (day cycles) were conducted during the 2011/12 growing season at two locations, Robertson and Stellenbosch, in the Western Cape region of South Africa. The characteristics of the different vineyards are displayed in Table 3.

Table 3 Vineyard characteristics of the sites in Robertson and Stellenbosch.

Descriptor	**Robertson**	**Stellenbosch**
Grapevine species	*Vitis vinifera*	*Vitis vinifera*
Cultivar	Shiraz	Shiraz
Clone	SH9C	SH9C
Rootstock	101-14 Mgt (*Vitis riparia* x *Vitis rupestris*)	101-14 Mgt (*Vitis riparia* x *Vitis rupestris*)
Year established	2001	2000
Row orientation	North-South	North-South
Terrain	Flat	Flat
Lat/Long/elevation	33°49'34"S 19°52'51"E 153m	33°56'26''S 18°51'56''E 157m
Farm name	ARC Infruitec-Nietvoorbij experiment farm (Agricultural Research Council)	Welgevallen experiment farm (Department of Viticulture and Oenology)
Grapevine spacing	2.7 x 1.8	2.7 x 1.5
Trellis/training system	9-wire hedge system with four sets of movable foliage wires (Vertical positioning system – VSP)	7-wire hedge trellis system with three sets of moveable foliage wires (Ballerina)
Irrigation system	Pressure compensated drip system	Pressure compensated drip system
Pruning system	Spur	Spur
Climate	Semi-arid	Mediterranean

3.2.2 Experiment layout and treatments

3.2.2.1 Robertson

Diurnal measurements were conducted as indicated in Table 4. Light and temperature measurements were performed on two bunches for each day cycle from 07:00 until 18:00, (Figure 1 and Figure 2). The first bunch (bunch one) consisted of thin thermocouples (TC's), which were used to quantify continuous diurnal berry temperature. These are further described in 3.2.6. A second bunch (bunch two) was chosen with approximately the same orientation and in the same row at a close distance but without TC's. The difference in measurements between the two bunches is described in Table 5. Two day cycles were conducted consecutively (on separate days) at a time, alternating between bunches measured on the east and the west sides of the canopy. Table 6 shows the diurnal cycles in Robertson for the 2011/2012 season. The corresponding bunch orientation, i.e. "east" refers to measurements conducted on a bunch on the east facing side of the canopy, whereas "west" refers to the bunch on the west facing side of the canopy.

Table 4 Intervals of day cycle measurements performed in Robertson in the 2012 season with time indicated as days after budburst (DAB).

	Days after bud burst(DAB)/Bunch orientation					
Measurement	**149 (east)**	**150 (west)**	**163 (west)**	**164 (east)**	**177 (west)**	**178 (east)**
Temperature near bunch 1			1 min	1 min	1 min	1 min
Humidity near bunch 1			1 min	1 min	1 min	1 min
Canopy temperature			1 min	1 min	1 min	1 min
Canopy humidity x1			1 min	1 min	1 min	1 min
Bunch temperature in bunch 1	15 min	15 min	15 min	15 min	15 min	15 min
14 Pulp thermocouples in bunch 1	15 min	15 min	15 min	15 min	15 min	15 min
9 within berry thermocouples of bunch 1	1 min	1 min	1 min	1 min	1 min	1 min
LiCor Quantum sensors bunch 1 & 2	1 min	1 min	1 min	1 min	1 min	1 min

Figure 1 Demarcated area (red) in which measurements (day cycles) were performed in Robertson.

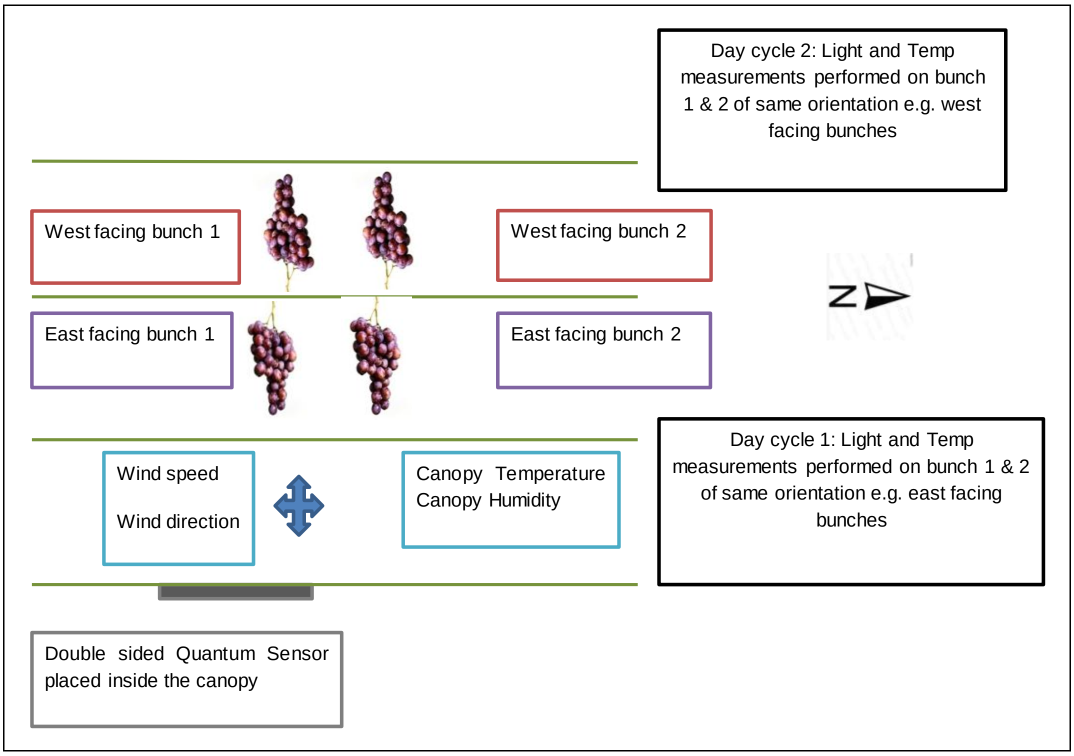


Figure 2 Experiment layout in Robertson illustrating the location of the weather vane, quantum sensor and canopy sensors in relation to bunches measured during day cycles as well as the location of the two bunches which are measured during a single day cycle.

Table 5 Difference in measurements performed on the two bunches in a single day cycle in Robertson.

BUNCH 1	**BUNCH 2**
N-S row direction	N-S row direction
East facing/West facing	East facing/West facing
9 TC's in 3 berries (skin, pulp, under skin)	-
Quantum sensor above bunch	Quantum sensor above bunch
Hourly/2 hourly Thermal Images	Hourly/2 hourly Thermal Images

Table 6 Measurement dates in Robertson represented as day cycles one to six with the corresponding bunch orientation.

Measuring Date	Day cycle	Bunch orientation
2012/02/15	1	East
2012/02/16	2	West
2012/02/29	3	West
2012/03/01	4	East
2012/03/14	5	West
2012/03/15	6	East

3.2.2.2 Stellenbosch

Diurnal measurements were conducted as indicated in Table 7. The experiment in Stellenbosch was conducted on a single grapevine (Figure 3). The "Ballerina training system" allows for four ripening zones: upper east-facing, lower east-facing, upper west-facing, lower west-facing (Figure 4). In each ripening zone, one bunch was selected per day cycle. The light and temperature measurements performed for each day cycle are discussed in greater detail below. Two day cycles were conducted consecutively, alternating between the east and west sides of the canopy in the same ripening zone, i.e. upper or lower. Table 8 shows the diurnal cycles in Stellenbosch for the 2011/2012 season. The corresponding bunch orientation, i.e. "east" refers to measurements conducted on a bunch on the east facing side of the canopy, whereas "west" refers to the bunch on the west facing side of the canopy.

Figure 3 Demarcated area (red) in which measurements (day cycles) were performed in Stellenbosch.

Table 7 Intervals of day cycle measurements performed in Stellenbosch in the 2012 season, with time indicated as days after budburst (DAB). The orientations of the measurements relative to the canopy are shown in brackets.

	Days after bud burst(DAB)/Bunch orientation and ripening zone							
Measurement	**114 (east, upper)**	**134 (east, lower)**	**155 (west, lower)**	**157 (west, upper)**	**170 (east, upper)**	**171 (west, upper)**	**190 (east, lower)**	**191 (west, lower)**
Weather station temp	60 min	60 min	60 min	60 min	60 min	60 min	60 min	60 min
Weather station humidity	60 min	60 min	60 min	60 min	60 min	60 min	60 min	60 min
Weather station wind speed	60 min	60 min	60 min	60 min	60 min	60 min	60 min	60 min
Weather station wind direction	60 min	60 min	60 min	60 min	60 min	60 min	60 min	60 min
Vineyard temp	15 min	15 min	15 min	15 min	15 min	15 min	15 min	15 min
Vineyard humidity	15 min	15 min	15 min	15 min	15 min	15 min	15 min	15 min
Canopy temperature	15 min	15 min	15 min	15 min	1 min	1 min	1 min	15 min
Canopy humidity	15 min	15 min	15 min	15 min	1 min	1 min	1 min	15 min
Bunch temperature	15 min	15 min	15 min	15 min	1 min	1 min	1 min	1 min
4 Pulp thin thermocouples			15 min	15 min	15 min	15 min	15 min	15 min
9 Within berry thin thermocouples		1 min	1 min	1 min	1 min	1 min	1 min	1 min
LiCor Quantum sensor			1 min	1 min	1 min	1 min	1 min	1 min
Thermal images	1 hr	1 hr	1 hr	1 hr	1 hr	1 hr	1 hr	1 hr

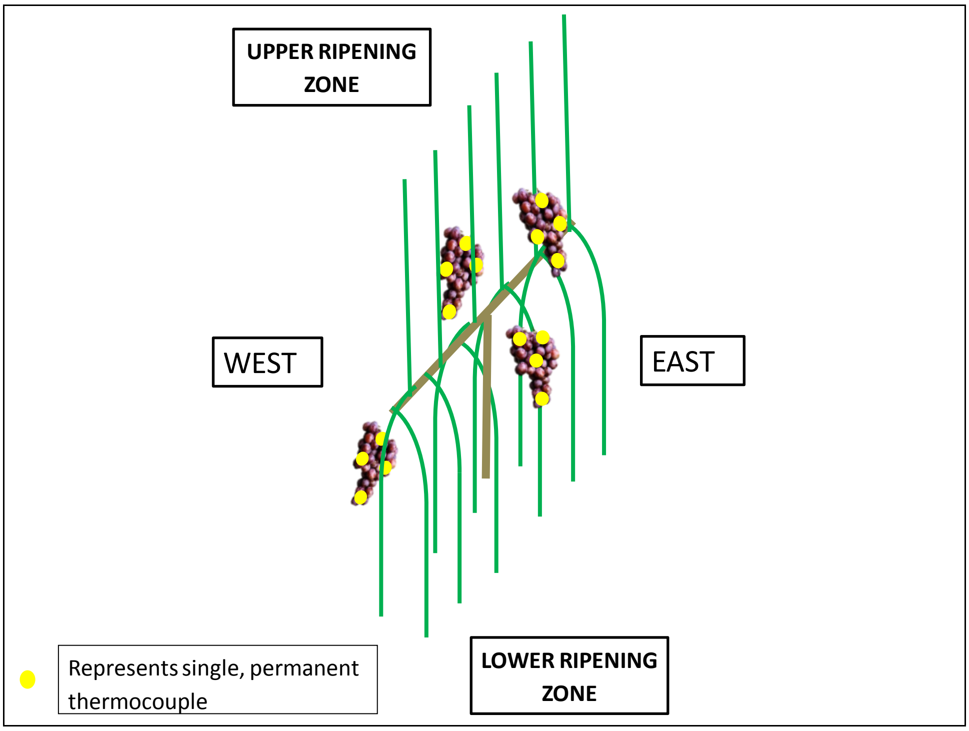


Figure 4 Experiment layout in Stellenbosch illustrating the four ripening zones of the Ballerina system, with the selected bunch in each zone, as well as the distribution of the permanent thermocouples.

Table 8 Measurement dates in Stellenbosch represented as letters B to I with the corresponding bunch orientation and ripening zone.

Measuring Date	Day Cycle	Bunch Orientation	Ripening zone
2012/01/11	B	East	Upper
2012/01/31	C	East	Lower
2012/02/21	D	West	Lower
2012/02/23	E	West	Upper
2012/03/07	F	East	Upper
2012/03/08	G	West	Upper
2012/03/27	H	East	Lower
2012/03/28	I	West	Upper

3.2.3 Macroclimate measurements

3.2.3.1 Weather station

3.2.3.1.1 Robertson

Air temperature measurements at hourly intervals were obtained from an automatic weather station within the network of the Institute of Soil, Climate and Water (ISCW), provided by the South African Weather Services (coordinates 33°47’38’’S; 19°53’2’’E elevation 210 m). It was situated approximately 3.6 km from the mini, automatic weather station situated in the vineyard.

Figure 5 Satellite image showing the relative distance between the two weather stations used in Robertson (indicated with the yellow markers and red circles). The ARC Infruitec-Nietvoorbij weather station is located in the row direction trial where the day cycles were performed and the WeatherSA weather station is located in the town of Robertson.

3.2.3.1.2 Stellenbosch

Air temperature, humidity, wind speed, wind direction and global radiation were obtained at hourly intervals for the specific day cycles from an automatic weather station on the ARC Infruitec-Nietvoorbij Stellenbosch Experiment Farm (co-ordinates 33º55’0’’S; 18º51’35’’E, elevation 149 m) situated approximately 2.71 km from the site (Figure 6).

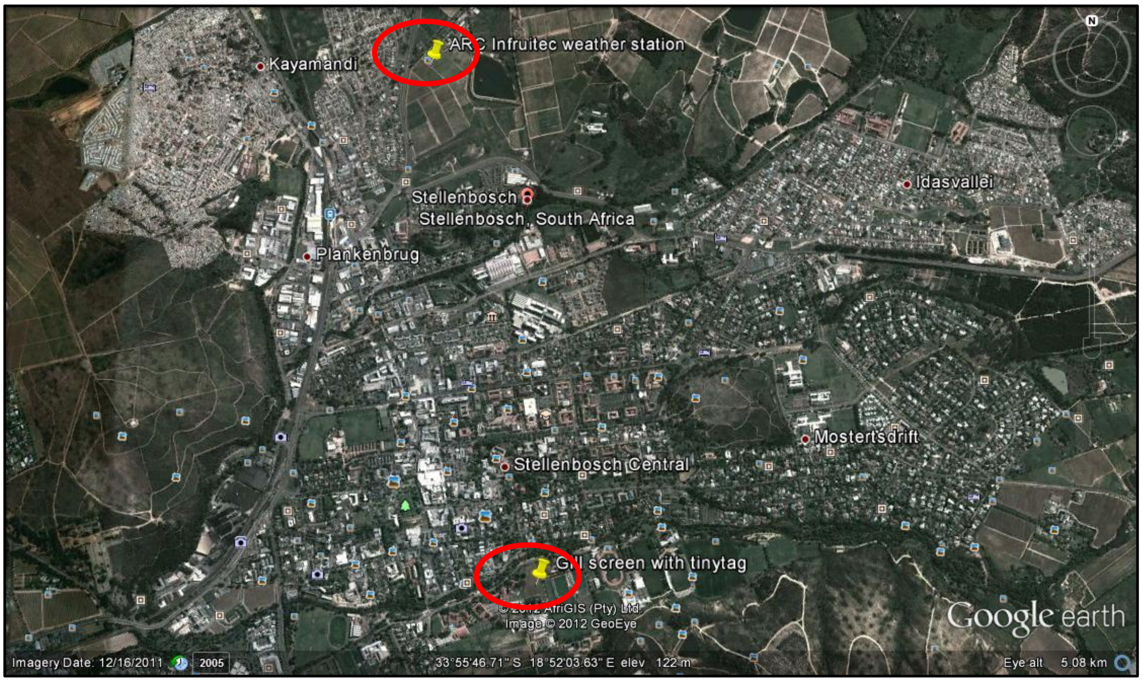


Figure 6 Satellite image showing the relative distance between the ARC Infruitec-Nietvoorbij Heritage garden weather station and the tinytag® inside a radiation shield placed directly above the canopy in the vineyard (both are indicated with the yellow markers and red circles).

3.2.4 Mesoclimate measurements

3.2.4.1 Mini weather station and radiation shield (gill screen)

3.2.4.1.1 Robertson

Air temperature, humidity, wind speed, wind direction and global radiation were obtained from a mini weather station situated in the vineyard on the ARC Infruitec-Nietvoorbij, Robertson Experiment Farm (33°49'35"S; 19°52'54"E, elevation 153 m). Hourly data was collected for the specific day cycles.

3.2.4.1.2 Stellenbosch

A temperature/relative humidity sensor (Tinytag® model TGP-4500, Gemini Data Loggers, West Sussex, United Kingdom) housed in a radiation shield (Tinytag® model LS-1, Gemini Data Loggers, West Sussex, United Kingdom) placed above the canopy (two rows east from the measured grapevine) logged data at a 30 minute interval. The sensor's temperature measurement range is between -25°C and +85°C, with a relative humidity measurement range of between 0% and 100%.

3.2.5 Microclimate measurements

3.2.5.1 Tinytags®

3.2.5.1.1 Robertson

Two canopy sensors were installed during the day cycles (Table 6). The first (Tinytag® model TGP-4017, Gemini Data Loggers, West Sussex, United Kingdom) measuring only temperature (-40°C to +85°C) at one minute intervals was placed in the bunch zone in the middle of the canopy, i.e. between the east facing and west facing bunches and between the two bunches being measured, and without a radiation shield. The second sensor (Tinytag® model TGP-4500, Gemini Data Loggers, West Sussex, United Kingdom), measuring temperature and relative humidity at one minute intervals, was placed next to bunch one, without a radiation shield.

3.2.5.1.2 Stellenbosch

An air temperature and relative humidity sensor (Tinytag® model TGP-4500, Gemini Data Loggers, West Sussex, United Kingdom), without a radiation shield, was placed in the upper and lower ripening zones of the Ballerina trellised grapevine for the entire growing season. Temperature and relative humidity data, at one minute intervals, were obtained for each diurnal cycle. On the remaining days of the growing season, data was logged at 15 minute intervals.

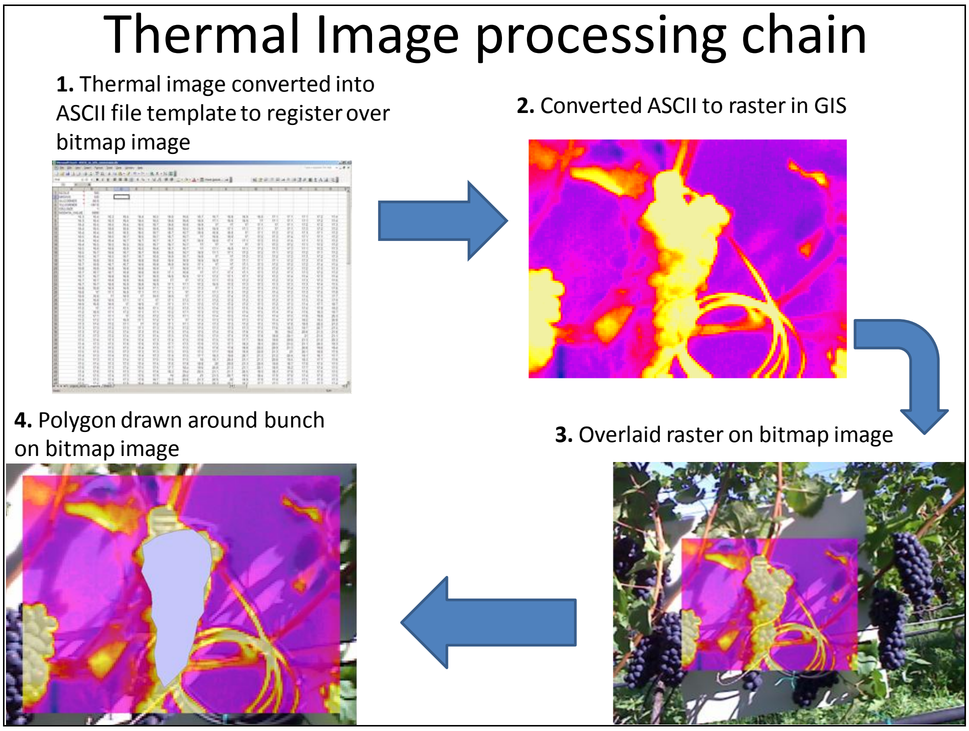
3.2.5.2 Thermal Imaging

3.2.5.2.1 Robertson and Stellenbosch

The thermal imager measures surface temperature indirectly as it is not in direct contact with the object being measured. Thermal images were obtained with the RAZ-IR® NANO thermal camera (SPI, Las Vegas, USA), which operates in the wavelengths 8-14 µm. This wavelength range is described as an atmospheric window where radiation is not absorbed to a great extent (Jones, 2004) The detector type is an Uncooled FBA Microbolometer and the pictures have a spatial resolution of 160 x 120 pixels. The field of view is 20.6° x 15.5°, and the accuracy is ± 2°C or ± 2% of readings. The thermal sensitivity is ≤ 0.1°C at 30°C. The emissivity was set as 0.98 for all measurements. The thermal imager was mounted on a tripod and held perpendicularly (Grant *et al.*, 2007) ca. 1 m from the bunch being measured. During day cycles, both bunches were imaged on the exposed side, which varied from hourly to two hour intervals. In order to aid in distinguishing the bunch from the background during analysis, opaque white sheets were set up against the row behind the grapevine being imaged.

3.2.5.2.2 Processing of thermal images for Robertson and Stellenbosch

Each thermal image was converted from a JPEG file format and saved as a text file using the software GuideIR Analyser 1.7 (Wuhan Guide Infrared Technology Co., Ltd, Wuhan, China). Bitmap images collected simultaneously with thermal images were saved separately. The text file was imported into ArcGIS 10 (Esri, California, USA) and converted into a raster image consisting of pixels with temperature values (°C). The bitmap image of the bunch was also imported into ArcGIS 10. The raster thermal image was overlaid on the bitmap image as accurately as possible using the shift option tool in the georeferencing sub-menu (Figure 7). A polygon shape file was created manually on the bitmap image, by selecting the outline of the bunch of interest. This shape file was applied to the overlaid raster thermal image, which was then ‘clipped’ resulting in the pixels of the bunch being selected from the thermal image. The ‘clipped’ image was converted into a text file for further statistical analysis, either by computing mean, maximum and minimum values for each bunch/time point or by using raw pixel temperature values to create histograms or pie-chart graphs in Statistica 10 ® software (Statsoft, Tulsa, UK).



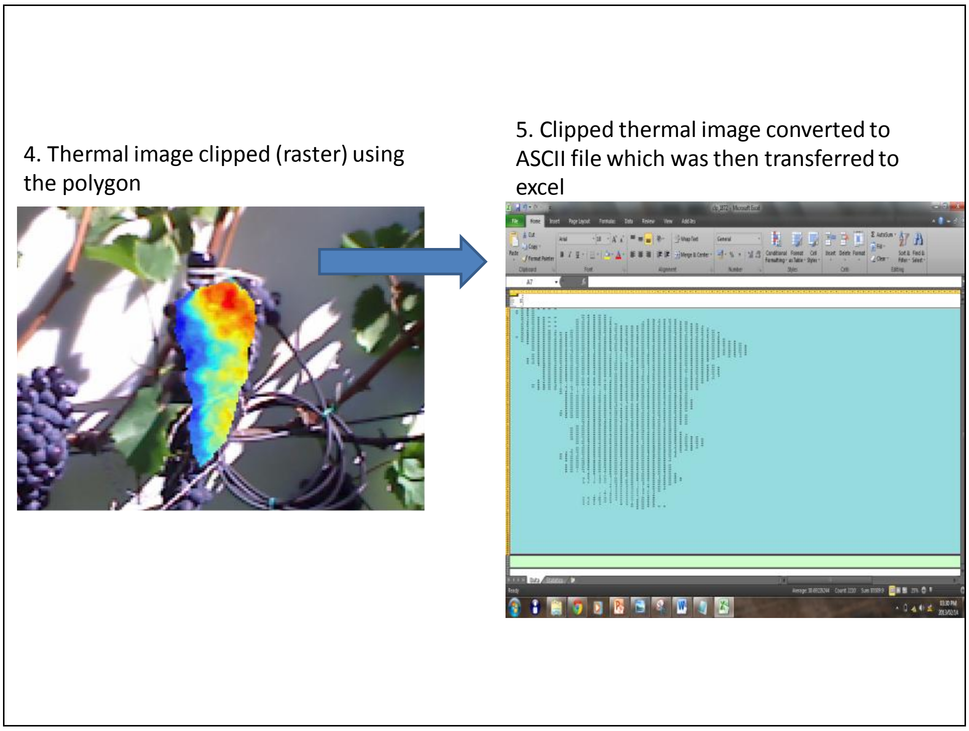
Thermal Image processing chain

1. Thermal image converted into ASCII file template to register over bitmap image

2. Converted ASCII to raster in GIS

3. Overlaid raster on bitmap image

4. Polygon drawn around bunch on bitmap image



4. Thermal image clipped (raster) using the polygon

5. Clipped thermal image converted to ASCII file which was then transferred to excel

Figure 7 Processing chain for the thermal images

3.2.5.3 Photosynthetically Active Radiation (PAR)

3.2.5.3.1 Robertson

One quantum sensor (LI-COR Environmental, model LI 190, Nebraska, USA) measuring photosynthetically active radiation in µ*E*.m^{-2}.s^{-1} at one minute intervals was placed above each of the two bunches being measured for day cycles three to six. Data was stored using a logger (Tinytag$^{®}$, model TGPR-1001, Gemini Data Loggers, West Sussex, United Kingdom).

3.2.5.3.2 Stellenbosch

One quantum sensor (LI-COR Environmental, model LI 190, Nebraska, USA) measuring photosynthetically active radiation in µ*E*.m^{-2}.s^{-1} at one minute intervals was placed above the bunch being measured for day cycles D to I. An additional quantum sensor was placed below the bunch on day cycles F, G and I. Data was stored using a logger (Tinytag® , model TGPR-1001, Gemini Data Loggers, West Sussex, United Kingdom).

3.2.5.4 Thermocouple (TC's)

3.2.5.4.1 Stellenbosch

Copper-constantan TC's (2.5 mm diameter and 8 mm length) were used to measure direct temperature (contact temperature) recorded using a data logger (Tinytag® Talk 2 model TK-4023, Gemini Data Loggers, West Sussex, United Kingdom). The TC has a white coating which reduces radiant heating (Smart, 1976). The temperature measurement range is between -40°C and 125°C. These sensors were used to measure interior bunch temperature (Smart & Sinclair, 1976; Bergqvist *et al.*, 2001), either at 15 minute or one minute intervals depending on the day cycle.

3.2.5.5 Thermal time accumulation for Robertson and Stellenbosch

In this study, thermal accumulation units above the 10°C baseline temperature was calculated in Robertson and Stellenbosch as a mean of all the day cycles in order to assess the differences between the east and west sides of the canopy. Temperature was accumulated at one minute intervals, measured by the thin thermocouples (Micro-BetaCHIP Thermistor Probes, Measurement Specialities, Shenzhen, China) placed in the three berries mentioned in 3.2.6. A datalogger was used to store temperature measurements (Campbell Scientific, model CR1000, Logan, Utah, USA).

Another way to observe differences between the east and west is temperature accumulation through the day. The Growing Degree Day (GDD) concept of Amerine & Winkler (1944a) is a temperature summation above a baseline of 10°C in the period concerned. This was based on the system developed in France by A.P. de Candolle in 1855 (Gladstones, 1992), which in turn was based on the observation that plant growth in spring was only initiated when the mean air temperature was above 10°C. The grapevine as suggested by Winkler (1965) is a conservative plant and remains in ecodormacy until this mean daily spring temperature is 10°C, unlike many deciduous fruit.

In a study done by Moncur *et al.* (1989) the widely accepted 10°C baseline temperature (Williams *et al.*, 1985; Mullins *et al.*, 1992) was questioned. This article suggested that 4°C for budburst and 7°C for leaf appearance were more accurate baseline temperatures. This study was done under controlled conditions with the plants placed in the different day/night temperature regimes with the difference in day and night temperature being 5°C. Gladstones (1992), however, questioned this and suggested that under natural conditions the difference is closer to 10°C and that this range reflects more the range between the mean day and mean night temperatures and thus fails to reflect extreme minima which may be physiologically important. Gladstones (1992) also questioned the use of the same temperatures throughout the experiment growth period, which does not reflect natural conditions where the temperature rises for the same period. A lag may also occur where the reaction in growth to low temperatures (even lower than 10°C) would only be visible once the mean air temperature is above 10°C. A baseline temperature is thus an accepted threshold. Other queries involving the heat summation method developed by Amerine & Winkler (1944a) include the use of the daily minima and maxima. Mullins *et al.* (1992) emphasized the importance of factors such as wind, cloud cover and fog, which may affect the ambient temperature through the day but may not influence the daily maximum or minimum values. Thus the development of data loggers has allowed for the calculation of ‘growing degree minutes’ in order to work out the growing degree days (Williams, 1987).

3.2.5.6 Thermal time accumulation for permanent thermocouples (TC’s) in Stellenbosch

Four thin TC’s made of copper-constantan with a diameter of 0.5 mm and a length of 3.3 mm were inserted into the pulp of four berries distributed over the exposed side of each bunch of each ripening zone (Figure 4). These thermocouples were inserted on 2 February 2012 and continued to log at 15 minute intervals for the rest of the season. Temperature above 10°C for each of these TC’s was accumulated every 15 minutes for the abovementioned period and measurements were stored in a datalogger (Campbell Scientific, model CR1000, Logan, Utah, USA).

3.2.6 Temperature measurements on a nano scale (temporary, thin thermocouples, Robertson and Stellenbosch)

Thin TC’s (dimensions mentioned in 3.2.5.6), were used to describe the diurnal temperature within the berry as a result of the smaller entry wound. Three berries were selected on bunch one: two berries on the exposed side and one berry situated at the back of the bunch (Figure 8). The two berries on the front side of the bunch represented berries mostly exposed to the sun whereas the berry at the back represented a shaded berry. Three thin copper-constantan TC’s were inserted into three different sections of each berry (resulting in a total of nine TC’s in three berries). The different sections (illustrated in Figure 8) are: the surface (on the skin), immediately under the skin and in the middle of the berry (pulp). Temperature was measured on one minute intervals for each diurnal cycle. Measurements were stored in a datalogger (Campbell Scientific, model CR1000, Logan, Utah, USA).

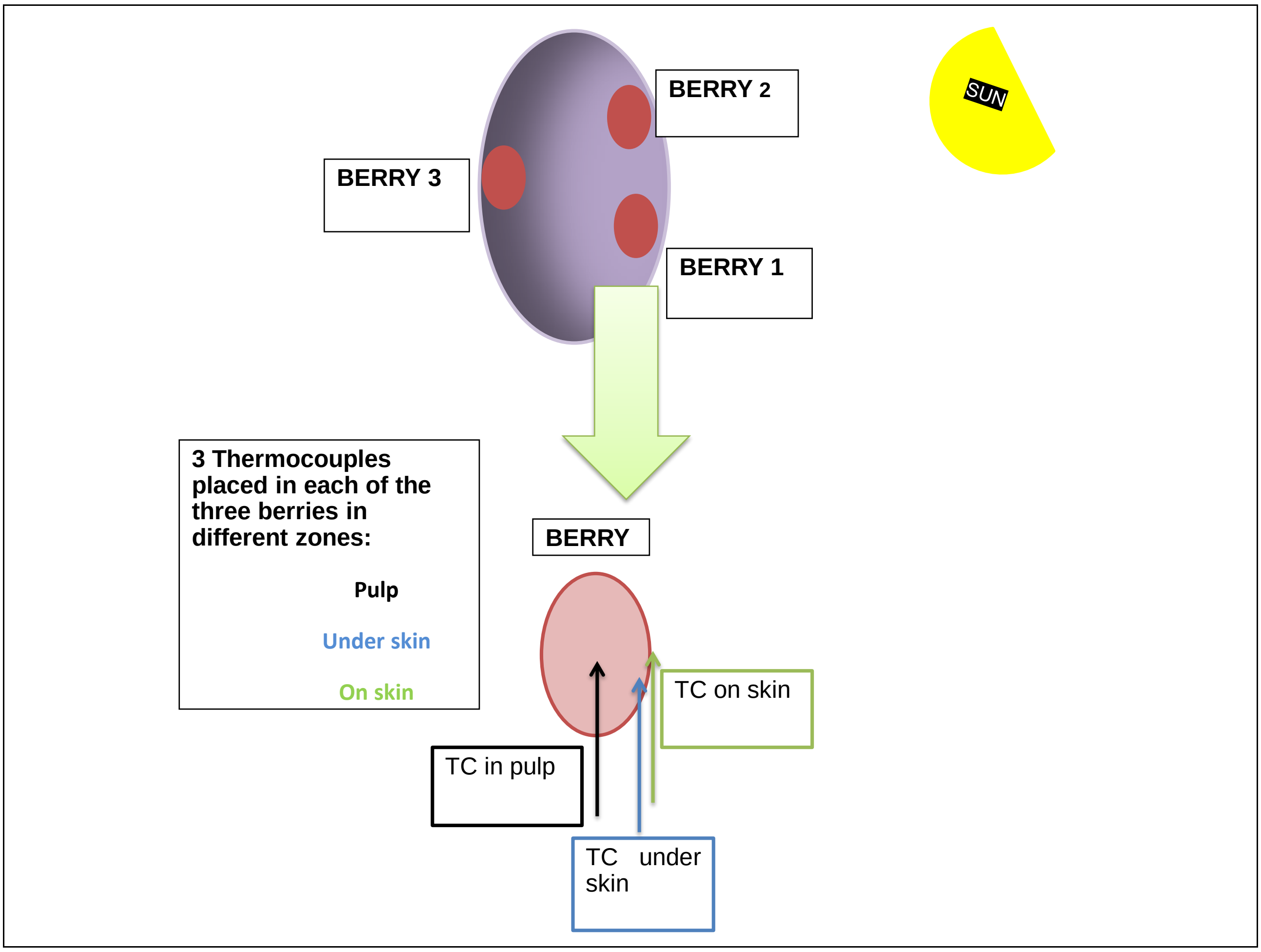


Figure 8 Diagram of the location of the three berries and the thermal couples within each berry.

3.2.7 Statistical analysis and software (Robertson and Stellenbosch)

Statistical analysis was conducted using Statistica 10 ® software (Statsoft, Tulsa, UK). LoggerNet Datalogger Support Software (Campbell Scientific, Utah, USA) was used to download the data from the data logger (Campbell Scientific, model CR1000, Logan, Utah, USA) attached to the thin TC's. Tinytag® Explorer® 4.6 Software (Gemini Data Loggers, West Sussex, UK) was used for data downloading and setting of the Tinytag® devices and LiCor quantum sensors. GuideIR Analyser 1.7 software (Wuhan Guide Infrared Technology Co., Ltd, Wuhan, China) as well as ArcGIS 10 (ESRI, California, USA) were used in the analysis of the thermal images.

3.3 Results

3.3.1 Mesoclimate

Figure 9 and Figure 10 show the daily mean, minimum and maximum temperatures for the season in Robertson and Stellenbosch with the diurnal cycle measurements indicated with reference lines.

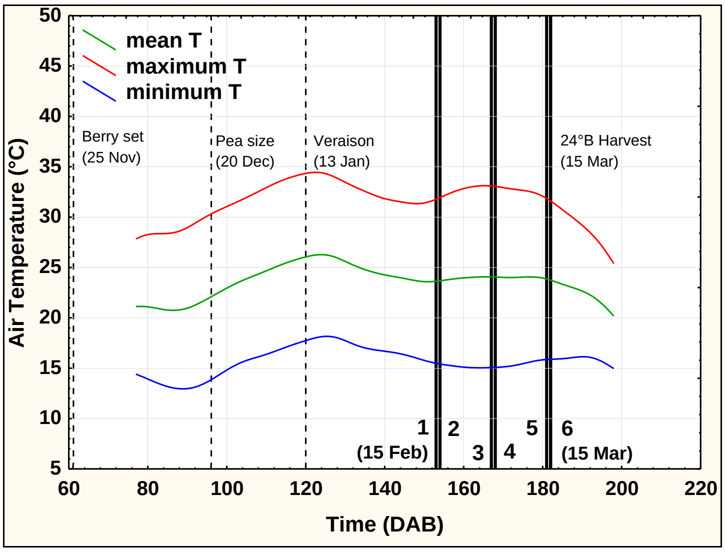


Figure 9 A distance-weighed least squares plot of daily minimum, maximum and mean temperatures (°C) from an automatic weather station in Robertson for the season 2011/2012. Time is represented as days after budburst (DAB), where budburst took place on 2011/09/15. Measuring dates are indicated by the reference lines one to six.

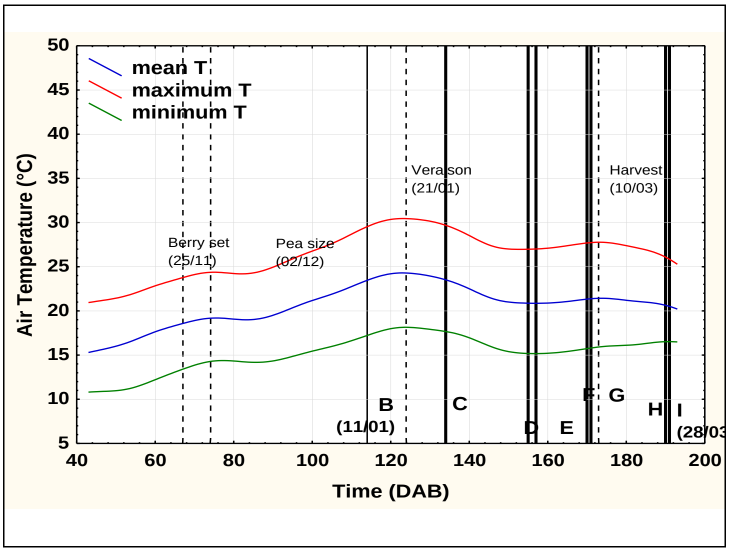


Figure 10 A distance-weighed least squares plot of daily minimum, maximum and mean temperatures (°C) from an automatic weather station in Stellenbosch for the season 2011/2012. Time is represented as DAB where budburst took place on 2011/09/19. Measuring dates are indicated by the reference lines B to I.

Figure 11 (Robertson) and Figure 14 (Stellenbosch) represent the ambient temperatures for all day cycles measured. The two regions show different trends with regard to the time when maximum diurnal temperatures occur. Robertson reached maximum temperatures in the afternoon whereas Stellenbosch reached the maximum around mid-morning, after which it started decreasing. The wind speed in Stellenbosch remained calm, ranging between 0.2 $m.s^{-1}$ to 1.0 $m.s^{-1}$ until about 12:00. From noon onwards the wind speed increased, ranging from 2 $m.s^{-1}$ to around 4.5 $m.s^{-1}$ (Addendum A, Figure 74d to Figure 81d). The wind direction from 12:00 to 18:00 in Stellenbosch (Figure 16) came from the south west with the exception of day cycles D and I, which experienced a north-westerly wind.

The south-westerly wind came from False Bay, which is approximately 18 km from the vineyard. The relative humidity in Stellenbosch decreased from around 90% in the early morning (06:00) to a minimum of between 40-50% around 11:00 to 14:00. It then either remained relatively constant until 16:00, after which it increased (Addendum A, Figure 76d, Figure 77b, Figure 79d and Figure 81d) or it constantly increased (Addendum A, Figure 74d, Figure 75d, Figure 78d and Figure 80d).

There was a definite decrease in relative humidity in Robertson from between 70-80% in the morning to between 14-40% in the afternoon (Addendum A, Figure 68d to Figure 73d). Similar to the conditions in Stellenbosch, the wind speed remained low in the morning and picked up after 13:00 with the exception of day cycle four (Addendum A, Figure 69d), where the highest wind speed (3.5 m.s^{-1}) was recorded at 12:00 and decreased rapidly in the afternoon. For the remainder of day cycles in Robertson, the wind speed did not exceed 3 m.s^{-1}, whereas in Stellenbosch the wind was mostly above 3 m.s^{-1} in the afternoon period. The wind direction in Robertson was more variable between days (Figure 13).

In Stellenbosch a difference in temperature was observed between the thermohygrometer hosted in the radiation shield situated in the vineyard above the canopy and that recorded in weather station situated 3.7 km from the vineyard (Figure 14 and Figure 15). Ambient temperatures measured by the sensor in the radiation shield were ca. 5°C higher than that measured by the weather station. The immediate environment may have contributed to this difference. The weather station was situated on grass, which may have reflected less light compared to the relatively bare soil in the vineyard. It has also been noted that there are differences between temperature and humidity measurements in a Gill screen compared to that in a Stevenson’s screen, the latter which was used for the weather station.

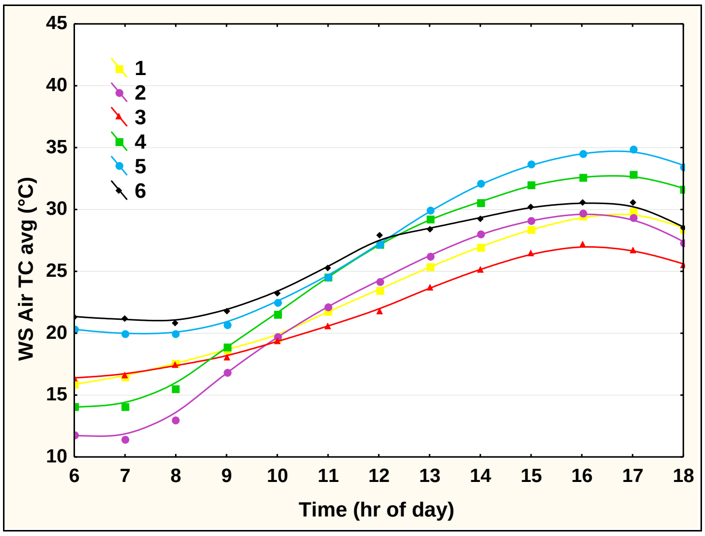


Figure 11 A mean graph of ambient, diurnal temperature (°C) for day cycles one to six, obtained from the mini weather station of the ARC, Infruitec-Nietvoorbij situated in the vineyard in Robertson.

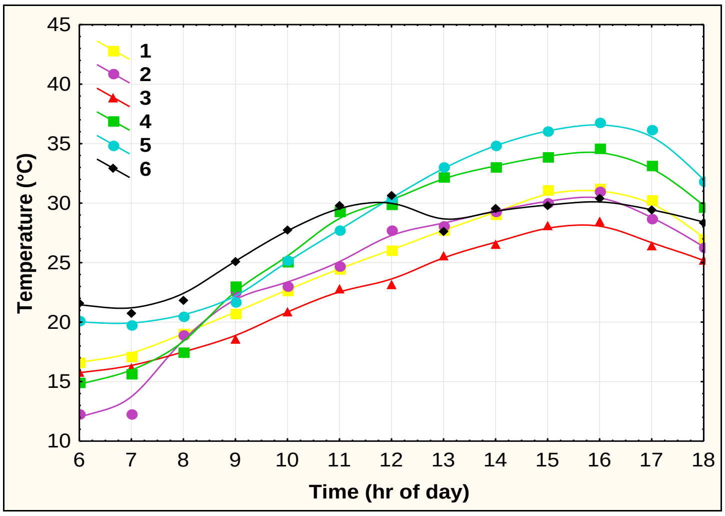


Figure 12 Distance-weighted least squares plot of air temperature obtained from the automatic weather station of the Institute of Soil, Climate and Water, distributed by the South Afircan Weather Service for day cycles one to six in Robertson.

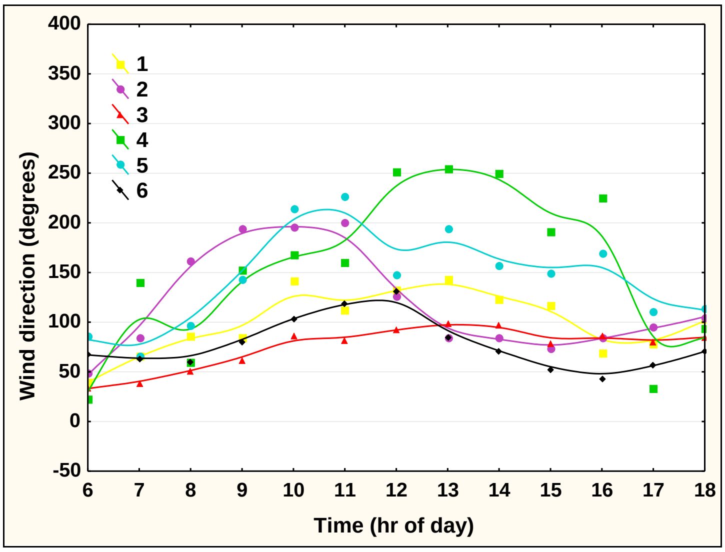


Figure 13 Distance-weighted least squares plot of the ambient, diurnal wind direction (degrees) for day cycles one to six, measured by the mini automatic weather station of the ARC, Infruitec-Nietvoorbij, situated in the vineyard in Robertson. North lies at 0˚.

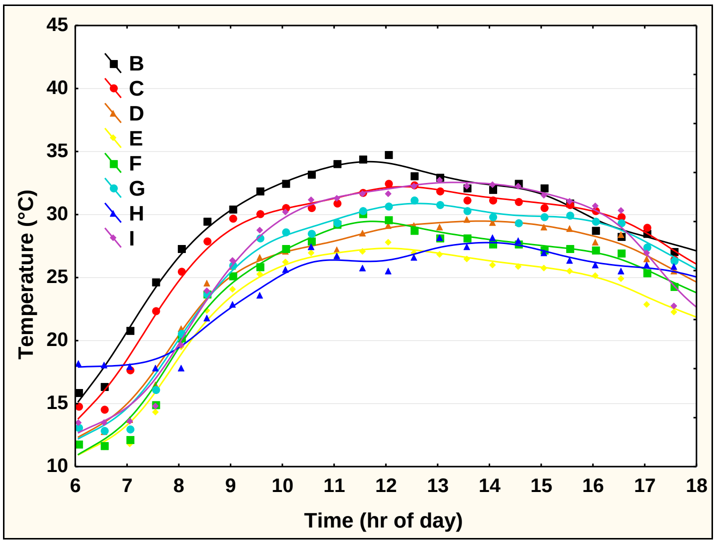


Figure 14 A means graph of ambient, diurnal temperature (°C) with a 30 minute interval for day cycles B to I, measured using a Tinytag® in a radiation shield placed above the canopy in Stellenbosch.

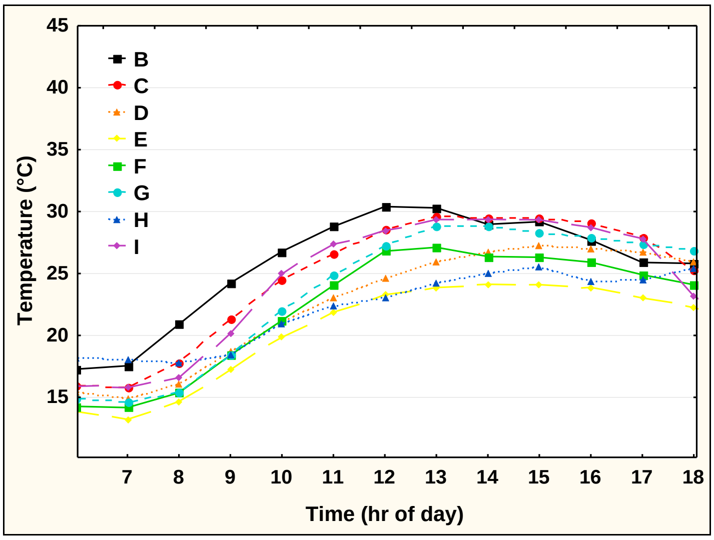


Figure 15 A distance-weighted least squares plot of hourly air temperature from the ARC Infruitec weather station for day cycles B to I in Stellenbosch.

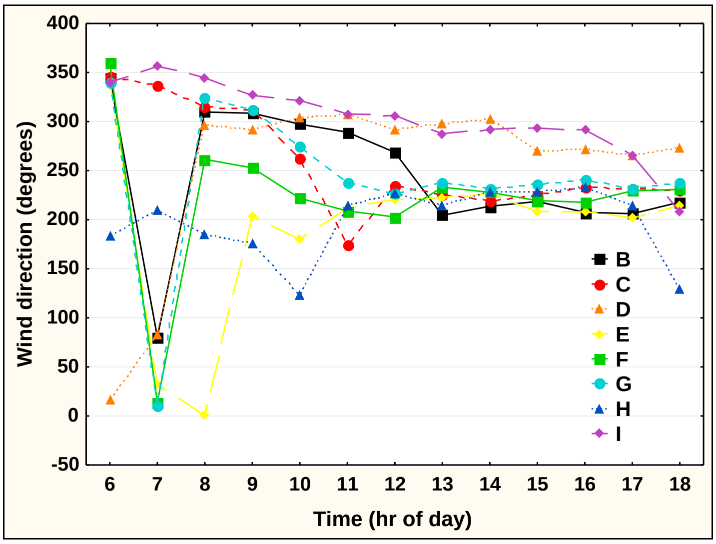


Figure 16 A distance-weighted least squares plot of ambient diurnal wind direction (degrees) for day cycles B to I, measured by the weather station at ARC Infruitec, Stellenbosch. North lies at 0˚.

3.3.2 Microclimate

3.3.2.1 Canopy temperatures

Figure 17 – 19 represent the diurnal canopy temperatures for day cycles three to six in Robertson and all day cycles in Stellenbosch. Absolute temperatures are illustrated along with the difference between the canopy and ambient temperatures.

Both sensors in Robertson showed similar trends. From 6:00 to 8:00, canopy air temperature assumed ambient temperature as a result of the absence of direct light going through the canopy. Between 08:00 and 12:00 for day cycles on the east side, canopy temperature exceeded ambient temperature for both canopy sensors with the sensor closest to bunch one having reached temperatures of 10°C above ambient (Figure 17b and 17d). The sensor in the more shaded part of the canopy showed a temperature of 8°C above ambient during this period on day cycle four.

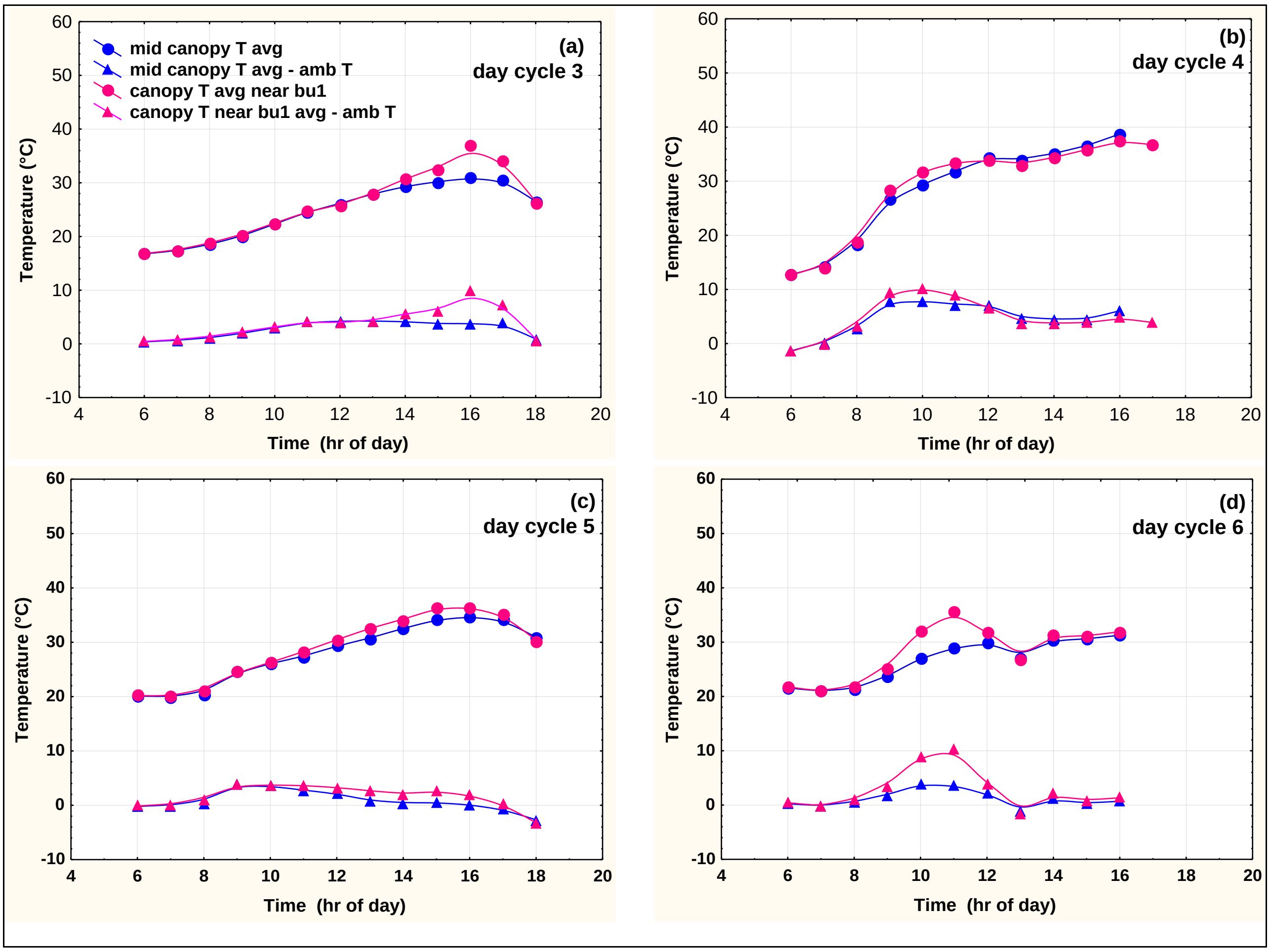


Figure 17 Diurnal temperature profiles in the canopy, illustrated for day cycles three to six in Robertson. Canopy sensor measuring air temperature (°C) closer to the edge of the canopy (pink) was placed near to bunch 1. Another sensor placed closer to the middle of the bunch zone, measured air temperature (°C) inside the canopy (blue). The triangular symbol represents the canopy sensors minus the ambient temperature measured by the weather station in the vineyard.

Similarly to what was observed in Robertson, canopy temperatures in Stellenbosch, before 08:00, were similar to ambient temperatures. Around 08:00 however, the difference between canopy temperature and ambient temperature was negative, which was not observed in Robertson (Figure 18 and Figure 19).

Diurnal canopy temperatures in the upper ripening zone in Stellenbosch showed two periods in the day when the canopy temperature exceeded that of the ambient temperature. The first peak occurred between 09:00 and 11:00 and the second peak occurred around 17:00 (Figure 18a and 18d and Figure 19a, 19b and 19d). The canopy sensor placed in the lower ripening zone showed only one period in the day where the canopy temperature exceeded ambient temperature (Figure 18b and 18c and Figure 19c). Day cycles C (east, lower) and D (west, lower) showed higher canopy temperatures during the afternoon period. Canopy temperature on day cycle H (east, lower) showed no drastic increase relative to the ambient and remained between 1-2°C above ambient for the period between 11:30 and 15:00.

In Stellenbosch, air in the canopy assumed ambient temperature between 12:00 and 16:00. For the upper ripening zone, this period varied slightly depending on the day cycle. Day cycle B had similar ambient and canopy temperatures from 12:00 until 16:00 (Figure 18a) whereas on day cycle E this period occurred from 11:00 to 14:00 (Figure 18d). The same sensor was used for both day cycles, with the time between measuring dates being more than a month.

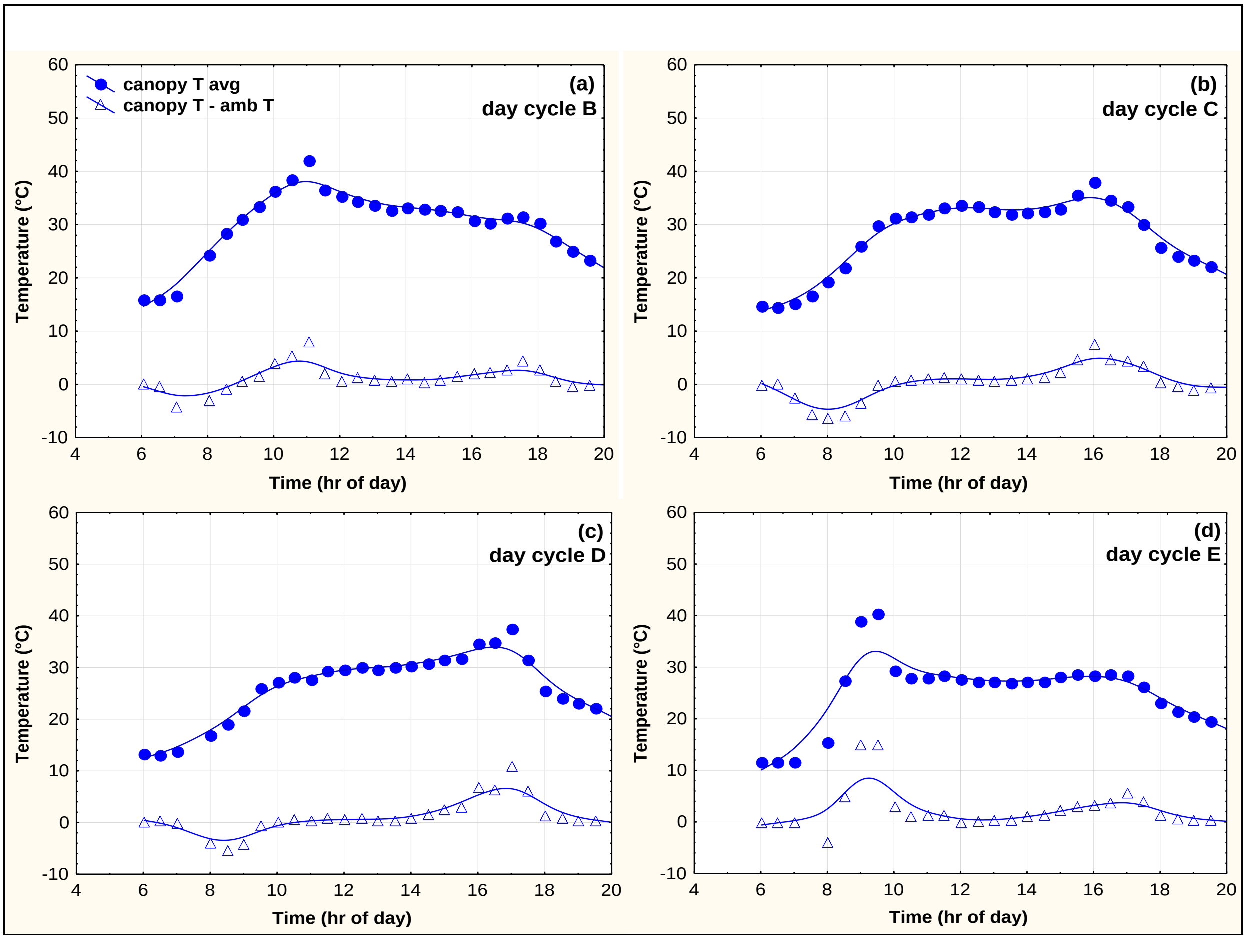


Figure 18 Diurnal temperature profiles in the canopy, illustrated for day cycles B to E in Stellenbosch. Canopy sensors were placed in the upper and lower ripening zones. Solid circles represent absolute canopy temperatures (°C). Triangles represent canopy temperature minus ambient air temperature (measured by the Tinytag® placed inside the radiation shield above the canopy).

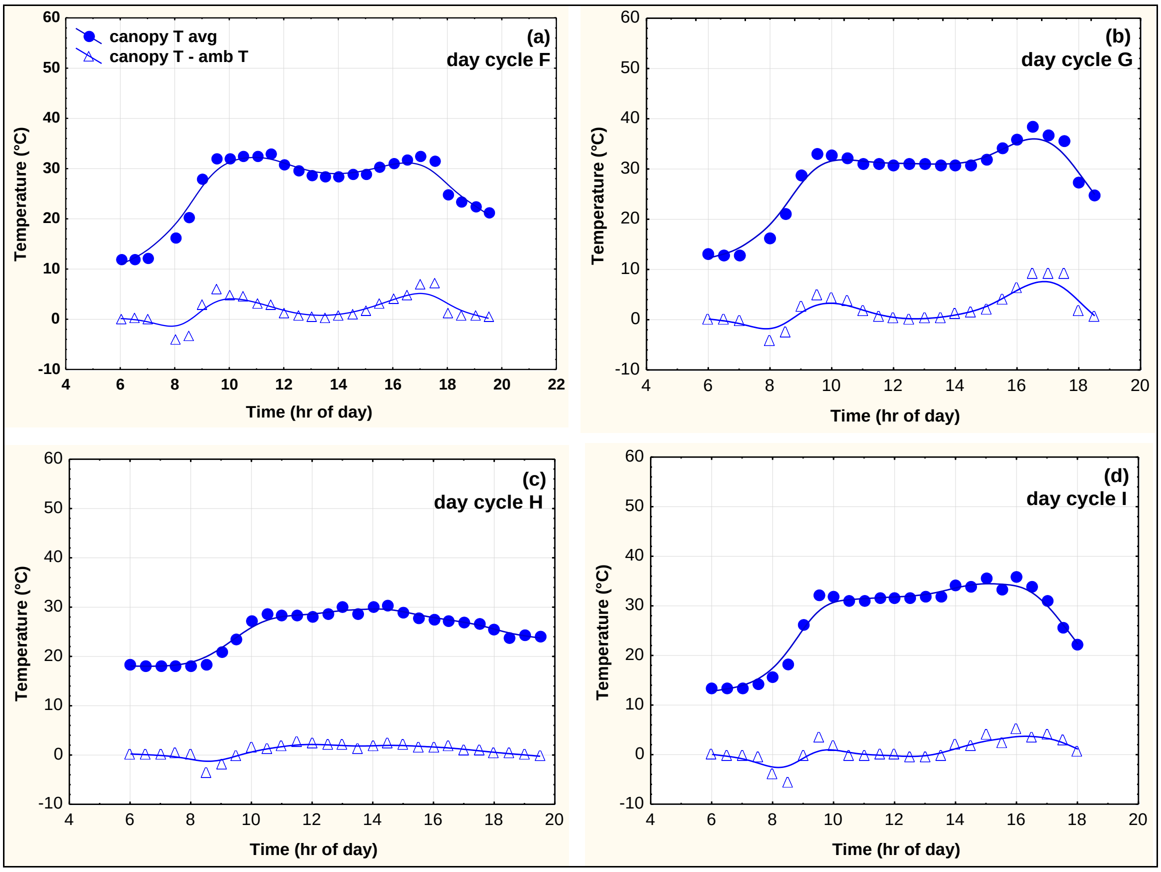


Figure 19 Diurnal temperature profiles in the canopy, illustrated for day cycles F to I in Stellenbosch. Canopy sensors were placed in the upper and lower ripening zones. Solid circles represent absolute canopy temperatures (°C). Triangles represent canopy temperature minus ambient air temperature (measured by the Tinytag® placed inside the radiation shield above the canopy).

3.3.2.2 Bunch surface temperature (thermal imaging)

A selection of results is described in this section for further discussion later on. Thermal images comprise of pixels, each of which represent a surface temperature value on the visible parts of the grape bunches measured. The distribution of the total pixels from Robertson and Stellenbosch for all day cycles is displayed in Figure 20. The majority (70%) of pixel temperature values are concentrated in the classes between 25°C and 40°C. The mean surface temperature of the exposed side of the bunch for all day cycles in Robertson and Stellenbosch was 31°C. The individual means of Robertson and Stellenbosch were quite similar at 31.2°C and 31.0°C. The maximum in Robertson was higher at 54.4°C and the minimum was slightly lower at 9.0°C compared to the maximum and minimum in Stellenbosch, i.e. 50.6°C and 10.5°C.

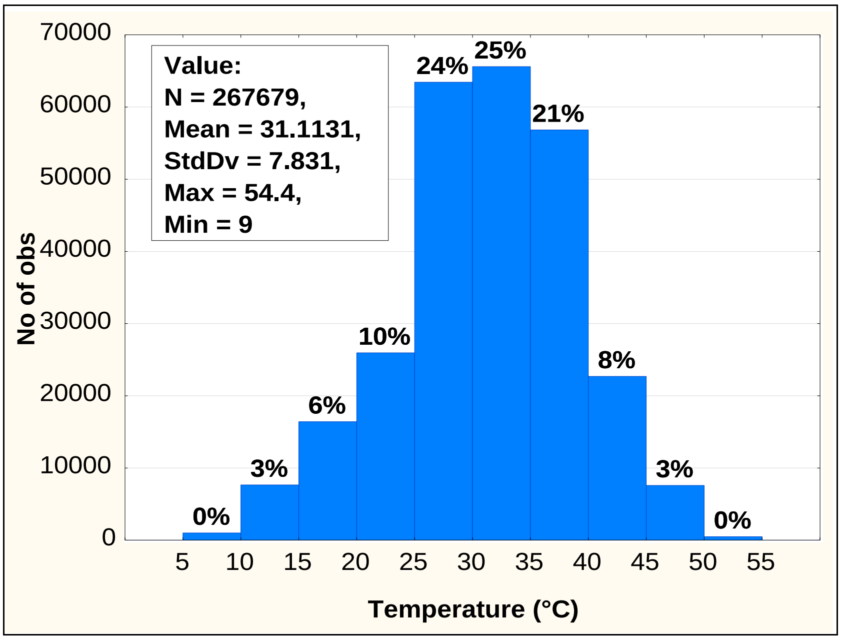


Figure 20 Histogram showing the surface temperature distribution of the exposed side of all bunches for all day cycles in Stellenbosch and Robertson. Number of observations refers to the number of pixels in a specific class.

Figure 21 illustrates the separate distribution of total surface temperature values for the exposed side of the bunch in (a) Robertson and (b) Stellenbosch. Robertson showed a higher distribution of pixel temperature values in the 35-40°C class in relation to the other classes, whereas in Stellenbosch the highest portion of pixel temperature values was in the 30-35°C class. Robertson also had a higher percentage of pixel temperature values (23%) below 25°C compared to Stellenbosch (16%). Robertson and Stellenbosch showed a similar distribution of temperature above 40°C of ca. 11%. Differences between the sites are expected as a result of the variability between different day cycles and/or on-bunch differences as well as different patterns of temperature change throughout the day.

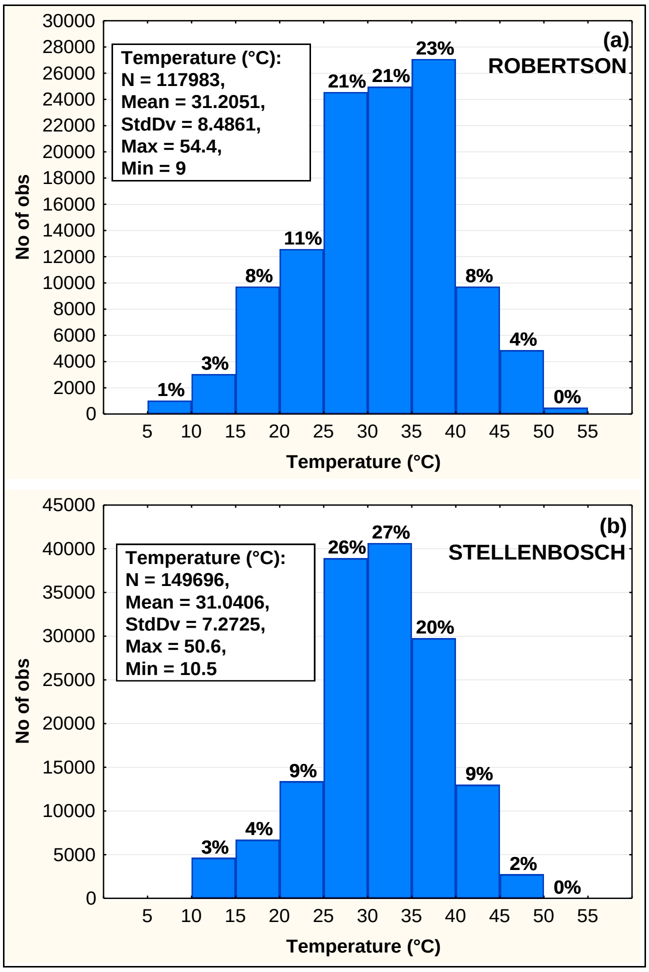


Figure 21 The distribution of surface temperature values measured by the thermal imager for all day cycles in (a) Robertson and (b) Stellenbosch. Number of observations refer to the number of pixels or temperature values.

In Robertson the distribution of pixel temperature values on the east side tended towards higher temperatures showing a mean value of 32.5°C and highest percentage of pixels in the 35-40°C class (Figure 22a). On the west side in Robertson the distribution of temperature tended slightly more towards lower temperatures with a mean of 30.1°C and the highest percentage of pixels in the class 25-30°C (Figure 22b). The maximum value on the east side was 1°C higher at 54.4°C compared to the maximum on the west side at 53.4°C. However, a slightly higher occurrence of pixels was observed above 40°C on the west side (14%) compared to the east side (11%). In Stellenbosch a similar trend was observed between the east and west side as in Robertson with slightly higher surface temperatures occurring on the east side as well as more variability in temperature (Figure 22c). Although the dominant class on the east side was lower (25-30°C) compared to the dominant class on the west side (30-35°C), the remainder of pixel temperature values were mostly distributed in the higher classes, whereas on the west side temperatures were concentrated in the lower classes.

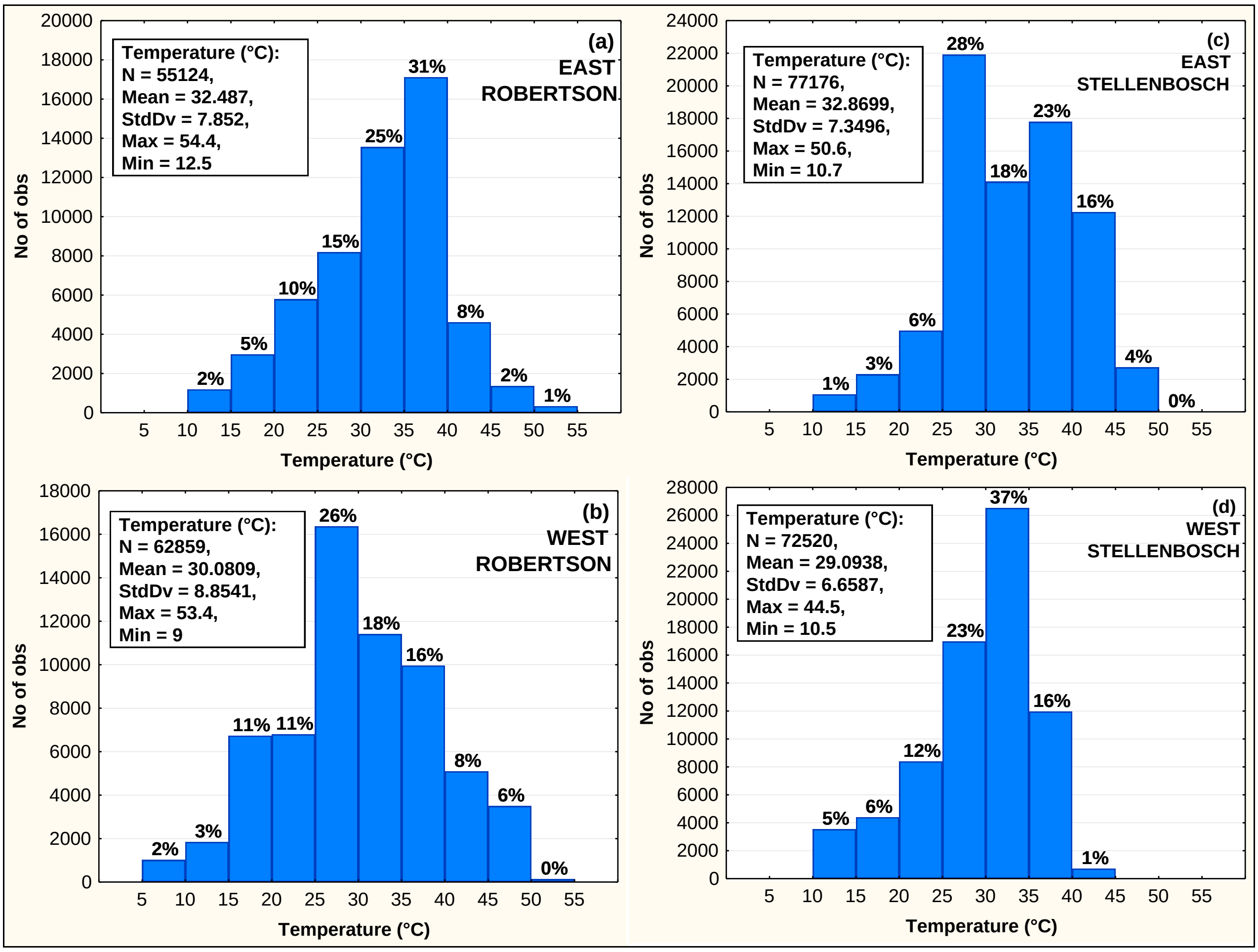


Figure 22 The distribution of surface pixel temperature values for all day cycles in (a) Robertson on the east side (b) Robertson on the west side (c) Stellenbosch on the east side and (d) Stellenbosch on the west side.

In Stellenbosch, the 25-30°C class was dominant in both the upper and lower ripening zones on the east side (Figure 23a and 23c). The pixel temperature values of the lower bunch tended towards slightly higher temperatures with an average of 33.1°C compared to the upper bunch with an average of 32.3°C. A high percentage (63%) of pixel temperature values were above 30°C on the east lower bunch compared to 47% above 30°C on the east upper bunch. The 30-35°C class was dominant on both the upper and lower bunches on the west side (Figure 23b and 23d). A slightly higher mean surface temperature of 29.4°C was observed on the lower bunch compared to 28.9°C on the upper bunch.

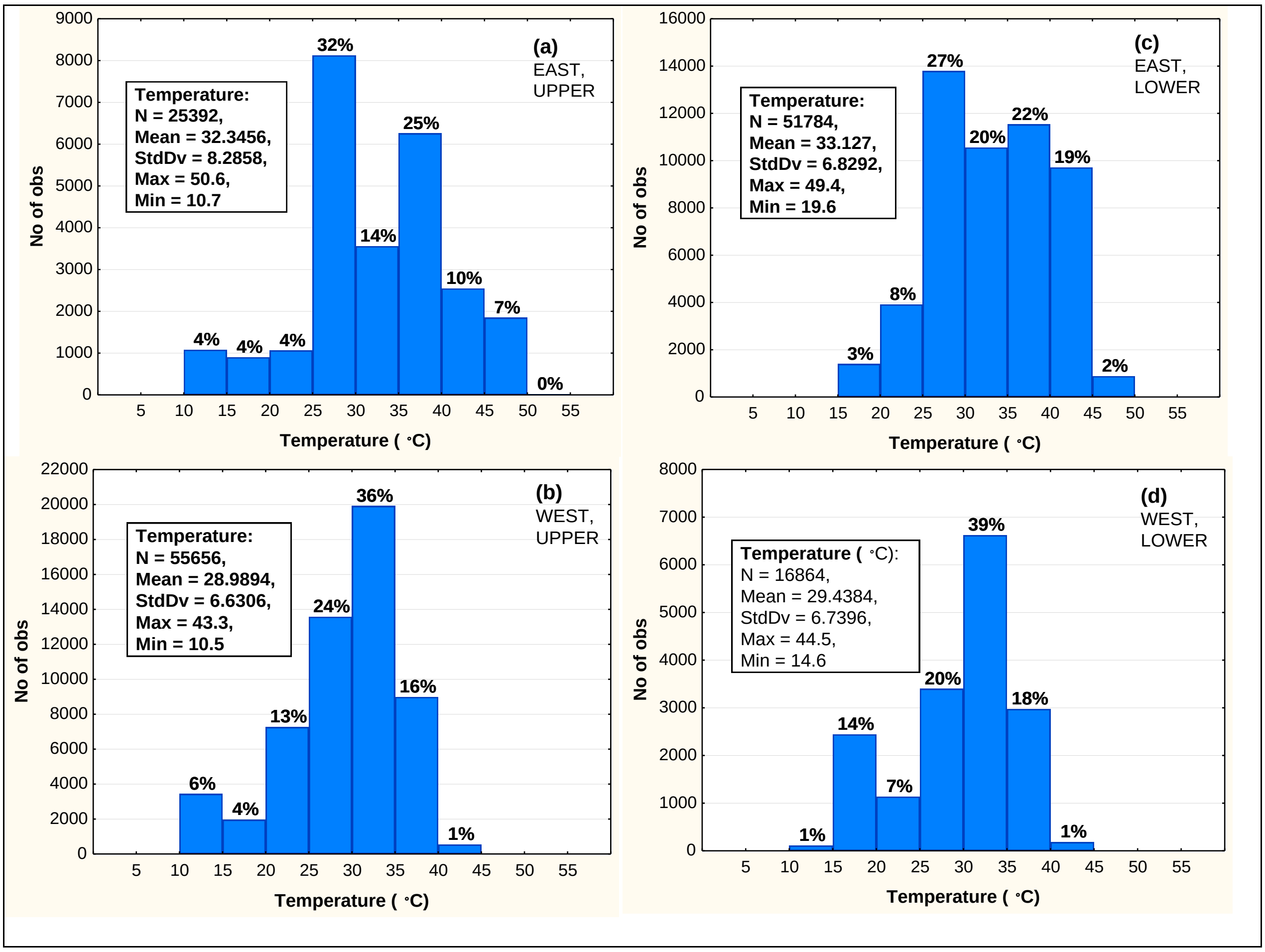


Figure 23 The distribution of surface temperature values in Stellenbosch (measured by the thermal imager) for all day cycles: (a) on the east side in the upper ripening zone (b) on the west side in the upper ripening zone (c) on the east side in the lower ripening zone and (d) on the west side in the lower ripening zone.

3.3.2.2.1 Morning and afternoon trends in bunch surface temperature

General trends

In Robertson, the distribution of surface temperature values for day cycles in the morning (before and including 12:00) and afternoon (after 12:00) on the east and west sides are illustrated in Figure 24. A wider range of temperature values from 10-55°C were observed up until 12:00 on the east side. In the afternoon period on the east side, all pixel temperature values were concentrated into the classes between 30-45°C. A less notable difference in variability occurred between the morning and afternoon periods on the west side. Although a wider distribution of pixel temperature values between classes was observed in the morning, a notable dominant class (25-30°C) occurred. In the afternoon period there was a slightly more even distribution of pixel temperature values between classes. Interestingly, a higher mean surface temperature of ca. 36°C was observed on the east side in the afternoon period compared to a mean of 31.4°C during the morning period (on the east side). Higher mean temperature was also observed on the west side in the afternoon (37.4°C) compared to the morning (25.4°C).

In Stellenbosch, the distribution of surface temperature values for day cycles in the morning and afternoon on the east and west sides, is illustrated in Figure 25. On the east side in the morning a wider distribution of pixel temperature values between classes 10-15°C and 45-50°C was observed compared to the afternoon period, which had a more notable dominant class (25-30°C) and all pixel temperature values ranged between classes 25-30°C and 40-45°C. The mean temperature in the morning on the east side was slightly higher (33.2°C) compared to the afternoon (32.5°C). Interestingly, on the west side in the morning, a wider distribution of pixel temperature values was observed ranging from 10-15°C to 35-40°C compared to the afternoon where the majority of pixel temperature values were between the classes 25-30°C and 35-40°C. A higher mean temperature of 32.6°C occurred on the west in the afternoon compared to the mean temperature 25.4°C in morning.

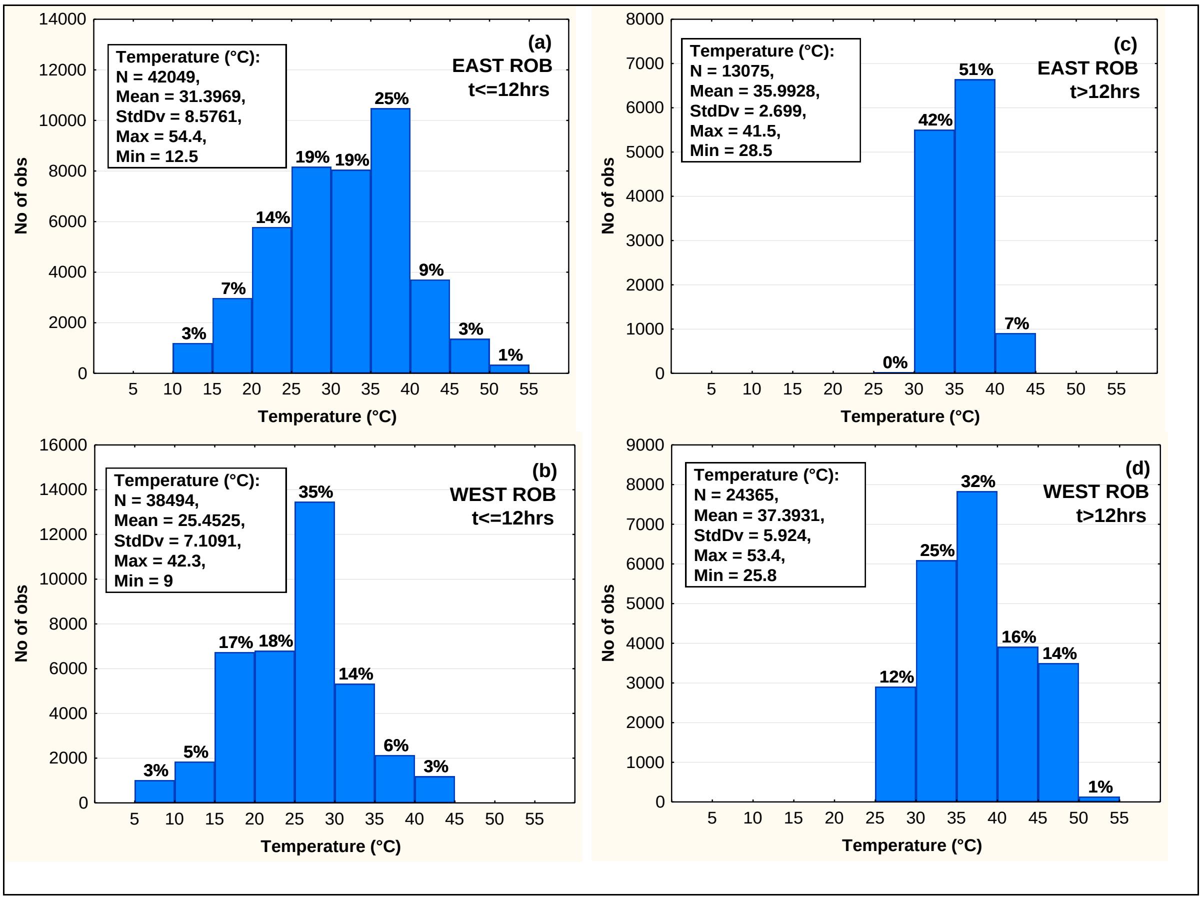


Figure 24 Distribution of surface temperature in Robertson for (a) the period of the day before and including 12:00 (t≤12 hours) on the east side (b) t≤12 hours on the west side (c) for the period of the day after 12:00 (t>12 hours) on the east side and (d) t>12 hours on the west side.

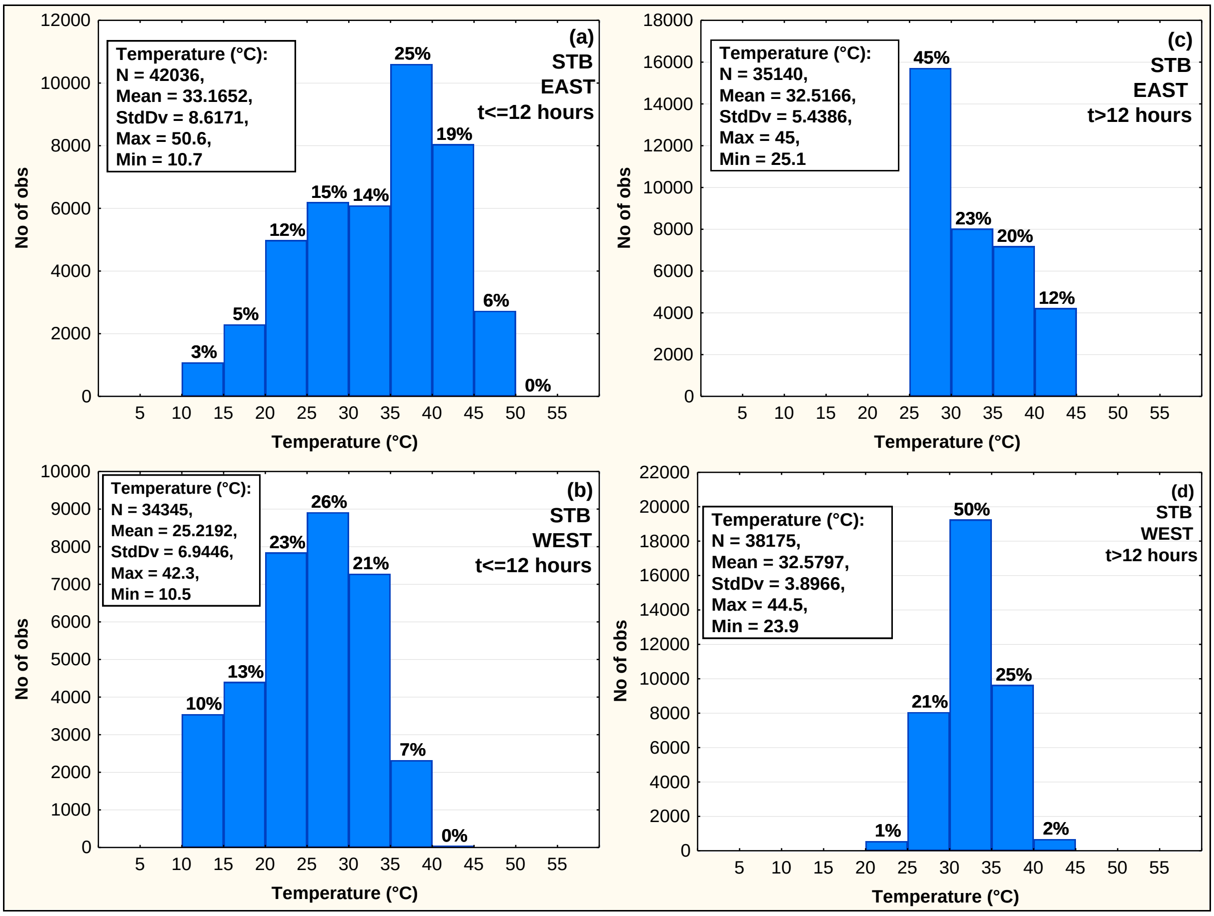


Figure 25 Distribution of surface temperature in Stellenbosch for (a) the period of the day before and including 12:00 (t≤12 hours) on the east side (b) t≤12 hours on the west side (c) for the period of the day after 12:00 (t>12 hours) on the east side and (d) t>12 hours on the west side.

Day cycles

Figure 26 demonstrates the distribution of pixel temperature values in the morning period for the separate day cycles performed on the east side in Robertson. The widest range of pixel temperatures occurred on day cycle four. More notable dominant classes occurred on day cycles one (35-40°C) and six (25-30°C) as well as a smaller range of classes. The class 25-30°C was absent on day cycles one and four. Day cycle six shows the least variability in temperature during the morning period.

In the afternoon period on the east side surface temperatures are concentrated in the classes 30-40°C for day cycles one and six. Day cycle four shows a higher portion between 40-45°C in relation to day cycles one and six (Figure 27b).

Figure 28 illustrates the distribution of pixel temperature values in the morning on the west side for day cycles two, three and five. The highest variability was observed on day cycle two with temperatures between 5-10°C and 30-35°C. Day cycles three and five showed less variability. Day cycle five showed the least variability with temperatures between 25-30°C and 40-45°C and 56% of pixel temperature values were in the 25-30°C class.

A wider distribution of pixel temperature values (between classes 25-30°C and 50-55°C) were observed on day cycle three (west) in the afternoon period compared to day cycles two and five (Figure 29). Day cycle two showed 80% of temperatures between 30-40°C and day cycle five consisted of a notable dominant class (35-40°C).

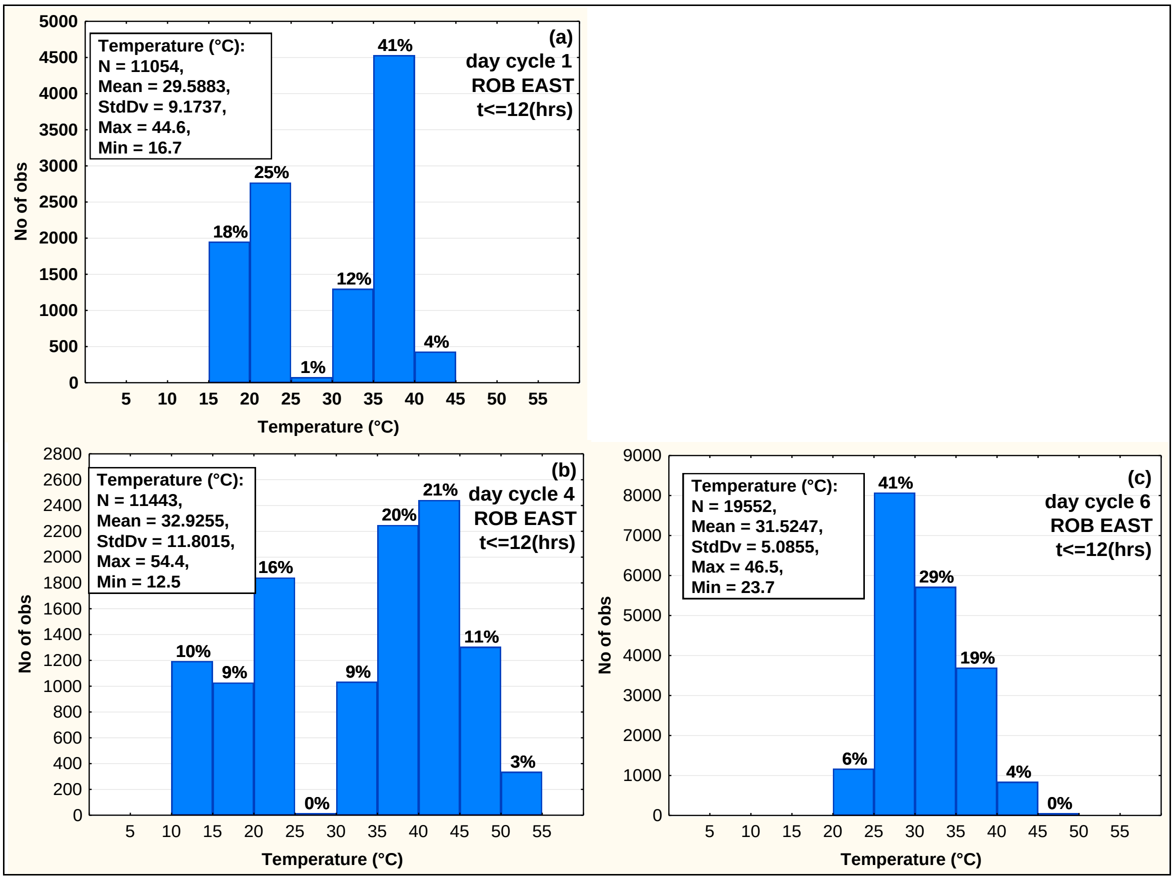


Figure 26 Surface temperature distribution in Robertson for the period before and including 12:00 (t≤12 hours) on the east side for (a) day cycle one (b) day cycle four and (c) day cycle six.

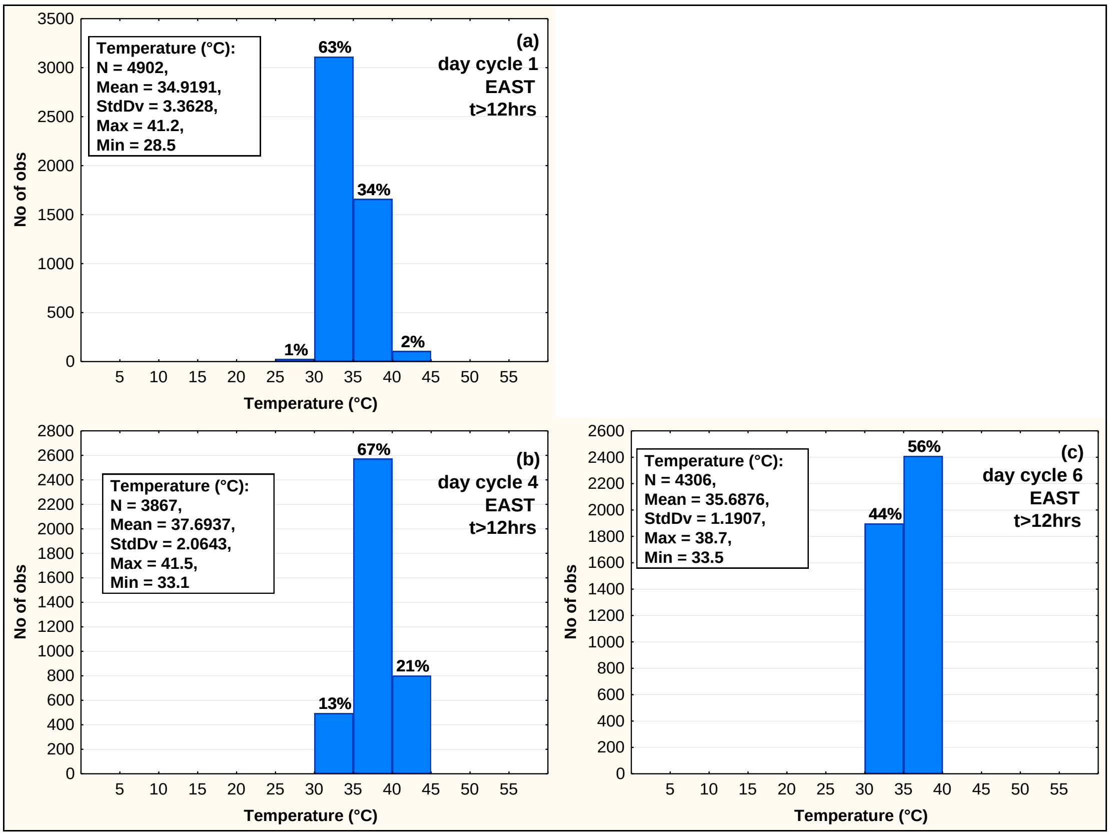


Figure 27 Surface temperature distribution in Robertson for the period after 12:00 (t>12 hours) on the east side for (a) day cycle one (b) day cycle four and (c) day cycle six.

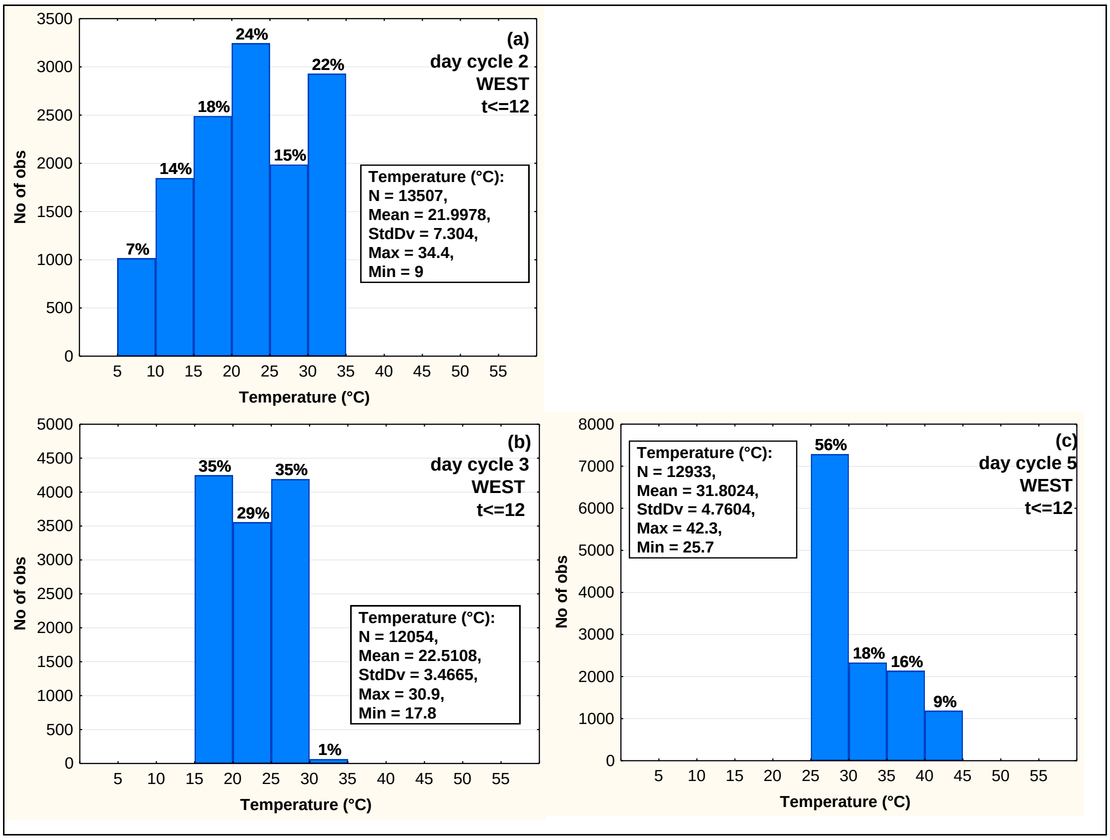


Figure 28 Surface temperature distribution in Robertson for the period before and including 12:00 (t≤12 hours) on the west side for (a) day cycle two (b) day cycle three and (c) day cycle five.

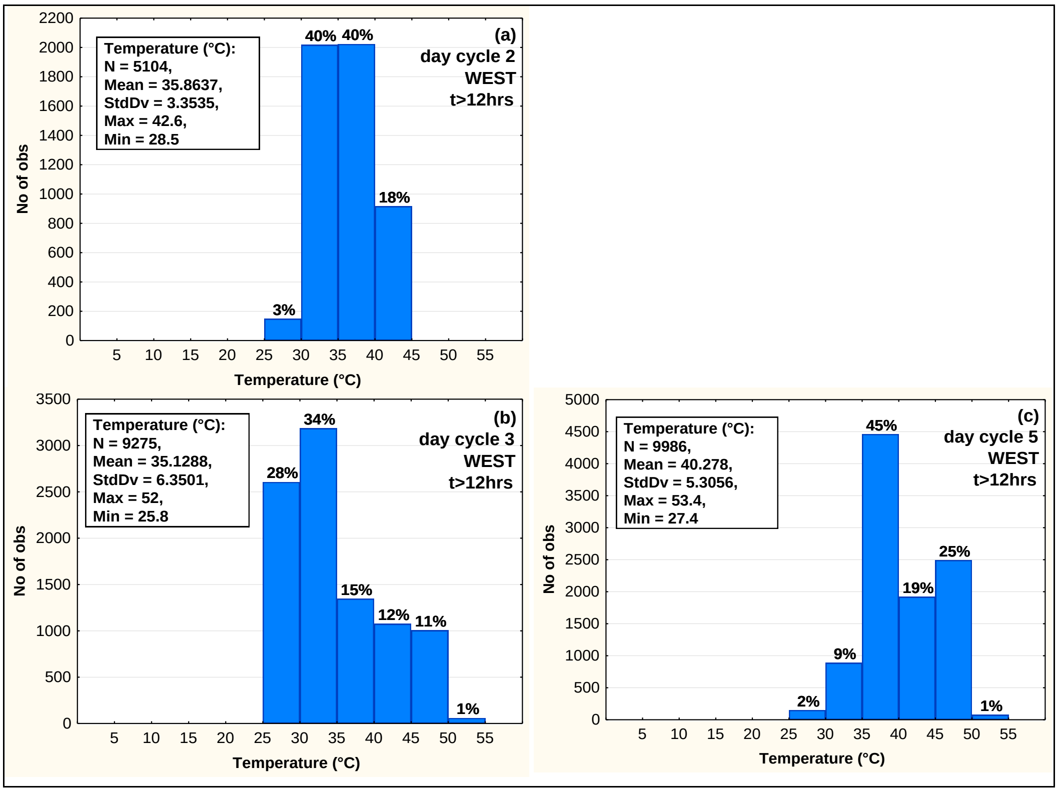


Figure 29 Surface temperature distribution in Robertson for the period after 12:00 (t>12 hours) on the west side for (a) day cycle two (b) day cycle three and (c) day cycle five.

Between-bunch variability

Figure 30 illustrates the distribution of pixel temperature values for bunches one and two in the morning period for all day cycles in Robertson on the east side. Similar trends in the temperature ranges and variability are observed between bunch one and two on the different day cycles. Differences between bunches on a measuring date lie in the dominant class. On day cycle one, the majority of pixel temperature values on bunch one was in the 20-25°C class whereas for bunch two, the majority of pixel temperature values were in the 35-40°C class. This difference in dominant classes between bunches was also observed for day cycles four and six.

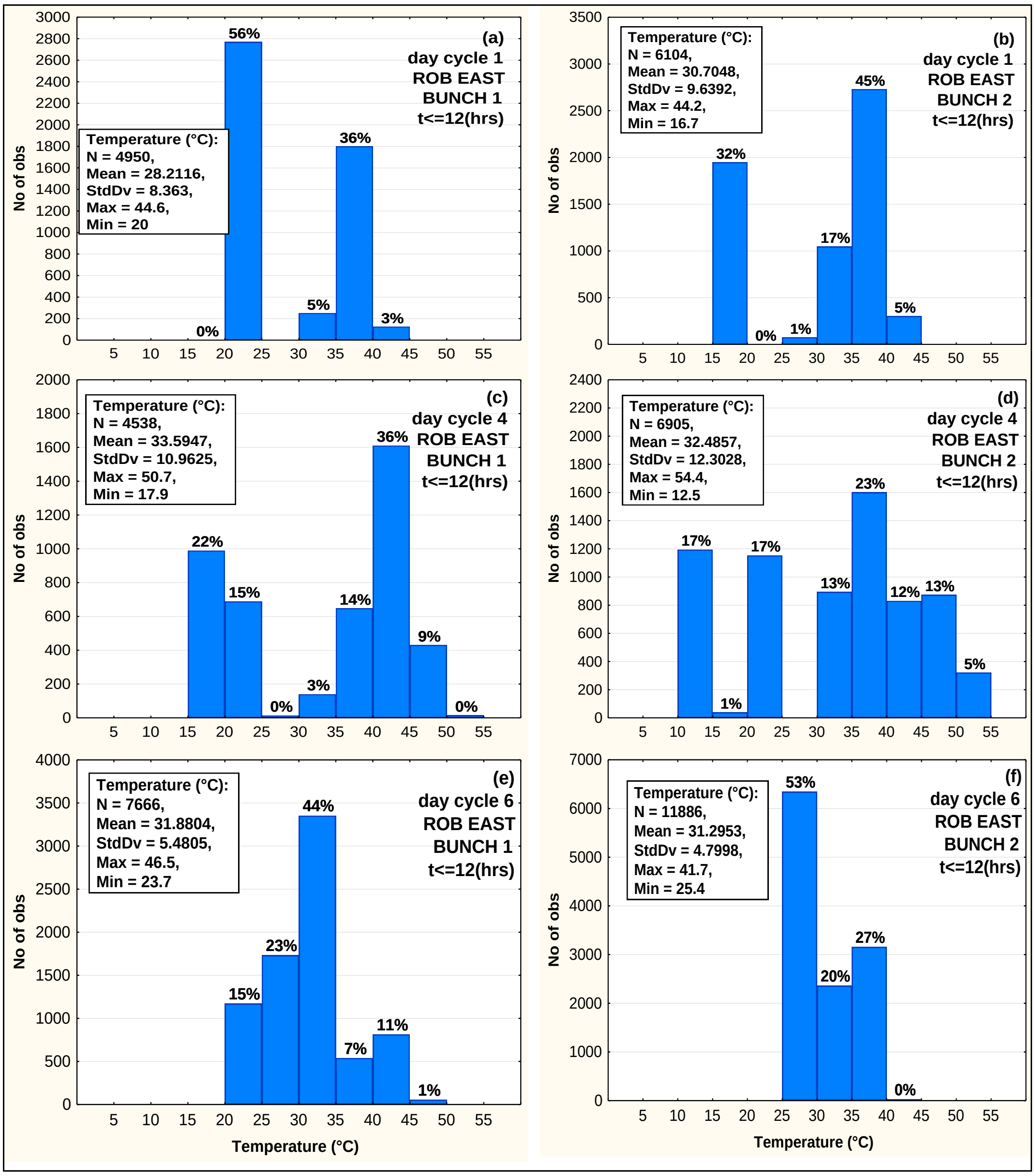


Figure 30 Distribution of surface temperature in Robertson on the east side for the period before and including 12:00 (t≤12 hours) for (a) day cycle one, bunch one (b) day cycle one, bunch two (c) day cycle four, bunch one (d) day cycle four, bunch two (e) day cycle six, bunch one and (f) day cycle six, bunch two.

Figure 31 illustrates the pixel temperature distribution for the morning period for all day cycles on the west side in Robertson. Similar to Figure 30 differences between bunches are visible in the dominant class. The absence or minimal proportion of certain classes occurred on one bunch whereas a higher proportion of the same class was observed on the second bunch. On bunch two on day cycle two 35% of pixel temperature values were observed in the class 25-30°C (dominant class) whereas on bunch one, no temperatures in this class were observed. On day cycle three 14% of pixel temperature values occurred in the 25-30°C on bunch one whereas 44% occurred in this class on bunch two. Similarly on day cycle five 1% of temperature pixel values occurred in the 30-35°C class on bunch one whereas 24% on bunch two occurred in this class.

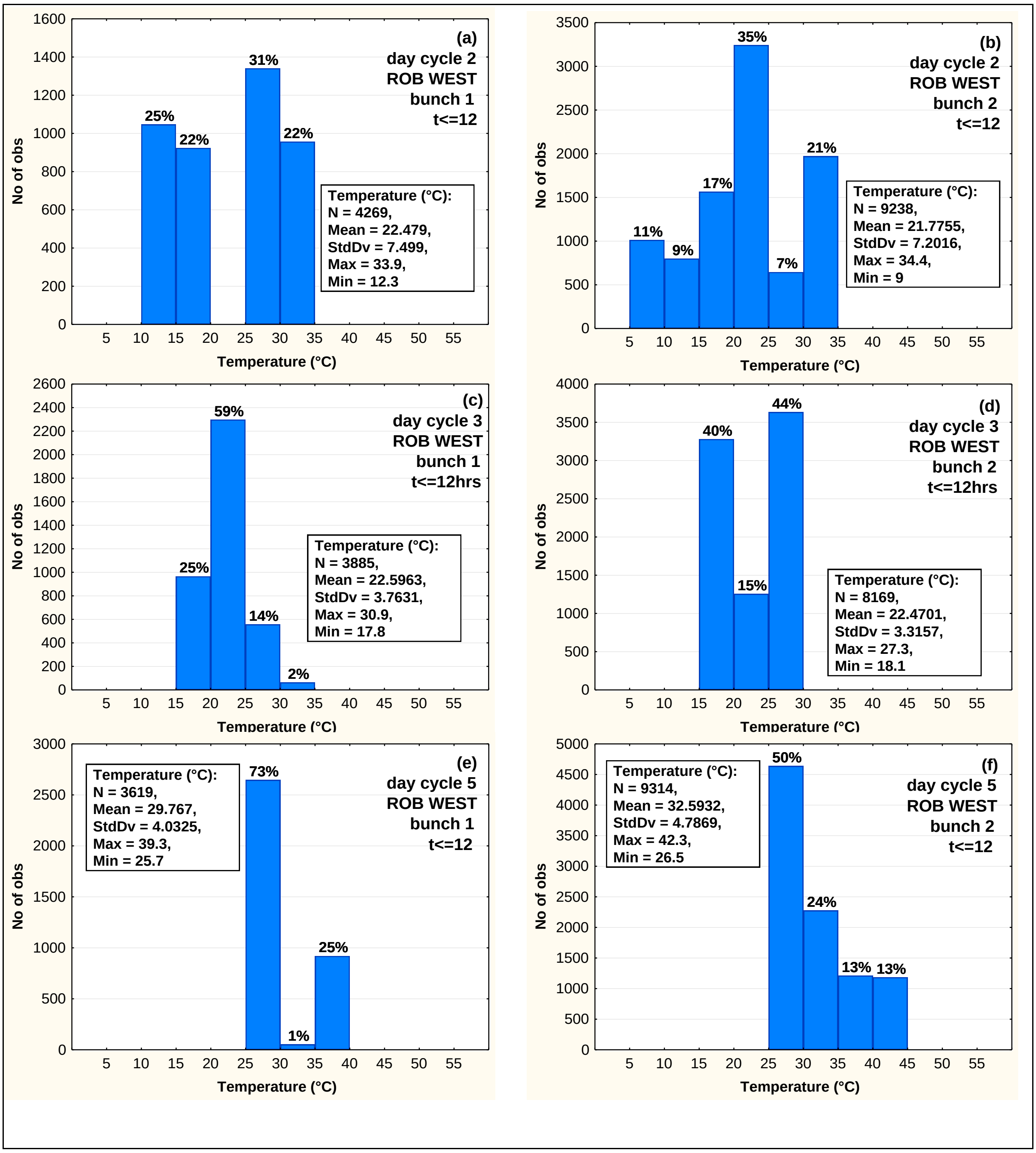


Figure 31 Distribution of surface temperature in Robertson on the west side for the period before and including 12:00 (t≤12 hours) for (a) day cycle two, bunch one (b) day cycle two, bunch two (c) day cycle three, bunch one (d) day cycle three, bunch two (e) day cycle five, bunch one and (f) day cycle five, bunch two.

Day cycle three showed the widest range of temperatures in the afternoon period (Figure 29b). Bunch two showed a slightly wider range consisting of temperatures from 25-30°C to 50-55°C compared to bunch one with pixel temperature values distributed between 25-30°C and 40-45°C (Figure 32).

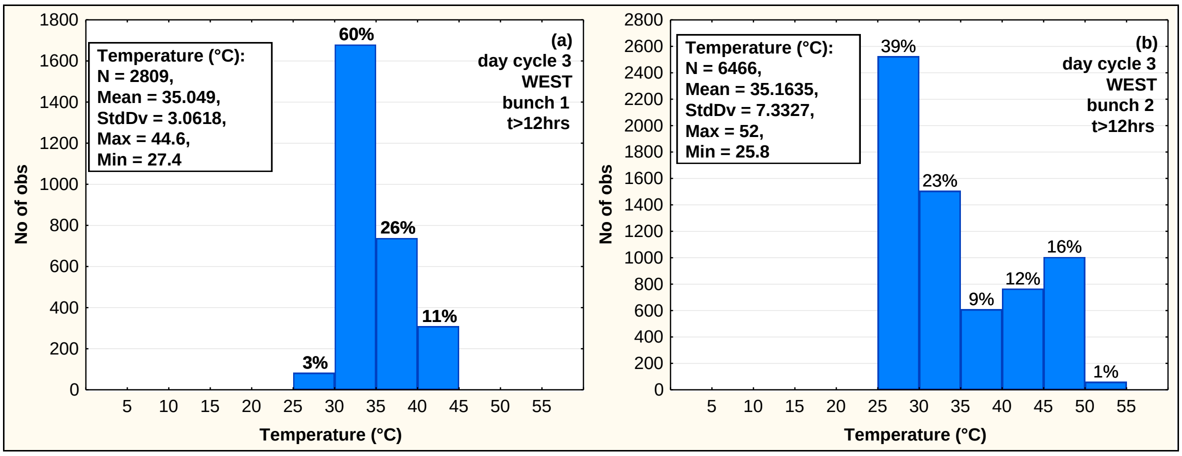


Figure 32 Distribution of surface pixel temperature values for bunch one and two on day cycle three in the afternoon period in Robertson.

3.3.2.2.2 Bunch surface temperature variability

On the east side, on-bunch variability in temperature in Robertson and Stellenbosch was low during the early morning (between 07:00 and 08:00) and during the afternoon period after 12:00. Variability increased slightly later in the morning between ca. 09:00 and 11:00 (Addendum A, Figure 68e-Figure 70e and Figure 74f-Figure 77f). On the west side little variability was observed in the morning period and increased in the afternoon period after 12:00 (Addendum A, Figure 72e, Figure 73e, Figure 78f and Figure 81f). On-bunch variability was particularly high on day cycle four (Addendum A, Figure 69e) with bunch two showing a slightly wider range of temperatures (Figure 30c and 30d). On the west side, day cycle two shows the lowest on-bunch variability through the day compared to day cycles three and five (Addendum A, Figure 71e-Figure 73e). Day cycle three showed a wider range of temperature in the afternoon period (Figure 29b) and particularly high on-bunch variability at 16:00 on bunch one (Addendum A, Figure 72e).

3.3.2.3 Berry temperature variability

Robertson

Figure 33 demonstrates the mean berry temperature for all day cycles on the east and west sides in Robertson. On the east side berry temperature increased from ca. 17°C around 7:00 to 33°C at 10:00. Berry temperature decreased slightly between 10:00 and 12:00 to ca. 29°C and increased again until just after 13:00 to ca. 32°C. After 13:00 temperature remained constant. On the west side berry temperature increased constantly from ca. 14°C around 07:00 to ca. 36°C around 15:00. A brief decrease in temperature of ca. 2°C occurred just after 15:00 and increased again to ca. 36°C at 16:00, after which berry temperature decreased to 27°C around 18:00. Figure 34 represents temperatures for berries on the visible (berries one and two) and back sides of the bunch for all day cycles on the east and west sides in Robertson. Berry temperature on the visible side of the bunch on the east side of the canopy increased rapidly during the morning period to just below 35°C at 10:00, after which temperature decreased ca. 5°C until 13:00 and increased again slightly for the remainder of the afternoon. The berry representing the back of the bunch on the east side of the canopy increased at a fast rate in the morning period and then continued to increase at a more constant rate before reaching a maximum of ca. 33°C around 16:00. Berry temperature on the visible side of west facing bunches increased at a constant rate through the day and reached maximum temperatures above 35°C in the late afternoon around 16:00. The temperature of berry three on the west side of the canopy increased similarly to berries situated on the visible side of the bunch until 12:00, but did not show the same increase in temperature after that period than the exposed berries. It reached maximum temperatures of ca. 34°C.

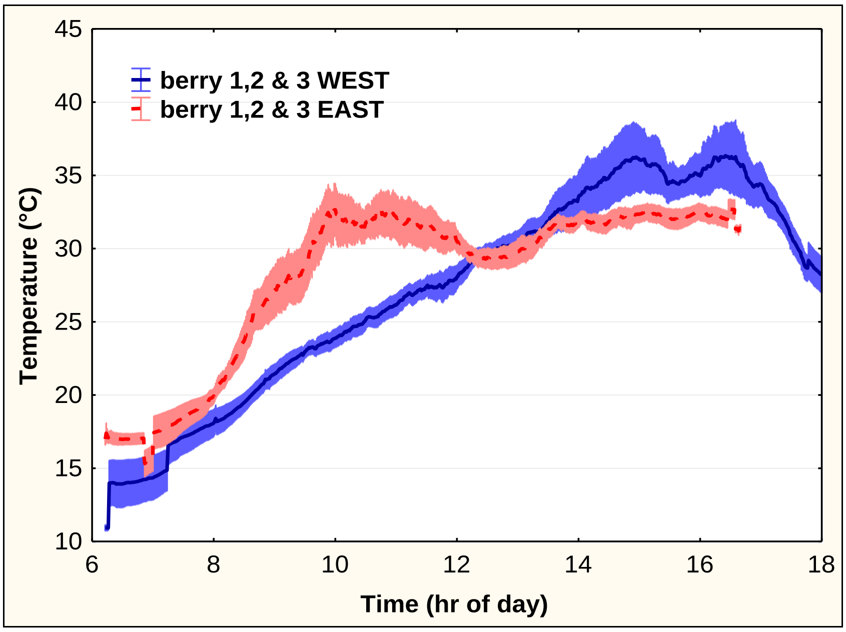


Figure 33 Berry temperatures for berries on the east and west sides of the canopy in Robertson. Temperature is illustrated as the mean of the surface, skin and pulp temperatures for berries one, two and three for day cycles one to six. Spreads indicate 95% confidence intervals.

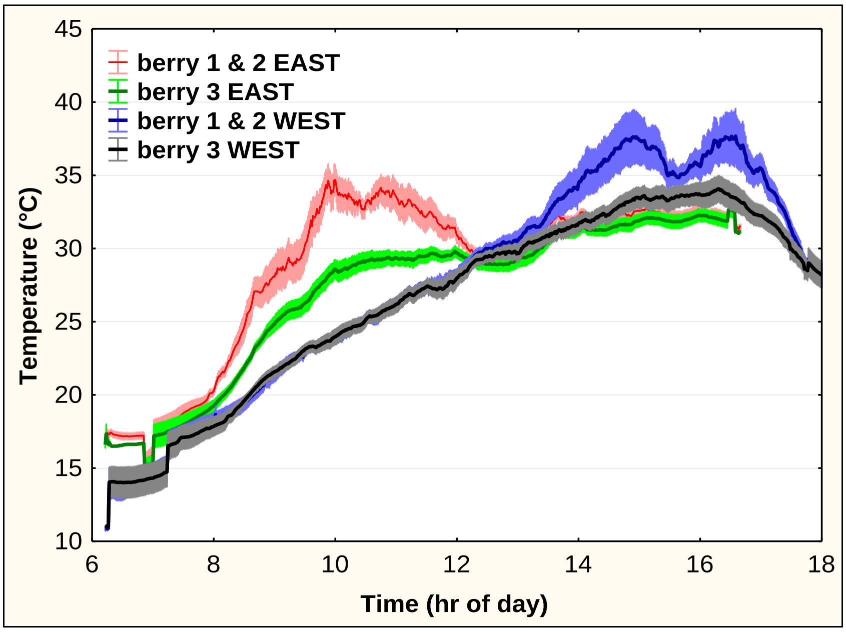


Figure 34 Berry temperatures for berries on the exposed (berry one and two) and shaded (berry three) sides of the bunch for all day cycles on the east and west sides of the canopy in Robertson. Spreads indicate 95% confidence intervals.

Stellenbosch

Figure 35 represents mean berry temperature for all day cycles on the east and west sides in Stellenbosch. Berries on the east side started below 15°C at 07:00 and increased rapidly to ca. 35°C at 10:00. Berry temperature then decreased at a constant rate to about ca. 28°C at 17:00, after which it decreased more rapidly to ca. 24°C after 18:00. Berries on the west side also started below 15°C at 07:00 and increased rapidly to just below 30°C at 11:00, after which it increased at a slower rate to ca. 24°C before 17:00. Berry temperature then decreased at a fast rate to ca. 25°C at 18:00. Figure 36 similarly illustrates berry temperature for all day cycles on the east and west sides in Stellenbosch, but with berry three (shaded berry) separated from berry one and two (exposed berries). The temperatures of berries one and two on the east side showed a similar trend to Figure 35, but temperatures reached ca. 38°C just after 10:00. Berries one and two on the west side followed the same trend as in Figure 35 but reached slightly higher temperatures at 17:00 (35°C). Berry three on the east and west sides followed similar trends through the day. The fastest rate of increase occurred in the morning period until 11:00 where berry temperature reached ca. 30°C. Temperature then remained relatively constant between 28°C and 30°C until about 16:00, after which it decreased to ca. 24°C at 18:00.

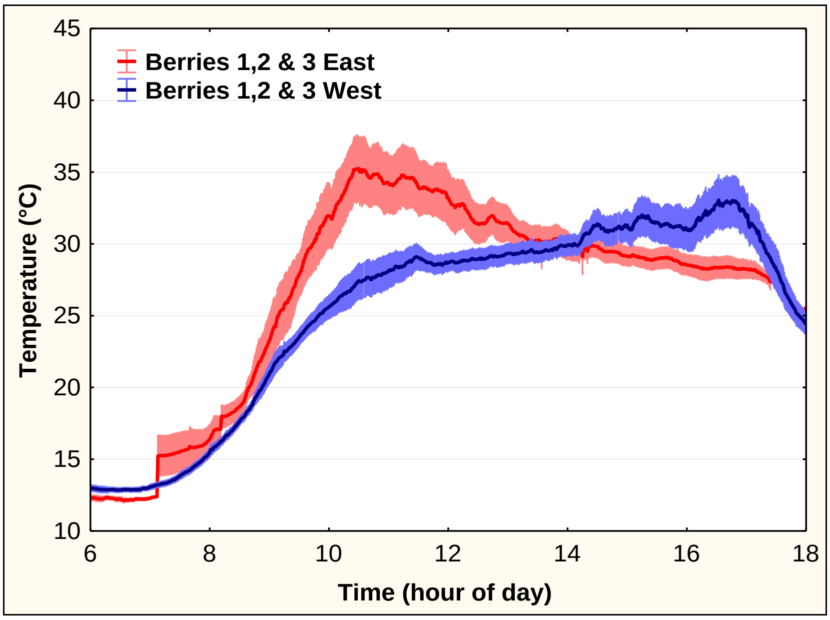


Figure 35 Berry temperature for berries on the east and west sides of the canopy in Stellenbosch. Berry temperature is illustrated as the mean of the surface, under skin and pulp temperatures of berries one, two and three for day cycles C to I. Spreads indicate 95% confidence intervals.

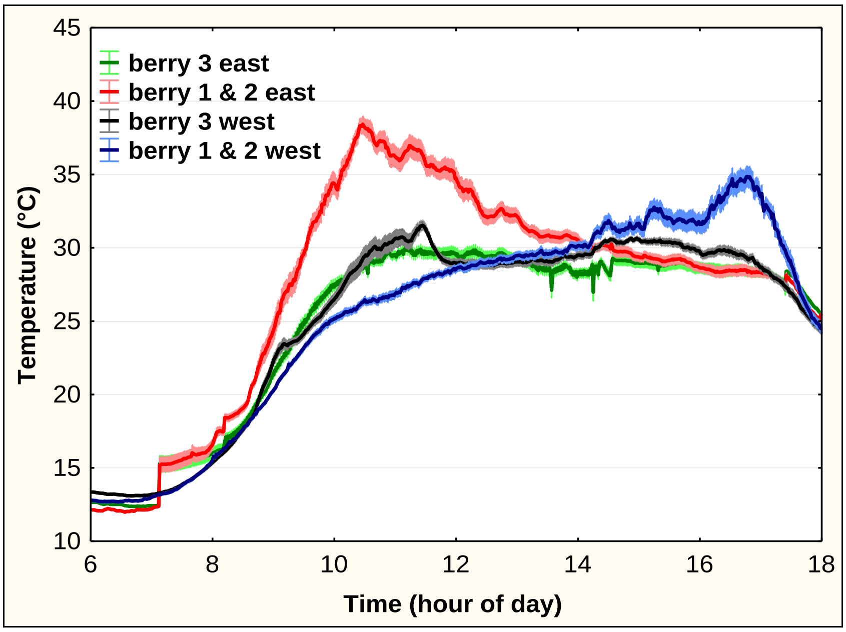


Figure 36 Berry temperature for berries on the exposed (berry one and two) and shaded (berry three) sides of the bunch for all day cycles on the east and west sides of the canopy in Stellenbosch. Berry temperature is illustrated as the mean of the surface, under skin and pulp temperatures for day cycles C to I. Spreads indicate 95% confidence intervals.

Figure 37 represents mean berry temperature for the upper and lower ripening zones on the east and west sides of the canopy. Berry temperature for day cycles in the east, lower ripening zone reached the highest temperatures (between 35°C and 40°C) just after 10:00, after which temperature decreased constantly for the remainder of the day. Berry temperature in the east, upper ripening zone increased at a rapid rate similarly to the east, lower ripening zone; with temperatures slightly lower (30-35°C). Berry temperature then decreased at a slower rate between 11:00 and 17:00. In the west, upper and lower ripening zones, berry temperature increased at a similar rate during the morning to just below 30°C at 11:00 and then continued to increase at a slower rate to 30-35°C, with the lower zone reaching slightly higher temperatures around 17:00. Temperature then decreased rapidly to 22-24°C at 18:00.

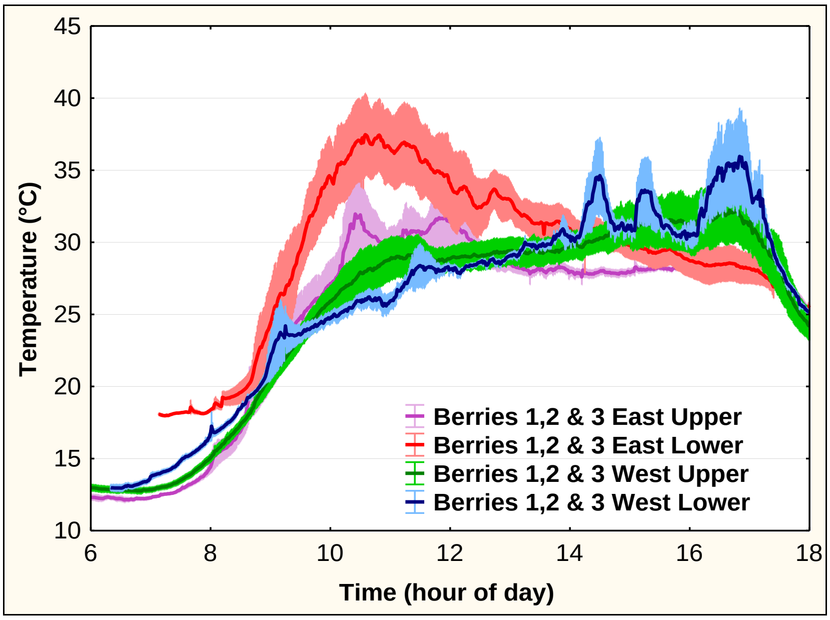


Figure 37 Berry temperature for berries on the east and west sides of the canopy in Stellenbosch for the different ripening zones. Berry temperature is illustrated as a mean of the surface, under skin and pulp temperatures of berries one, two and three for day cycles C to I. Spreads indicate 95% confidence intervals.

3.3.2.4 Thermal time accumulation (berry temperature)

Figure 38 (Robertson) and Figure 39 (Stellenbosch) illustrate the temperature accumulation of berry temperatures above a baseline temperature of 10°C (calculated per minute) for the period from 08:00 to 16:00/18:00 for all day cycles on the east and west sides. Both graphs show a similar trend with regard to the difference in temperature accumulation between berries situated on the east and west sides of the canopy. It is apparent in both figures that there was a separation in thermal accumulation between the east and west berries, which reached a maximum between 12:00 and 13:00. The difference in thermal accumulation between the east and west sides in Stellenbosch is much less with no difference occurring towards the afternoon (16:00). In Robertson the east side accumulates more heat units throughout the day.

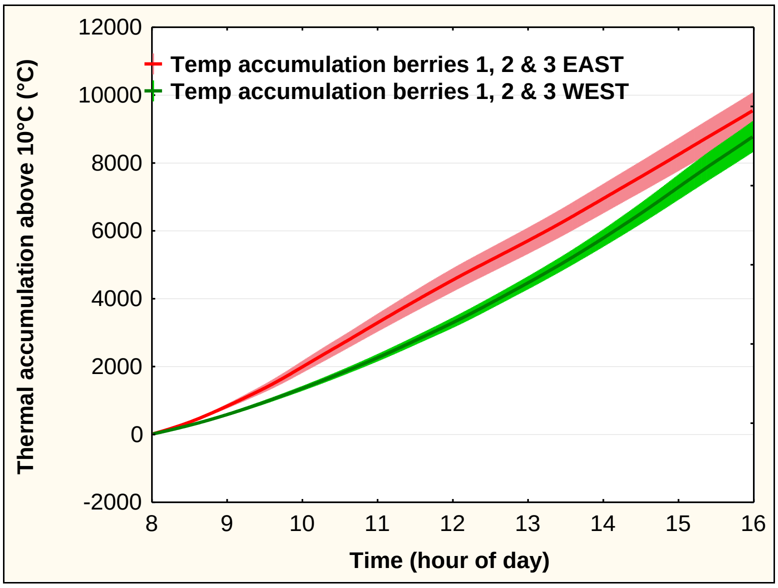


Figure 38 Thermal accumulation (08:00 to 16:00) above 10°C for berries on the east and west sides of the canopy in Robertson at one minute intervals. Thermal accumulation is illustrated as the mean of the surface, under skin and pulp temperature accumulation of berries one, two and three for day cycles one to six. Spreads indicate 95% confidence intervals.

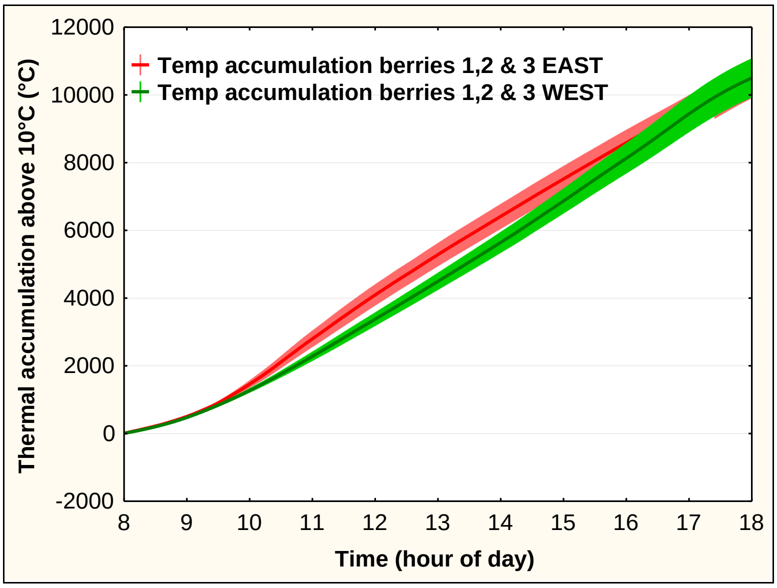


Figure 39 Thermal accumulation (08:00 to 18:00) above 10°C for berries on the east and west sides of the canopy in Stellenbosch at one minute intervals. Thermal accumulation is illustrated as the mean of the surface, under skin and pulp temperature accumulation of berries one, two and three for day cycles D to I. Spreads indicate 95% confidence intervals.

Figure 40 demonstrates the temperature accumulation of the 16 permanently installed thermocouples in Stellenbosch for February and March. There was a tendency for bunches on the east side to accumulate higher temperatures than bunches on the west side. The east upper and lower bunches seemed to have accumulated significantly higher temperatures than the lower west facing bunch. Variability was more apparent amongst thermocouples within a bunch, specifically the east, lower bunch.

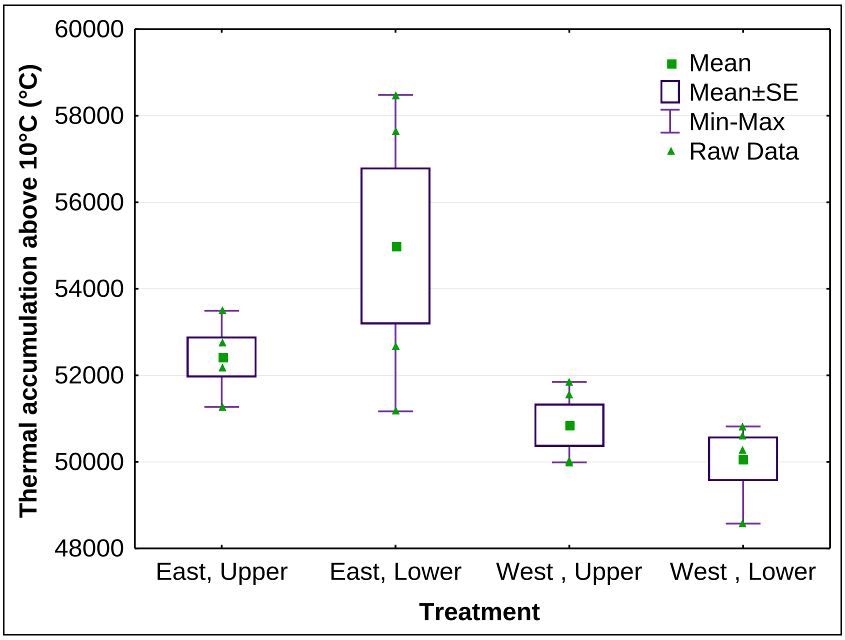


Figure 40 Thermal accumulation above 10°C on a 15 minute interval for permanently installed thermocouples in Stellenbosch from the 10/02/2012 to the 27/03/2012. Means are shown with standard errors (boxes) and minimum and maximum values (whiskers).

3.4 Discussion

3.4.1 Mesoclimate

General decreases in ambient temperature from 12:00 onwards in Stellenbosch (Figure 14) coincided with increases in wind speed (Addendum A, Figure 74d to Figure 81d) from the south westerly direction (Figure 16) as well increases in relative humidity (Addendum A, Figure 74d, Figure 75d, Figure 78d and Figure 80d). This south westerly wind or sea breeze that came from False Bay may have caused the decrease in ambient temperature in the afternoon (Bonnardot *et al.*, 2001) as well as the increase in relative humidity. Day cycle H differed to the rest of the measuring dates in that there was no obvious increase in relative humidity after 17:00 as well as no notable decrease in ambient temperature after 12:00 (Addendum A, Figure 77b). Although the wind speed that initially came from the south-west increased from 2.0 $m.s^{-1}$ at 17:00 to around 4.5 $m.s^{-1}$ at 20:00, there was no increase in relative humidity on this measuring date. This may have been a result of the change in wind direction after 17:00 from the south-west to the south-east (Figure 16). The wind that came from the south-east had to travel a longer distance from the sea, over mountain ranges before reaching the vineyard and may not have had an effect on the ambient temperature or humidity in the vineyard. An interesting measuring date was day cycle I where relative humidity in the vineyard increased 30% in 1.5 hours from 16:30 to 18:00 (Addendum A, Figure 79d). During this period, the wind swung around from a north westerly direction to a south-westerly direction (Figure 16) and the ambient temperature decreased ca. 8°C (Figure 14). A sharp decrease in interior bunch temperature of 12°C was observed as well as a decrease in berry temperature of 12°C and 20°C for berries one and two on the exposed side of the bunch and 10°C for berry three at the back of the bunch. (Addendum A, Figure 79e and 79g). This illustrates the considerable effect a sea breeze can have on grape temperature. According to Smart & Sinclair (1976) wind speed is one of the most important factors impacting fruit temperature.

The lower wind speed in the afternoon in Robertson compared to Stellenbosch as well as variability in wind direction (Figure 13) between days make it difficult to recognise any trends with regard to the effect on ambient temperature. Wind direction may also have been less important with regard to the cooling effect due to the distance from the sea being around 85 km.

With regard to the observed differences between temperature reaction of the weather stations compared to the sensors housed within a radiation shield such as the Gill screen, it is expected that a sensor in the Gill screen would respond quicker to temperature changes than the Stevenson screen, due to the differences in air movement and sunlight interception between the different configurations (Roswell, personal communication, 2012).

3.4.2 Microclimate

3.4.2.1 Canopy temperatures

The microclimates of Stellenbosch and Robertson showed different trends with regard to diurnal canopy temperature. In Stellenbosch during the period around 08:00, there was an apparent negative difference between canopy temperature and ambient temperature (Figure 18 and Figure 19). This negative difference was as a result of the vineyard ambient temperature being higher than canopy temperature and increasing at a faster rate between 07:00 and 09:00 (Figure 41). The positioning of the sensor in the Gill radiation shield above the canopy may have resulted in it heating up at faster rate initially as it was exposed to direct sunlight before the canopy sensor.

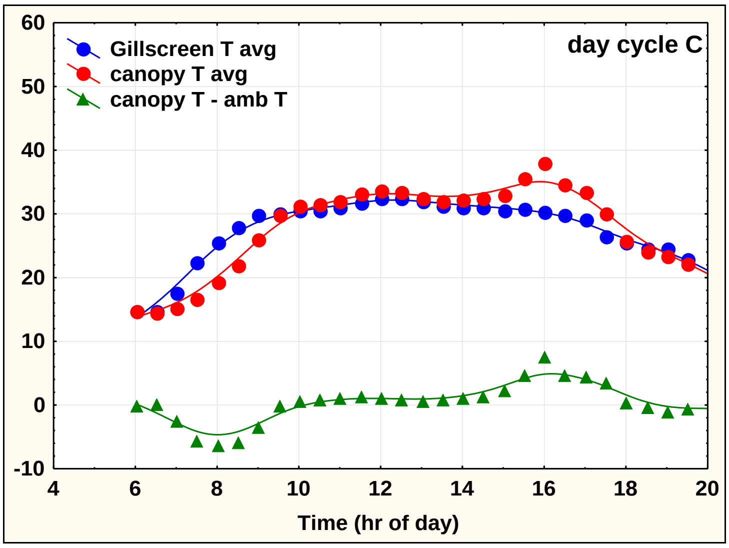


Figure 41 A distance-weighted least squares plot of ambient air temperature (temperature sensor housed in a radiation shield), canopy temperature and the difference between them for day cycle C (east, upper).

Another trend observed in Stellenbosch, which was absent in Robertson, was the occurrence of two peaks in canopy temperature, which resulted in canopy temperature exceeding ambient temperature. This occurred in the upper ripening zone in the morning and afternoon. Similar peaks were observed in Photosynthetic active radiation (PAR) on day cycles E, G and I, illustrating the filtering effect of light through the gaps in the canopy (Addendum A, Figure 78c, Figure 79c and Figure 81c) . On day cycle I the exposure of the back side of the (west facing) bunch caused a notable increase in temperature of berry three around 10:00 (Addendum A, Figure 79g). Overall surface temperature of the visible side of the bunch increased, but variability within the bunch remained low, observed by the small standard deviation (Addendum A, Figure 79f). Figure 42 is a visual illustration of the variability in bunch surface temperatures, showing low variability during the morning period despite the filtering effect of the sun.

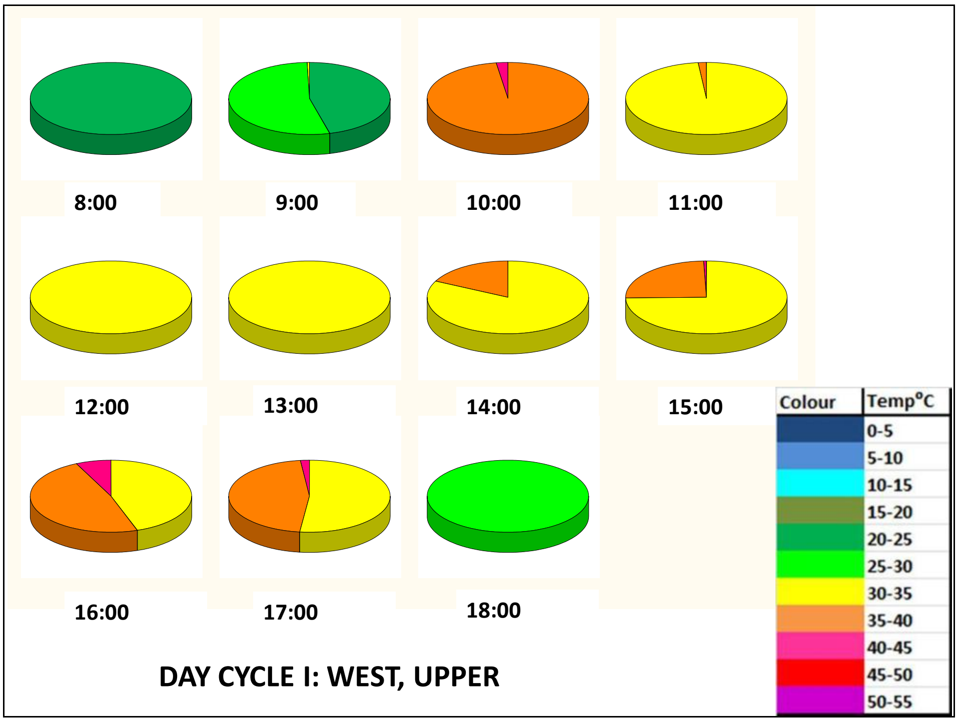


Figure 42 Diurnal bunch surface temperature distibution of pixel temperature values on day cycle I in Stellenbosch.

Day cycle F showed peaks in PAR similar to day cycles E, G and I but for very short periods of time (Addendum A, Figure 75c). This may have been due to its positioning, as the sensor was placed above the bunch and appears to have been shaded by leaves (Figure 43). The sensor placed below the bunch showed a similar trend around 10:00 but double the intensity. This emphasises the importance of sensor positioning in a variable environment such as a vineyard canopy. The rapid increase in canopy temperature and light in the morning and afternoon as mentioned above is expected, due to the low-density canopy with a high number of canopy gaps. Figure 44 shows the canopy sensor and quantum sensor placed in a gap in the canopy on day cycle E (west, upper). Larger gaps in the canopy may have led to bunches being exposed for longer periods. This may have negative repercussions for grape quality or composition, with grapes also possibly being more susceptible to sunburn in warm areas. However, the bunch may have been more homogenous as a result of both sides of the bunch receiving direct radiation, in contrast to a dense canopy where only one side of the bunch receives direct sunlight. This may be more desirable in cooler areas where exposure to direct radiation for longer periods of time will not cause a drastic increase in berry temperature (i.e. areas with a prominent cooling sea breeze effect).

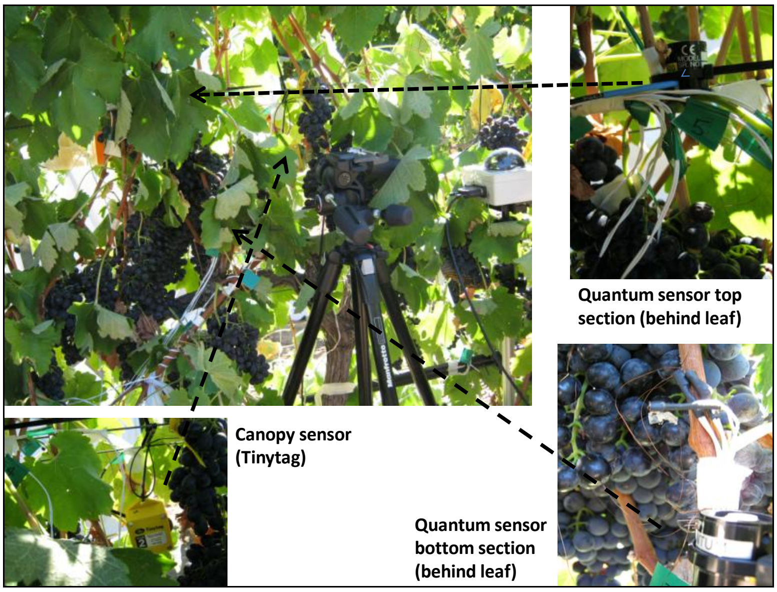


Figure 43 Positioning of the quantum sensors (above and below the bunch) and canopy sensor (Tinytag®) in the upper ripening zone on day cycle F (east).

Figure 44 The sensor measuring canopy air temperature, which was placed in a thin section of the canopy, in the upper ripening zone. Image was taken on day cycle E (west).

The canopy sensor placed in the lower ripening zone illustrated a single peak in canopy temperature between 16:00 and 18:00 for day cycles C and D (Figure 18b and 17c). Photosynthetic active radiation above the bunch on day cycle D illustrated three rapid peaks of high intensity only during the afternoon between 14:00 and 16:00 (Addendum A, Figure 80c). Although there was more than one peak in PAR, canopy temperature only peaked once during this period. This may have been due to the positioning of the quantum sensor above the bunch relative to the canopy sensor underneath the downward shoots. Another possibility may have been that the peaks in radiation were too fast to cause any notable change in canopy temperature. Canopy temperature on day cycle H (east, lower) remained between 1-2°C above ambient from mid-morning to early afternoon, without any notable peak relative to ambient temperature (Figure 19c). This may be a combination of the cooler ambient conditions and the position of the sensor in the canopy. This day cycle took place more than a month after day cycle D and thus shoot positioning may also have changed. A notable increase in PAR above the bunch was however observed on day cycle H (Addendum A, Figure 77c). This may have been due to the quantum sensor positioned above the bunch in a more open situation.

The differences in the measurements between the upper and lower ripening zones illustrate the impact of canopy configuration (Figure 45). The canopy temperature sensor or quantum sensor placed in the lower ripening zone did not experience a double peak, which was observed in the upper ripening zone. Light had to travel through more leaf layers to reach the sensor(s) in the lower ripening zone. The upper canopy appeared to have been thinner as a result of the downward positioning of the shoots in creating the ballerina configuration.

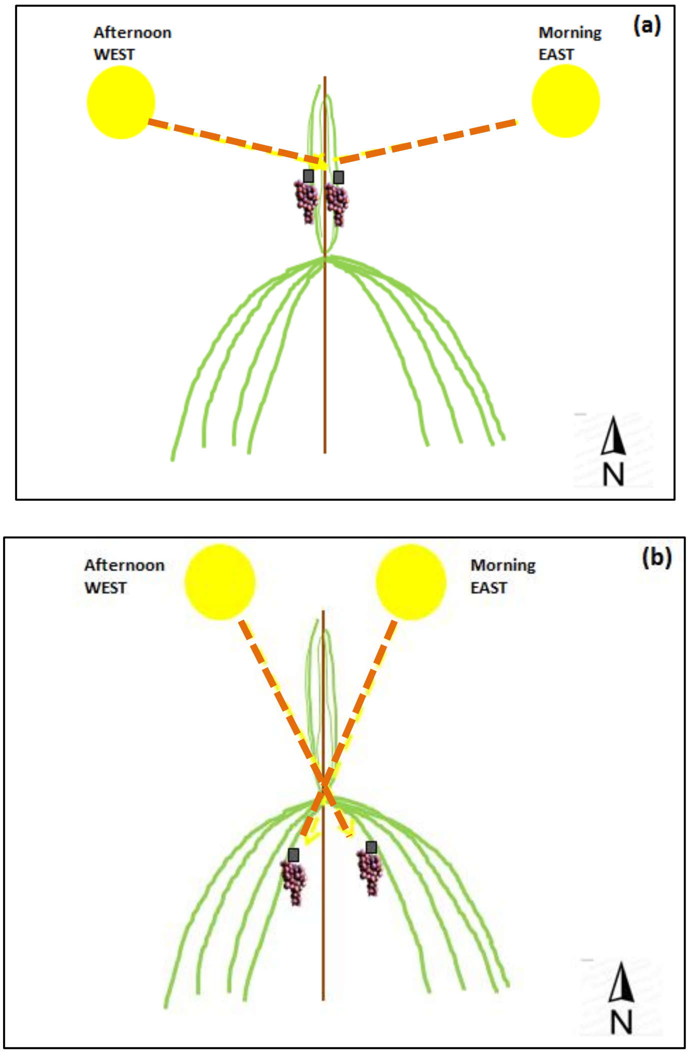


Figure 45 Path of light through the canopy for (a) the upper ripening zone and (b) the lower ripening zone of the Ballerina training system

Canopy temperature assumed ambient temperature for the period in the early morning and when the sun was above the canopy (Figure 18d). It appeared that the sensor was sensitive to the direct radiation around mid-morning or in the afternoon, depending on its position. As to whether the sensor (without a radiation shield) was measuring accurately is questionable, as it largely depended on its position relative to direct radiation. A canopy is a variable environment and thus the canopy temperature measured by the sensor may change drastically over a short distance. Whether or not the sensor is placed in a radiation shield, the position in which it is placed relative to the direct incoming radiation, will determine the temperature. The use of a single sensor for characterising the canopy climate has to be questioned, in terms of the position it needs to be in to define canopy temperature adequately. A sensor placed in a gap in the canopy would increase to a higher temperature than a sensor shaded by leaves. Both of those situations occur in a canopy and thus both need to be quantified to capture canopy variability sufficiently. In addition, the material of the sensor has different thermal properties compared to air and thus may differ in reaction to temperature. Although these sensors are widely used in viticulture applications, they will be much more accurate without incidence or direct/diffuse radiation, as is the case for instance when they are used to monitor the temperature within a cold room. Canopy air temperature therefore preferably needs to be quantified using a shielded sensor.

On day cycle four in Robertson, the canopy sensor further in the canopy showed similar temperatures above ambient to the more exposed sensor (Figure 17b). The canopy may have been slightly more open and the sensor possibly received direct sunlight. Both sensors on this date remained 4°C above ambient temperature for the rest of the day whereas on day cycle six, both sensors assumed ambient temperature from 13:00 onwards. The canopy sensors on day cycle four may have been positioned slightly more to the east side of the canopy.

3.4.2.2 Bunch surface temperature (thermal Imaging)

Careful analysis of the thermal images was required due to certain mean, minimum and maximum bunch surface temperatures that were anomalous to what was expected. These images were in general affected by a technical problem related to the thermal imager, and it was decided to remove it before further analysis. This occurred particularly on the east side of the canopy during the late afternoon in Stellenbosch and Robertson, and apparently resulted from the direct rays of light falling straight into the line of vision of the lens. Faulty images in which human hands were visible showed skin surface temperatures of around 43°C, which should be unlikely as body temperature is usually regulated around 37°C. A further reference for faulty thermal images was the leaf surface temperature, which is illustrated as being above 43°C in shaded conditions in the later afternoon. This seems impossible as leaves are known to be better regulators of temperature than berries as a result of the stomata. Jones (1999) investigated the use of thermal imagery in detecting stomatal closure as a means for plant stress and thus irrigation scheduling. This is due to the close relationship leaf temperature has with the stomatal conductance. Van Zyl (1986) demonstrated the potential viability in using the infrared thermometer to determine crop water stress by comparing it to a well irrigated reference vines. Figure 46 is an illustration of two faulty images with extremely high surface temperatures of skin, bunches and leaves. The thinness of the canopy is visible, which may have allowed direct rays of light to pass through, entering the camera lens, and creating a glare effect.

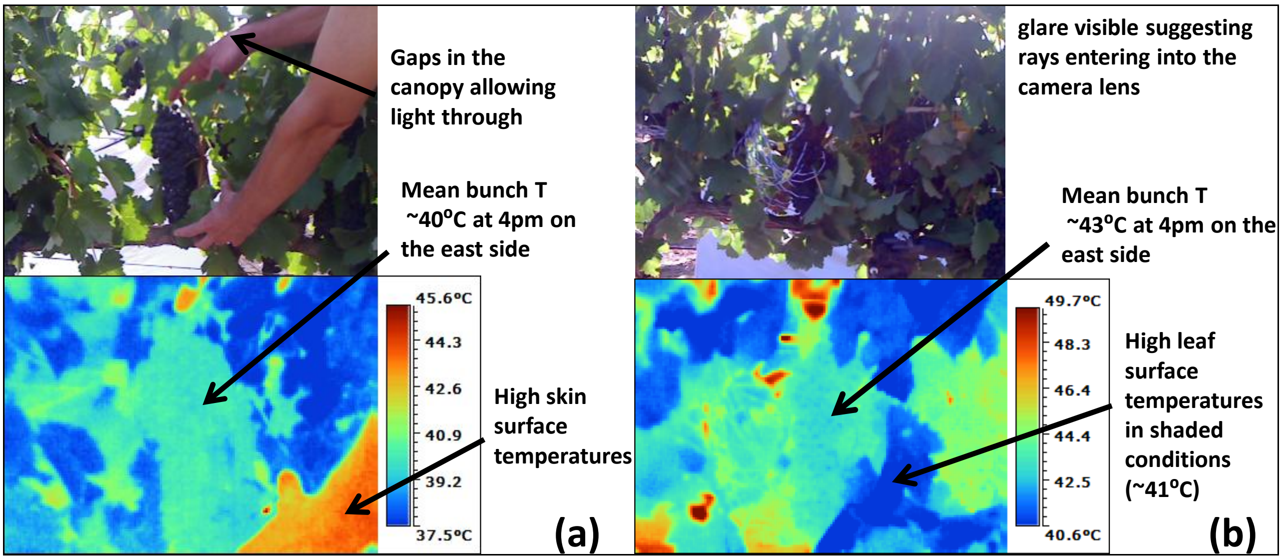


Figure 46 Faulty thermal images showing values anomalous to what is expected. Images taken on the east side in Robertson at (a) 17:00 on day cycle six and (b) 16:00 on day cycle four. Images show surface bunch temperatures above 40°C.

In Robertson and Stellenbosch the small proportion of surface temperatures below 25°C (Figure 20) may be due to the fact that from 06:00 the bunch may have experienced lower surface temperatures for a very short period before rapidly increasing when bunches were exposed to direct radiation or warmed by rapidly increasing ambient temperatures. There is an uneven distribution of pixels between Robertson and Stellenbosch (due to the different number of day cycles/bunches measured between the sites) and as a result, it is not possible for the direct comparison of the absolute number of pixels. More focus is thus concentrated on the trends or tendencies between classes. The differences in bunch size as well as the distance of the camera from the bunch can also affect the total pixel number; therefore the focus is on relative rather than absolute comparisons.

In Robertson, slightly higher and lower maximum and minimum bunch surface temperatures were observed in comparison to Stellenbosch (Figure 21). This could have been the effect of a more continental climate 85 km from the sea compared to the Stellenbosch vineyard, 18 km from the sea. Bonnardot *et al.* (2001) also described smaller variability in diurnal temperature in sites 10 km and 20 km from the sea compared to 50 km from the sea. Maximum ambient temperatures in Robertson are mostly between 30°C and 35°C with the exception of day cycle three (Figure 11), whereas in Stellenbosch maximum ambient temperatures are mostly between 27°C and 32°C with the exception of day cycle B (Figure 14). The daily maximum ambient temperatures in Robertson were mostly above 30°C through the season (Figure 9), whereas in Stellenbosch daily maximum ambient temperatures were mostly below 30°C (Figure 10). Higher maximum temperatures along with the dominant class in a higher temperature range, illustrate the higher temperatures that occurred in Robertson compared to Stellenbosch (Figure 21). The lower maximum temperatures and the relatively cooler dominant class found in Stellenbosch may have been due to the cooling effect of the sea breeze that increased in the afternoon period, preventing higher surface temperatures. Mean February temperatures for the past thirty years (Figure 47) illustrate a higher temperature class for Robertson (23.1-24°C) compared to Stellenbosch (22.1-22.5°C) (H Schloms, personal communication).

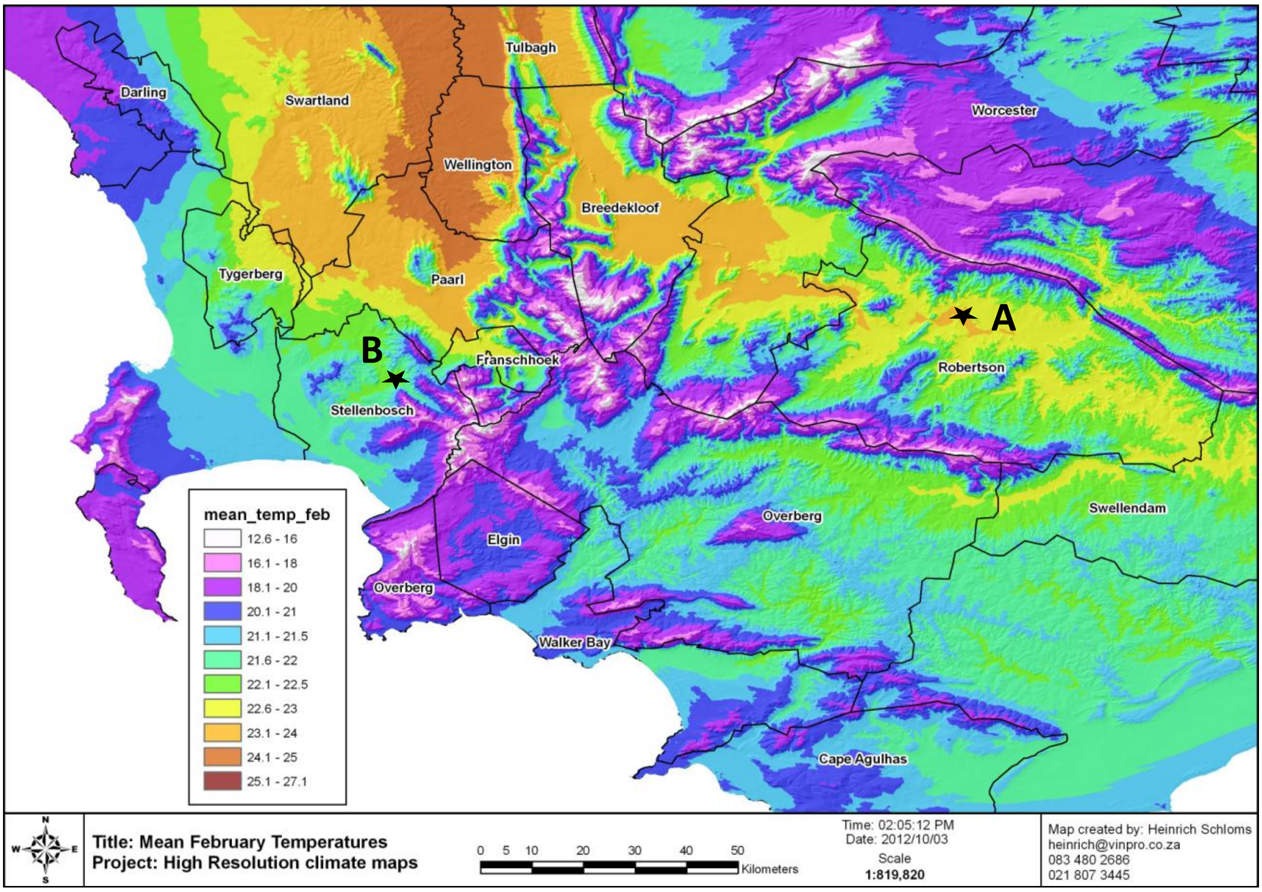


Figure 47 Mean February temperature classes for the past thirty years in the Western Cape. Weather stations represented as stars with labels A (Robertson) and B (Stellenbosch).

Temperatures on the east side in Robertson appeared higher compared to the west (Figure 22a and 22b) as a result of the slightly higher mean (32.5°C) and dominant class (35-40°C) compared to the west side. Some grape producers in the Western Cape believe that bunches on the west side experience higher temperatures, especially in warmer areas, when vineyards have been planted with a north-south row direction. The occurrence of higher temperatures on the east side in Robertson thus comes as a surprise and is very relevant to practical viticulture and grape composition. The west side had a slightly higher percentage (14%) above 40°C compared to the east side (11%), which may have been due to ambient temperatures reaching their maximum in the afternoon when west facing bunches were exposed. Despite the east side in Stellenbosch having a dominant class in a lower temperature range, a higher proportion of pixel temperature values in the upper classes on the east side was observed relative to the west (Figure 22c-22d). The lower surface temperatures on the west side in Stellenbosch may have been a result of the south westerly wind that picked up after 12:00 (sea breeze), also suggested to be responsible for the decrease in ambient temperatures during the afternoon period. Bunches that faced the east side were exposed to direct radiation, and were also experiencing rising ambient temperatures (Figure 14) and a lower wind speed (Addendum A, Figure 74d to Figure 76d and Figure 77d) from the north-east and north-westerly direction (Figure 16). A wider distribution of pixel temperature values between classes (higher variability) was also observed on the east side compared to the west side. This may have been due to the rapid increase in surface temperature from low temperatures in the early morning to high temperatures of above 40°C in the later part of the morning. This rapid increase to such high temperatures on the east side in the later morning may have been a result of the combination of rapidly increasing ambient temperatures and incoming direct shortwave radiation (Figure 14 and Addendum A, Figure 74c to Figure 77c).

The slightly higher pixel temperature values observed in the lower bunches on the east and west sides in Stellenbosch (Figure 23) may have been a result of the proximity to the soil which was mostly bare. Reflection of light from the soil may have caused higher temperatures. It was illustrated by Hunter *et al.* (2010) that high levels of PAR were reflected from the soil surface, particularly around 12:00 for the north-south row orientation. The architecture of the canopy may also have played a role where bunches in the lower ripening zone were in a more open situation with no upper canopy protection from direct radiation particularly as the sun approached solar noon. Bunches in the upper ripening zone were generally shaded during this period by the overhanging shoots, as a result of no tipping/topping.

3.4.2.2.1 Morning and afternoon trends in bunch surface temperature

General trends

Ambient temperatures in Stellenbosch during the morning period increased at much faster rate compared to Robertson (Figure 11 and Figure 14), which explains the more distinct difference between temperature variability in the morning and afternoon. Variability in the afternoon period on the east side in Robertson and Stellenbosch decreased (Figure 24c and Figure 25b) as a result of the shaded conditions when the bunch was protected from direct radiation by the canopy. The only radiation that the visible side of the bunch would have received was reflected or diffused radiation. The absence of direct radiation, creating shaded conditions in the afternoon, would have reduced the possibility of variability in temperature. The mean temperature on the east side in Robertson was higher in the afternoon compared to the morning, which may have been as a result of the increasing ambient temperatures towards the afternoon (Figure 11). In Stellenbosch a higher mean temperature occurred on the east side in the morning as a result of rapidly increasing ambient temperatures (Figure 14), in addition to the increasing radiation received by the east facing bunches.

On the west side in Robertson, a less notable difference in variability was observed between the morning and afternoon periods (Figure 24b and d). A wide distribution of surface temperature pixels occurred in the morning (with a distinct dominant class) whereas a more even distribution of surface temperature pixels occurred in the afternoon. A wide range of pixel temperature values in the morning in Robertson may have been as a result of cooler mornings. A lower mean temperature was observed in the morning compared to the afternoon which is explained by the exposure of west facing bunches in the afternoon when ambient temperatures are at a maximum. The higher temperatures on the west side may thus be at a higher risk to extreme temperature events such as sunburn, but this may also be possible for the east side in the morning, on condition that shorter periods of extreme temperatures could also lead to damage. In Stellenbosch higher variability was observed in the morning on the west side compared to the afternoon. This may have been as a result of cool ambient temperatures in the morning which increased rapidly before 12:00 as well as the variable canopy which consisted of a higher gap fraction allowing for the filtering of light through, which may have caused increased temperatures on the west side in the morning. As expected, a higher mean temperature was observed in the afternoon period compared to the morning as a result of direct exposure.

Day cycles

The wider range of temperature classes in the morning on day cycles one and four along with the absence of the 25-30°C class (Figure 26) illustrates the rapid increase in surface temperature that occurred during the morning period on the east side. This was also demonstrated in Figure 33 where berry temperature on the east side in the morning increased at a rapid rate from ca. 17°C around 07:00 to 33°C around 10:00 compared to the west side that increased at a constant rate throughout the day. Day cycle four specifically showed the widest range in temperature. Ambient conditions on this measuring date included lower morning temperatures (ca. 14°C) around 07:00 relative to day cycles one and six, after which it increased at a faster rate reaching similar temperatures to day cycle six at 12:00 (ca. 28°C) but higher than day cycle one (Figure 11). This rapid increase in ambient temperature during the morning from low to high may have contributed to the wide range in surface temperature on day cycle four. In the afternoon variability decreased for all day cycles on the east side. Day cycle four showed a higher afternoon mean compared to day cycles one and six, which was as a result of the higher portion of pixel temperature values above 40°C. The individual means for the day cycles in the afternoon on the east side were all above the means for the morning period (Figure 26 and Figure 27). This may have been a result of images taken in the early morning around 07:00 when ambient temperatures were at their lowest, decreasing the mean morning temperatures (Figure 11). After being directly illuminated prior to 12:00, bunches may have maintained their heat or slightly increased their temperature in response to increasing ambient temperatures during the afternoon (Figure 11). This was also observed in the separate berry temperatures for berries one and two (exposed side) and three (back side) on bunch one for day cycle six (Addendum A: Figure 70f). Berries one, two and three decreased in temperature from 11:00 until 13:00 when the sun path moved overhead and the bunch became shaded. From 13:00 until 14:00 there was an increase in berry temperature in all three berries, after which the temperature remained constant at a similar temperature to ambient. The dip in berry temperature around 13:00 also coincided with a rapid decrease in global radiation (Addendum A, Figure 70c) which may have been a result of a cloud covering the sun or a result of leaves shading the bunch. Day cycles one and four illustrated a slight increase in berry temperature of all berries (one to three) after 12:00. Berry temperature was around 4°C above ambient during this period. Such high surface temperatures on the east side in the afternoon may also have been a result of heat escaping from the pulp *via* the skin in the form of latent heat; however, pulp temperature was higher than surface temperature on only one occasion (Figure 48). This may have also been as a result of the relative positioning of the sensors.

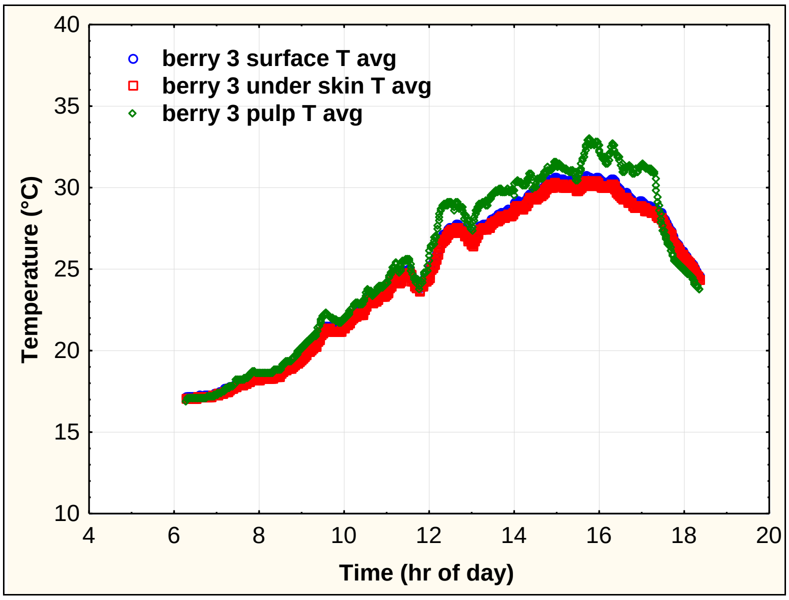


Figure 48 Within-berry temperature of berry three on day cycle three on the west side in Robertson.

On the west side, day cycle two showed distribution of surface temperature among a wider range of classes during the morning period compared to day cycles three and five (Figure 28a). This was due to the occurrence of lower bunch surface temperatures compared to day cycles three and five, which may have been a result of the lower ambient temperatures observed during the earlier part of the morning. Day cycle five in the morning period had less variability compared to day cycles two and three and a prominent proportion of temperature values occurred between 25°C and 30°C (56%) in the morning (Figure 28c). This measuring date had higher ambient temperatures throughout the day relative to day cycles two and three and it started around 20°C at 07:00 (Figure 11). The higher ambient temperatures may have caused higher surface temperatures on day cycle five compared to day cycles two and three.

Between-bunch variability

On the east side in Robertson on day cycle one, pixel temperature values were distributed sparsely for both bunches, which was as a result of fewer images collected on this date. This emphasizes the importance of more frequent measurements as temperatures increase quickly which may be unaccounted for when performing fewer measurements (Figure 30a and 30b). The similar ambient conditions in which bunch one and two were situated, may have contributed to the similar trends in bunch surface temperature variability observed between bunches on the same day cycle. Differences in the major classes between bunches may have been determined by the relative positioning in the canopy. Looking again at day cycle one where the dominant classes differed, bunch one was in a more protected (shaded) situation with leaves surrounding it, whereas bunch two was in a more open situation (Figure 49), which would explain the higher portion of temperature pixel values in a higher class (35-40°C) (Figure 30a and 29b, Figure 50 and Figure 51).

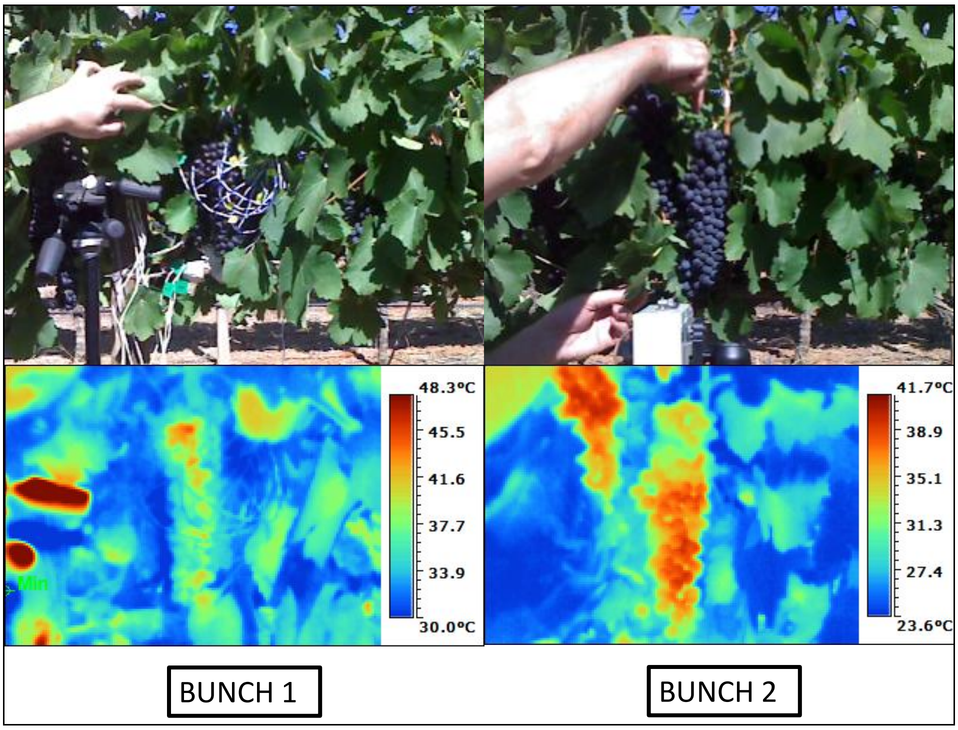


Figure 49 Thermal and bitmap images of bunch one and two on day cycle one at 10:00 on the east side in Robertson.

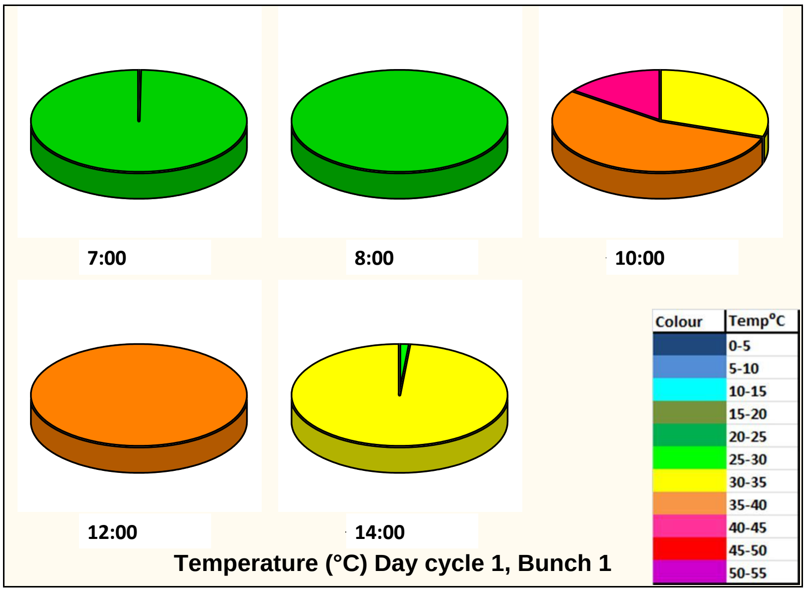


Figure 50 Diurnal bunch surface temperature distibution of bunch one on day cycle one on the east side of the canopy in Robertson.

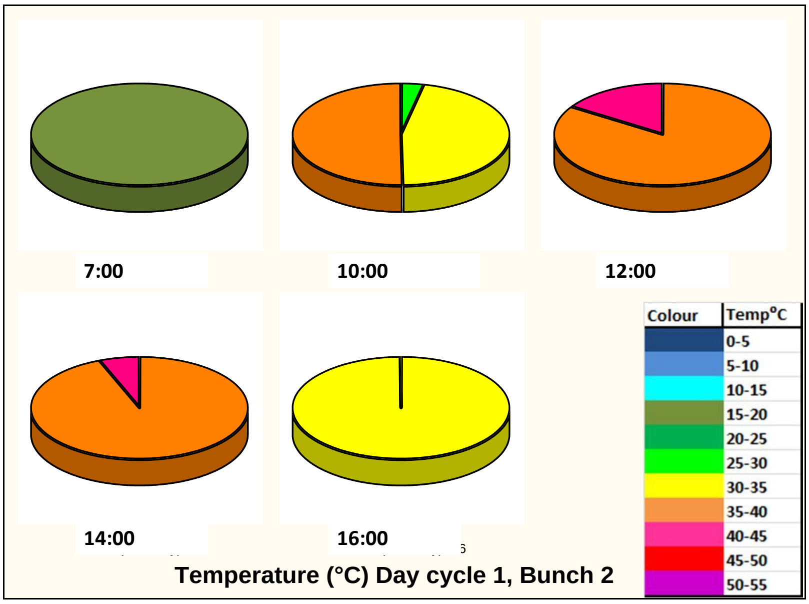


Figure 51 Diurnal bunch surface temperature distibution of bunch two on day cycle one on the east side of the canopy in Robertson.

On day cycle four, bunch two had a wider range of surface temperatures from 10-15°C to 50-55°C. Differences in the range of temperatures through the morning between bunch one and two were possibly a result of the positioning within the canopy (Figure 52). Bunch one was further away from the soil and further back in the canopy whereas bunch two was much closer to the soil and extending further out of the canopy. Bunch two was thus more susceptible to extremes as a result of soil irradiation and reflection and poor protection by the canopy.

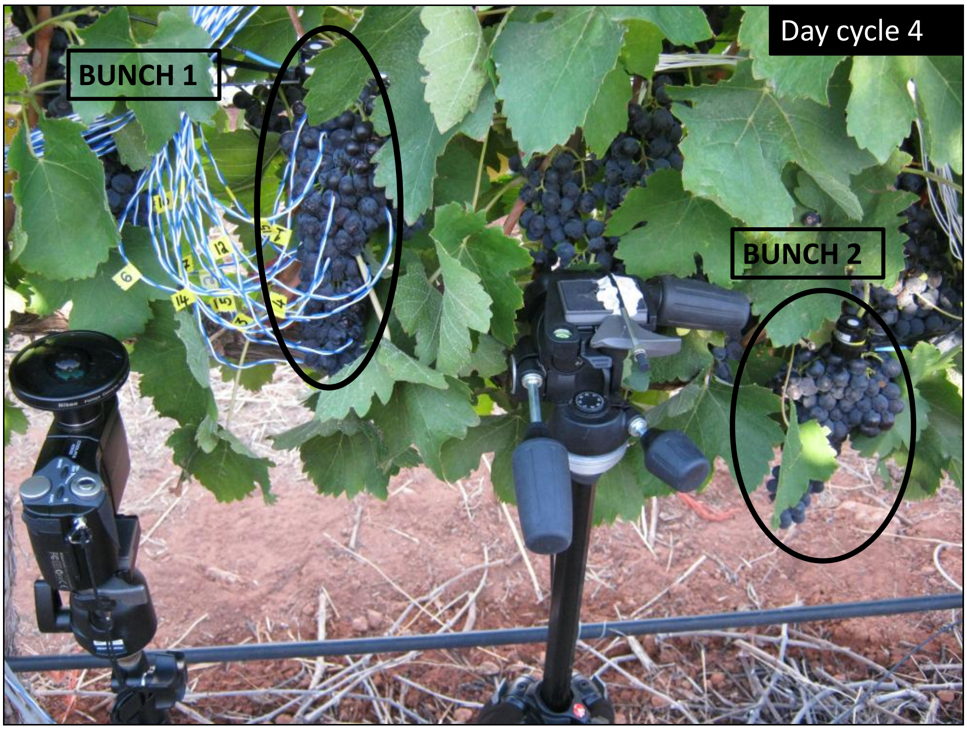


Figure 52 Bunches one and two on day cycle four in Robertson on the east side.

On day cycle three in Robertson, a large difference in the mean bunch surface temperatures between bunch one and two were observed at 16:00. Bunch two in a more open situation had a mean bunch surface temperature of ca. 18°C above ambient, whereas bunch one in a slightly more shaded position, had a mean bunch surface temperature of ca. 9°C above ambient (Figure 53). Such high temperatures of bunch two thus increase the risk of sunburn, which may also be indicated by the shrivelling of berries at the top of the bunch.

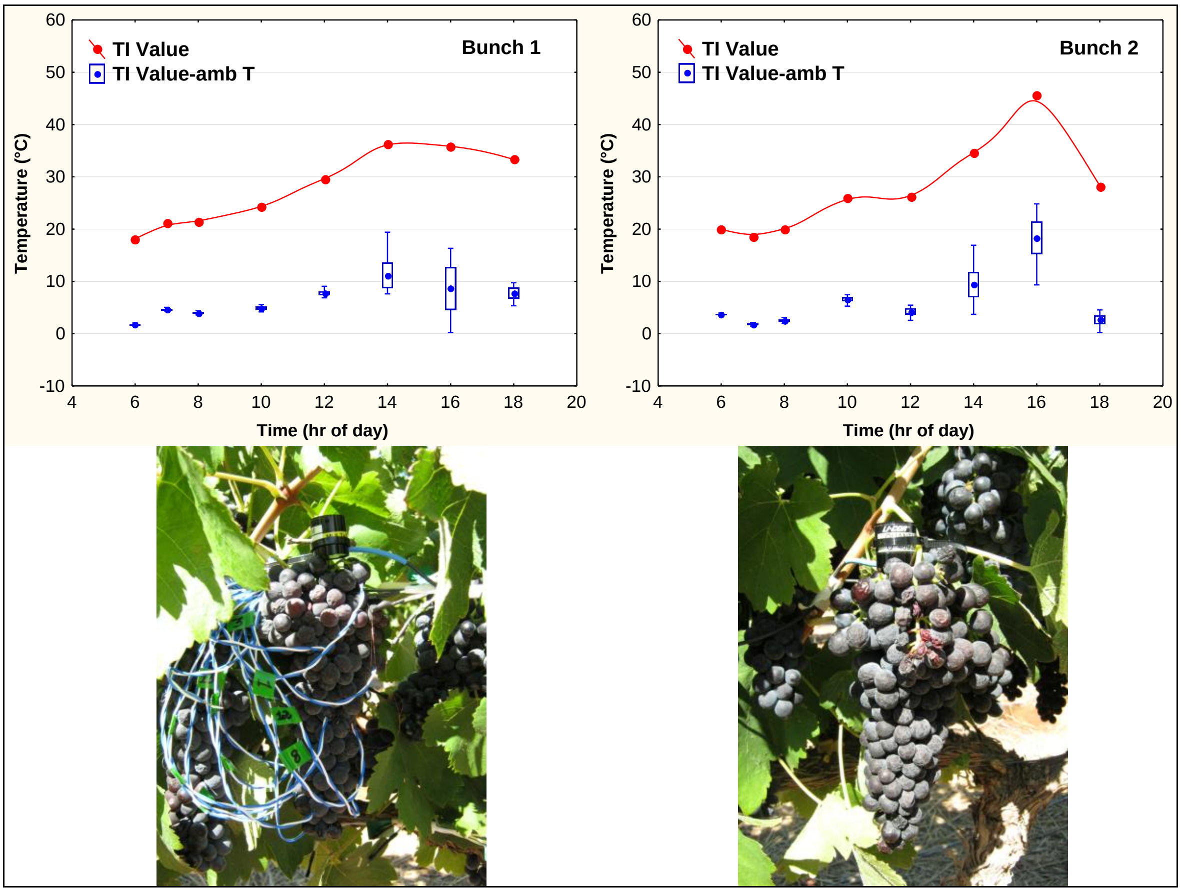


Figure 53 The diurnal mean, minimum and maximum (whiskers) and standard deviation (boxes) of the difference between bunch surface temperature (measured by the thermal imager-TI) and ambient temperature of the weather station for bunch one and two on day cycle three in Robertson as well as the absolute mean bunch surface temperature..

3.4.2.2.2 Bunch surface temperature variability

Bunch variability was low when bunches were shaded during the early morning and afternoon periods on the east side (Addendum A, Figure 68e-Figure 70e and Figure 74f-Figure 77f) and during the morning period on the west side (Addendum A, Figure 71e - Figure 73e, Figure 78f and Figure 81f). Variability increased as a result of the direct sun exposure which was observed with the radiation sensors (Addendum A, Figure 69c and 67e). On the east side, day cycle four showed the highest variability compared to day cycles one and six (Figure 26b) with a wider range of temperatures on bunch two during the morning period (Figure 30c and 29d). On-bunch variability was slightly higher for bunch one at 09:00, but similar for bunches during peak radiation at 10:00 (Figure 54 and Addendum A, Figure 69c and 67e). The wider range of temperatures observed on bunch two (Figure 30c and 30d) was thus as a result of the larger diurnal variability during the morning period (Figure 55 and Figure 56), when temperatures of between 10°C and 15°C occurred on bunch two at 07:00 and temperatures of 50-55°C occurred at 10:00. The wider range of temperatures on bunch two was as a result of its positioning relative to bunch one. Bunch two was closer to the soil and extending further out of the canopy (Figure 52), i.e. more exposed to direct radiation and soil reflected radiation. Van Zyl & Van Huyssteen (1980) observed significantly higher bunch temperature on bush vines than on the lengthened Perold and slanting trellis systems as a result of the reflected heat from the soil as well as higher exposure. However, the on-bunch variability for both bunches should not be overlooked. Temperatures of between 30-35°C and 50-55°C were observed on bunch one when the bunch was receiving maximum insolation around 10:00 (Figure 55 and Addendum A, Figure 69c). Huge variability in berry temperature was also observed on bunch one. A difference of 10°C occurred between berries one and two at 10:00 (Addendum A, Figure 69f).

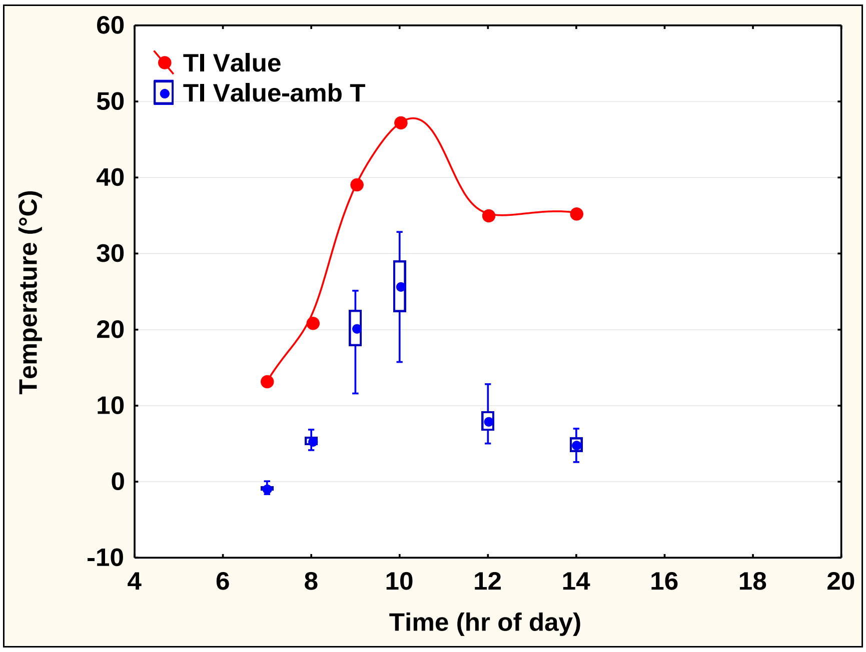


Figure 54 Surface temperature of bunch two on day cycle four (east) in Robertson with the mean bunch surface temperature (red) and difference between bunch surface temperature and ambient temperature (blue). Whiskers indicate minimum and maximum values and boxes represent the standard deviation.

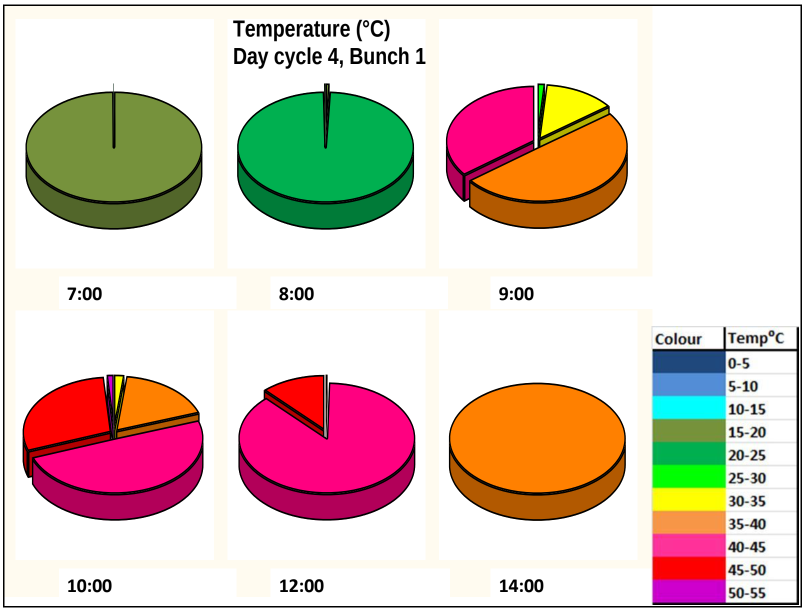


Figure 55 Diurnal and on-bunch distribution of pixel temperature values for bunch one on day cycle four (east) in Robertson.

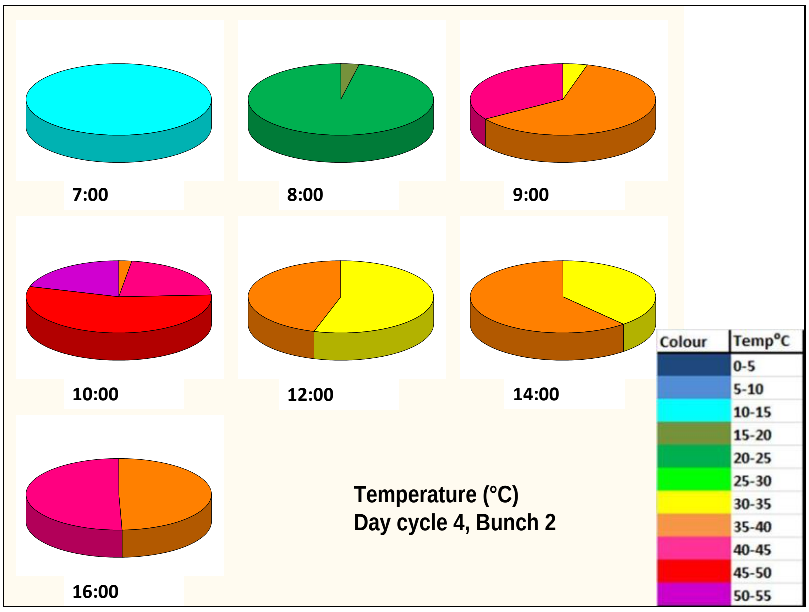


Figure 56 Diurnal and on-bunch distribution of pixel temperature values for bunch two on day cycle four (east) in Robertson.

Very little on-bunch variability was observed on day cycle two relative to day cycles three and five on the west side (Figure 57-Figure 58 and Addendum A, Figure 71e-Figure 73e). Ambient temperatures on day cycle two were relatively higher than on day cycle three, indicating the possible contribution of canopy architecture and/or bunch structure (Addendum A, Figure 71b-Figure 72b). Highest variability was observed on day cycle three despite high ambient temperatures, *r*eaching 35°C in the afternoon on day cycle five (Addendum A Figure 72b, 70e and Figure 73b, 71e). Bunch one on day cycle two had more protection by the surrounding leaves relative to bunch one on day cycle three which extended further out of the canopy with no leaves situated above the bunch (Addendum A, Figure 71a and Figure 72a). In addition to the sparse canopy on day cycle three, the protruding top section of the bunch (‘hotspot’) contributed to its high variability, which is demonstrated in the thermal image in Addendum A, Figure 72a. Figure 59 illustrates the comparable structures of the different bunches on the different measuring dates on the east side. Bunches on day cycles two and five were flatter, whereas on day cycle three a bulge on the upper part of the bunch was observed. Different bunches were chosen so their morphology/ positioning could be different. The lower section of bunch one on day cycle three experienced more shaded conditions relative to the protruding top section which created more variability within the bunch.

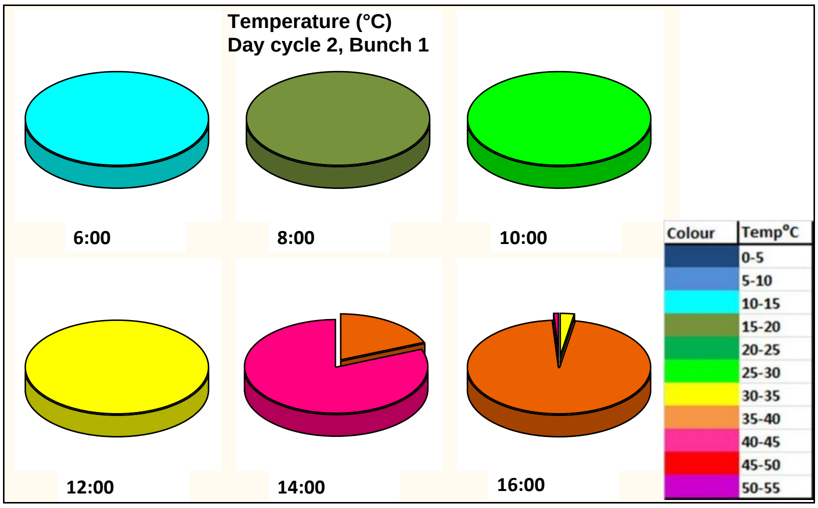


Figure 57 Diurnal and on-bunch distribution of pixel temperature values for bunch one on day cycle two (west) in Robertson.

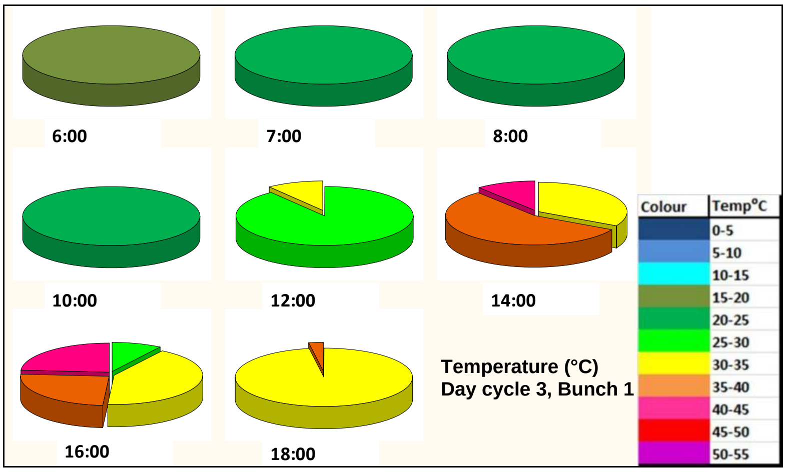


Figure 58 Diurnal and on-bunch distribution of pixel temperature values for bunch one on day cycle three (west) in Robertson.

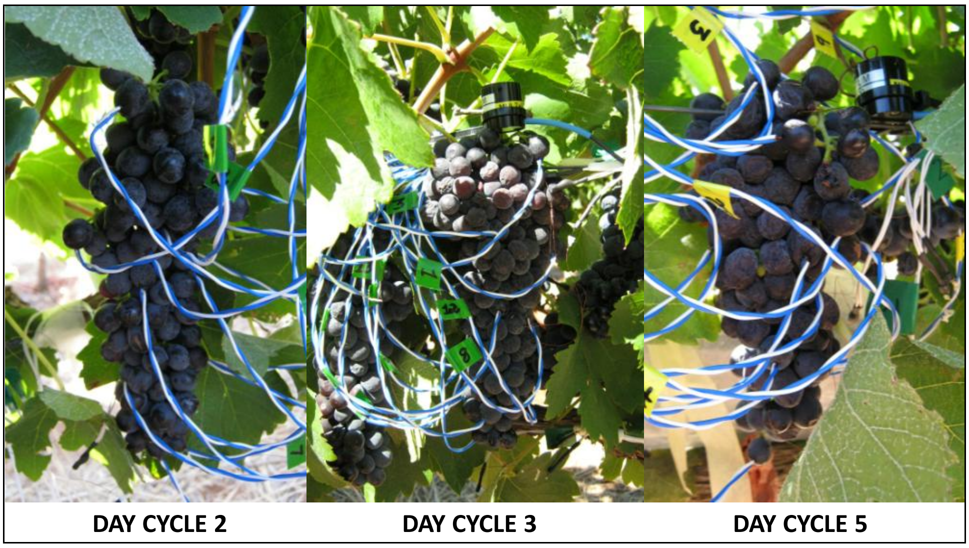

DAY CYCLE 2 DAY CYCLE 3 DAY CYCLE 5

Figure 59 Images of the different bunch structures of bunch one for day cycles two, three and five on the west side in Robertson.

3.4.2.3 Berry temperature variability

Figure 33 to Figure 37 show the difference in trends between berries on the east and west sides of the canopy for both Robertson and Stellenbosch. The higher berry temperatures in the afternoon on the west side in Robertson were as a result of the maximum ambient temperatures in addition to the direct radiation received by exposed bunches or berries. Interestingly, berries situated on the east side of the canopy, on the visible side of the bunch, increase in temperature at a seemingly faster rate during the morning period compared to the berries on the west side during the afternoon. A more rapid increase in berry temperature would have been expected on the west side as a result of the higher ambient temperatures. A suggestion may be that berries situated in cool conditions such as berries on the east side in the early morning are more reactive to direct radiation and/or increasing ambient temperatures. Berries that are in shaded conditions during the morning period (west berries) increase at a more constant rate through the day, with temperatures similar to ambient (Addendum A, Figure 71f to Figure 73f), and when exposed, are less reactive as a result of the already warm conditions in the berry. For an exposed berry on the west side to increase to the same extent as an exposed berry on the east side, more energy may be required to reach the higher temperatures. Global radiation in Robertson showed similar values for the 10:00 and 16:00 periods which is when bunches are exposed on the east and west sides.

Berry three situated at the back of the bunch on the east side in Robertson also showed a rapid increase in temperature in the morning (Figure 34), suggesting the possible conduction through the bunch or the possible effect of diffuse radiation which, according to Smart (1985), can be reflected from opposite canopies (VSP trellising systems) and the soil. Berry temperatures were between 6-10°C above ambient temperature when east facing bunches were experiencing maximum exposure (Addendum A, Figure 69c, 69f and Figure 70c, 70f). The continued increase in berry temperature for the remainder of the day was as a result of the increasing ambient temperatures towards the afternoon, which is observed in Addendum A, Figure 69f and Figure 70f where minimal differences between berry and ambient temperatures occur from 13:00 onwards. On the west side, berries on the exposed (berry one and two) and back (berry three) sides of the bunch increased similarly for the morning period (Figure 34). In the afternoon, berry three continued to increase at a much slower rate and reached a lower maximum compared to berries on the visible side of the bunch, which is assumed to be due to the absence of direct radiation. Berries on the back of the bunch followed the ambient temperature trend very closely through the day with a maximum difference of ca. 4°C (Addendum A, Figure 71f to Figure 73f). Slight differences between berry three and ambient temperatures are expected as a result of the dark colour of the berry, which may absorb more diffuse radiation.

In Stellenbosch, berry temperature on the east side increased at a faster rate and to a higher temperature compared to berry temperature on the west side in the afternoon (Figure 35). The rapidly increasing ambient temperatures observed in the morning period may have been the cause of the faster increasing berry temperature on the east side. The cooling effect of the sea breeze on the ambient temperature after 12:00 (Figure 14) may have also impacted the berry temperature on the west side, resulting in lower temperatures compared to the east side in the morning. Another interesting observation was the similar rate of temperature increase for berries on the east and west sides in the morning, which coincided with the fastest increase in ambient temperature. The berries on the west appear to have responded more to the quick increase in ambient temperature in the morning than to the direct sun exposure in the afternoon, as only a slight increase in temperature was observed in the afternoon. The thin canopy may also have contributed to this rapid increase in berry temperature in the morning on the west side as a result of the filtering effect of the light through the canopy, which was observed specifically on day cycle I where the berry situated at the back of the bunch showed a sharp increase in temperature in the morning (Addendum A, Figure 79g). The afternoon sea breeze may have prevented the berries from reaching high temperatures.

From both situations in Robertson and Stellenbosch, it can be suggested that the berries in cooler conditions reacted to direct sunlight with a faster and higher increase in temperature relative to its cool conditions than a berry that was already experiencing warm conditions. The physiological impact of berries experiencing a temperature ‘shock’ compared to berries increasing at a more constant rate needs to be understood, i.e. what happens to berry composition when the temperature increases at a rapid rate as opposed to a berry increasing at a constant rate to a higher temperature?

Berry three on the east and west sides in Stellenbosch, which was located at the back of the bunch, increased at a similar rate in the morning, reaching temperatures of ca. 30°C (Figure 36). After 11:00 berry three on the east decreased slowly, whereas berry three on the west increased, but not to the extent as was observed with the exposed berries as a result of the absence of direct radiation. Temperature for a berry situated on the back of the bunch in Stellenbosch was more temperate than a berry on the front side of the bunch. Temperature for berry three followed ambient temperature closely and was rarely more than 2°C above it (Addendum A, Figure 75g-Figure 78g and Figure 80g-Figure 81g). More than half of the bunch may be experiencing similar conditions to berry three with no drastic increase in temperature and remaining relatively constant through most of the day. Berries situated in the interior portion of the bunch may also experience similar conditions to berry three, leaving only the outer part of the bunch on the visible side experiencing extreme conditions. In a study by Haselgrove *et al.* (2000) bunches in shaded conditions had a higher anthocyanin content compared to exposed bunches which regularly experienced temperatures exceeding 35°C. This suggests the possibility of higher quality grapes in conditions experienced by berry three.

3.4.2.4 Thermal time accumulation (berry temperature)

Thermal accumulation between the east and west sides of the canopy in Robertson started to diverge after 09:00 when berries on the east side became exposed (Figure 38). This difference was greatest between 11:00 and 12:00 and diminished towards the end of the day when berries on the west side picked up thermal accumulation units as a result of direct sun exposure. At 16:00 a difference in thermal accumulation was observed, which if occurred right through the season, may cause differences in grape composition between the east and west sides of the canopy.

Thermal accumulation for the day cycles in Stellenbosch showed a similar trend between the east and west sides until around 13:00. Towards the end of the day there was no difference in the thermal accumulation between the east and west facing bunches (Figure 39). This may have been a result of the temperature suppressing effect of the south westerly wind in the afternoon, specifically on bunches on the east side that were shaded. The thinness of the canopy and the consequent exposure of bunches right through the day may also have reduced the difference in temperature accumulation between bunches on the two sides of the canopy.

There are thermal accumulation indices which have been adapted for the prediction of sugar accumulation in berries during ripening using weather station data or land surface temperatures (R. Zorer, personal communication). Figure 60 illustrates the difference in thermal accumulation between berries and the corresponding accumulation of ambient temperatures. It was observed that berry temperatures for day cycles on the east and west sides of the canopy accumulated higher temperatures than the weather station, which suggests the risk of using air temperature to predict berry ripening and emphasizes the importance or need for the development of bunch and berry temperature models validation in the field.

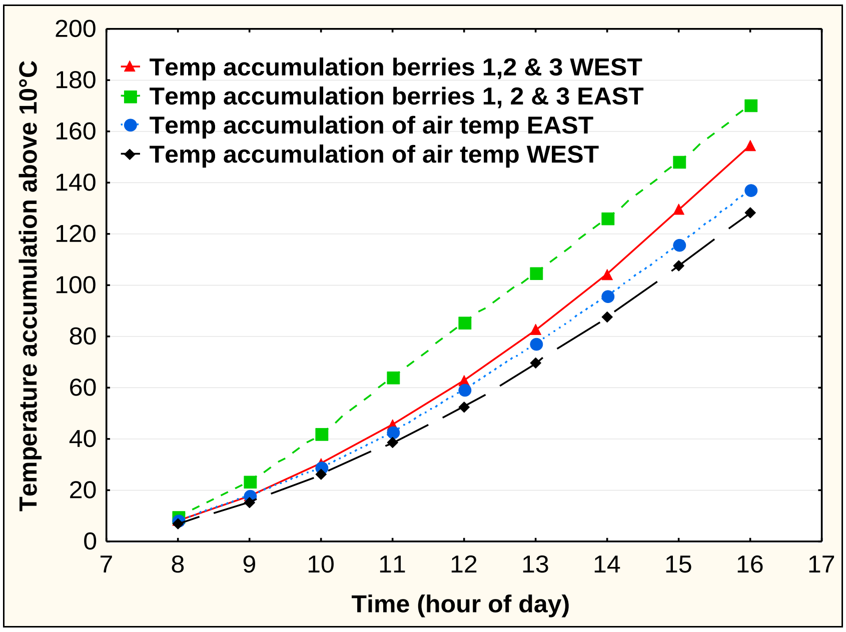


Figure 60 Mean hourly air (weather station) and berry thermal accumulation above 10°C for berries situated on the east and west sides of the canopy in Robertson. Berry thermal accumulation is illustrated as the mean of the surface, under skin and pulp temperature accumulation of berries one, two and three for day cycles one to six. The hourly values for the thermocouples in the berries were calculated as an average of the 60 minute values.

Thermal accumulation is a useful method to evaluate overall temperature differences, such as between the east and west sides, but fails to illustrate the detail which may be physiologically important. Detail such as observed in Stellenbosch on day cycle H in the lower ripening zone on the east side where the temperature for berry two was above 35°C for four hours (Addendum A, Figure 77g) and on day cycle I when temperatures were above 40°C for 2 hours (Addendum A, Figure 79g). Kliewer & Torres (1972) observed a complete inhibition of berry coloration in Tokay grapes when temperatures were 35°C under controlled conditions. Lower temperatures of ca. 20°C are believed to enhance pigmentation and maintain acid levels compared to temperatures around 30°C (Buttrose *et al.*, 1971). It appears that lower temperatures such as those experienced by berry three are more conducive to better quality. However, it must also be noted that many of the studies on the effect of temperature on berry composition are performed under controlled conditions, where a single temperature is set for the day (Buttrose *et al.*, 1971), which is not observed under natural conditions.

Through the season (Stellenbosch)

The thermocouples (TC's) installed permanently for just under two months demonstrated a tendency for higher thermal accumulation for bunches on the east side (Figure 40). This may have been a result of the exposure of east bunches coinciding with the fast increasing ambient temperatures during the morning, whereas bunches on the west side were exposed when ambient temperatures were decreasing due to the south westerly wind. The greatest variability was observed amongst TC's within a bunch, specifically the east lower bunch which was considerably exposed (Figure 61). Thermocouples 7 and 8 situated at the top of the bunch showed a higher temperature accumulation than TC's 5 and 6 located on the lower section of the bunch. Due to its structure, berries situated at the top of the bunch are exposed to higher temperatures and thus experience sunburn, which is seen in the berries located near TC's 7 and 8 (Figure 61). Berries on the bottom of the bunch appear shaded from the overhanging top section. A visual illustration of the variability within this bunch is demonstrated in the pie charts below (Figure 62) as well as in the thermal image (Addendum A, Figure 76a) with the top of the bunch showing the 'hotspot' and cooler temperatures are observed lower down. Variability is shown statistically with increasing standard deviations occurring from around 09:00 to 13:00

(Addendum A, Figure 76f). The top sections of bunches in the lower ripening zone are more exposed and for longer periods as a result of a lack of upper canopy protection due to the downward positioning of the shoots. The large differences in thermal accumulation amongst berries within a bunch emphasize the variability observed in a bunch and the consequent importance of TC positioning. The lower and upper sections of the lower east bunch appeared to be the extreme portions and possibly not a representation of the entire bunch. The upper east bunch showed much less variability in thermal accumulation between TC's through the season (Figure 40). A shorter period of higher variability was observed through the day (Addendum A, Figure 75f) as a result of the shorter exposure time, which is illustrated by the radiation sensor (Addendum A, Figure 75c). The architecture of the canopy that surrounded the bunch prevented longer exposure to direct radiation (Addendum A, Figure 75a) as was observed with the lower bunch. Furthermore, the flatter structure of the bunch in the upper east ripening zone (Figure 63) may have contributed to the reduced variability between TC's. Further study is needed on the effects of bunch morphology (berry size, compactness, bunch form) on bunch thermal properties, as this may differ considerably between cultivars.

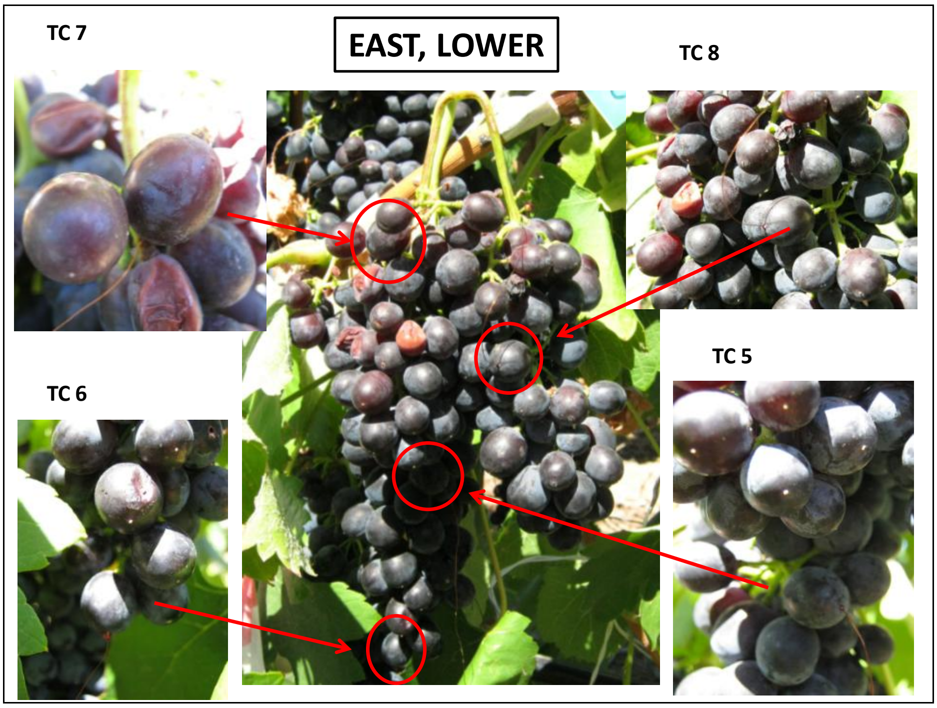


Figure 61 Permanent thermocouple positions (TC 5-8) for the lower, east bunch. Day cycles C and H were performed on this bunch.

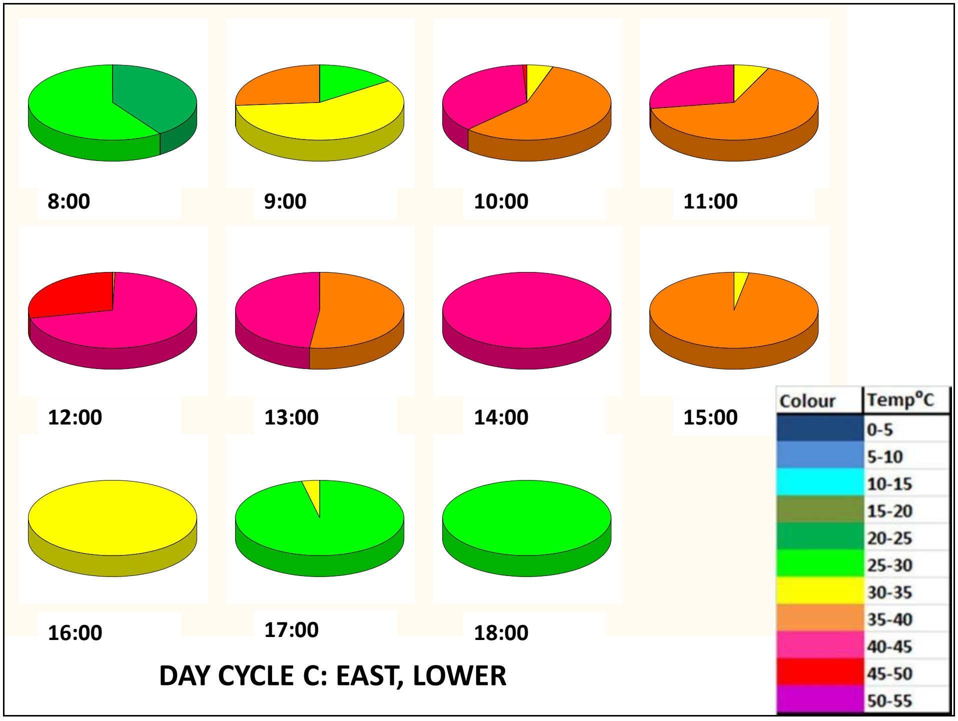


Figure 62 Diurnal bunch surface temperature distibution of pixel temperature values on day cycle C (east, lower) in Stellenbosch.

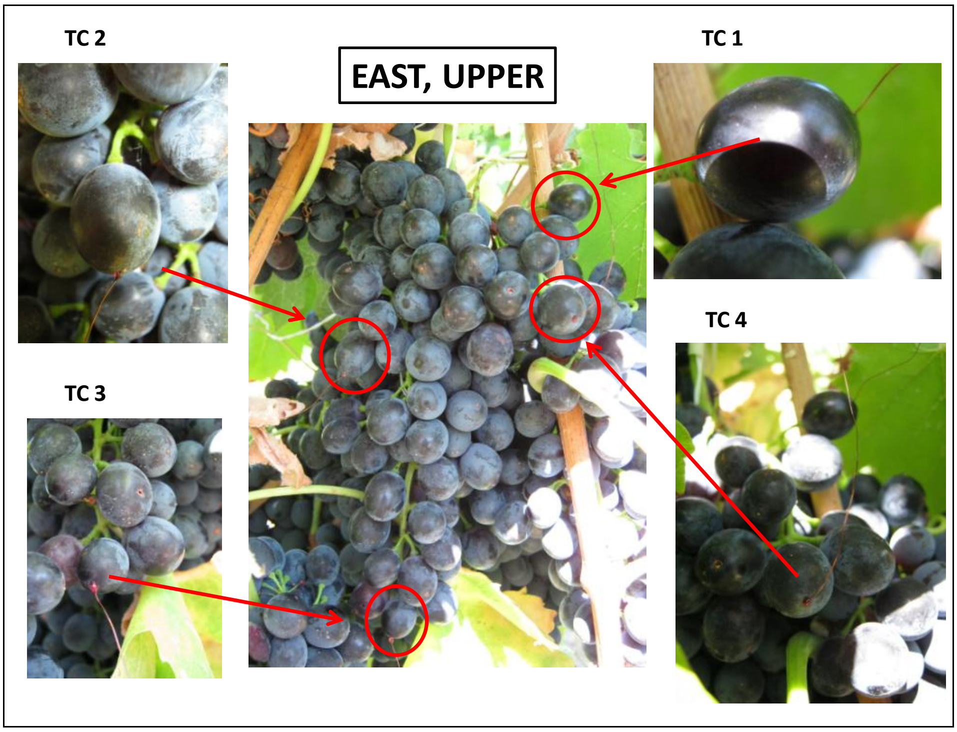
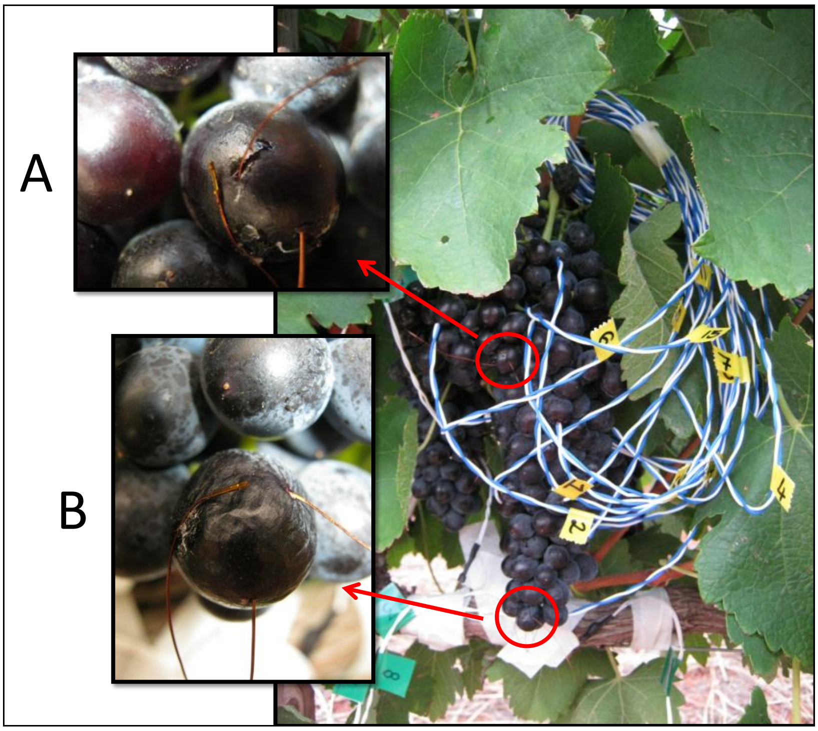


Figure 63 Permanent thermocouple positions (TC 1-4) for the upper, east bunch. Day cycles B and F were performed on this bunch.

3.4.2.5 *Within-berry temperature*

According to the hourly data no notable differences were observed in the temperatures of the surface, under the skin and in the pulp of berries one and two (on the visible side of the bunch) or three (on the back side of the bunch) in Robertson (Addendum A, Figure 68g-68h to Figure 73g-73h). The high resolution data of one minute intervals, produced situations contrary to this on certain berries and on certain day cycles. On day cycle one on the east side, during the period between 08:30 and 11:30, surface temperature for berry one appeared to be lower and more variable than pulp and under skin temperatures (Figure 64). Berry two showed little or no difference between surface, under skin and pulp temperatures throughout the day as well as notably less variability in the surface temperature compared to berry one. A slightly cooler surface on berry one may have been a result of air movement around the sensor which was slightly above the skin whereas for berry two, the full length of the sensor was in contact with the skin of the berry as a result of it being slightly less turgid than berry one (Figure 64). This illustrates the importance of sensor positioning/placement, which can affect results if not administered correctly. A further point of importance is the measurement interval. Larger intervals, such as the hourly berry temperature data, may not account for the quick changes observed with the one minute interval data. The sensors below the skin and in the pulp may have been buffered from the movement of air or wind around the berry. Although wind speed was below 1 m.s^{-1} during this period (Addendum A, Figure 68c), these thin thermocouples are more sensitive to temperature changes than the traditional thermocouples and may thus respond to turbulence around the berry. The timing however, is however interesting, as it coincided with a rapid increase in global radiation (Addendum A, Figure 68c), which means that the bunch was mostly likely exposed during this period and surface temperatures would be expected to be higher than under skin and pulp temperatures. Thermal imaging posed as a useful tool in determining whether such measurements as observed above, were anomalous to what was expected. At 10:00 the bunch surface temperature range was between 30°C and 45°C (Figure 65) whereas the berry surface temperature measured by the probe was below 30°C during this period (Figure 64), which further confirms that the TC on the skin was not only measuring contact skin temperature.



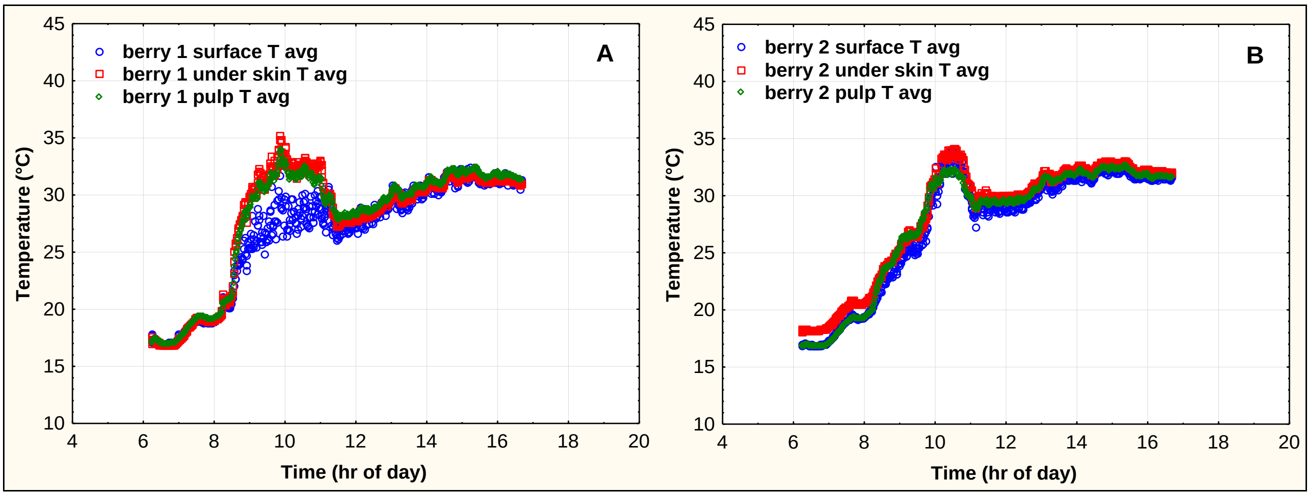


Figure 64 Temperatures on the surface of the skin, under the skin and in the pulp of berries one (A) and two (B) on day cycle one (east) in Robertson.

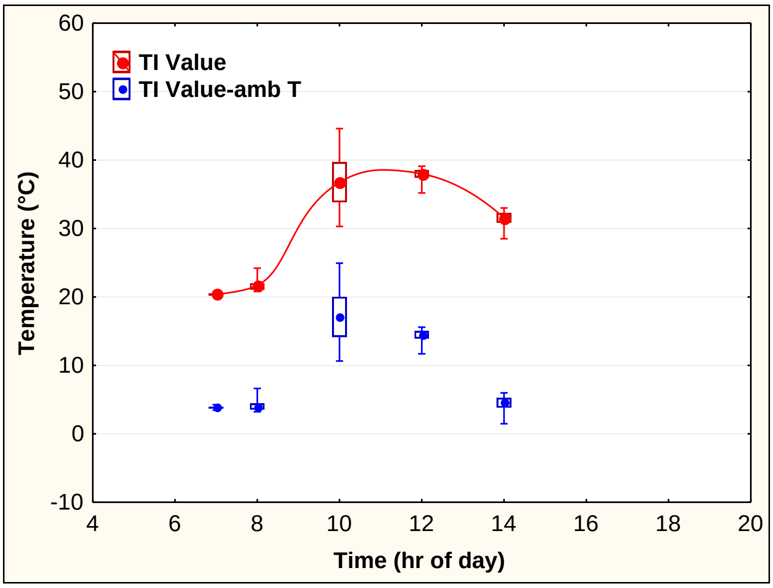
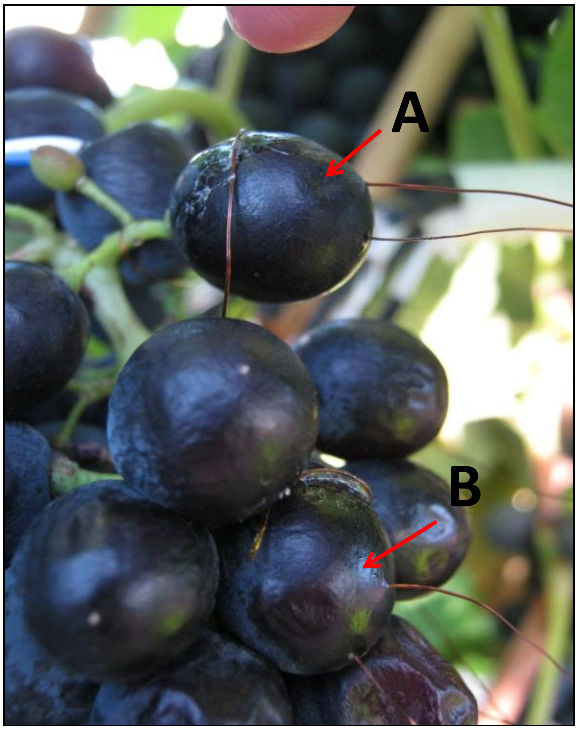


Figure 65 The diurnal mean, minimum and maximum (whiskers) and standard deviation (boxes) of the absolute bunch surface temperature values as well as the difference between bunch surface temperature and ambient temperature of the weather station for bunch one on day cycle one in Stellenbosch.

On day cycle four, on the east side, a similar situation occurred as in day cycle one (berry one) where surface temperature was lower than pulp and under skin temperatures, as well as more variable, between 09:00 and 10:00 (Figure 66). This coincided with time when the bunch was exposed to direct radiation (Addendum A, Figure 69c). Wind speed, however, increased to 2.0 $m.s^{-1}$ around 09:00 and may have been strong enough to influence the sensor on the skin, but not enough to influence temperature inside the berry (Addendum A, Figure 69d). The combined effects of turbulence around the berry (which was slightly separated from the rest of the bunch) and the direct radiation, may have contributed to the variability in surface temperature. Berry two situated just below berry one, but with more protection from surrounding berries, showed less prominent differences between the surface, under skin and pulp temperatures (Figure 66). Surface and under skin temperatures were slightly higher than the pulp between 09:00 and 11:30. The combined average of the three sensors in berry two around 10:00 was ca. 10°C higher than berry one (Addendum A, Figure 69f). The protected position of berry two and the direct skin contact with the surrounding berries, may have contributed to the high temperatures experienced in berry two as well as the lower variability in surface temperature compared to berry one. Berry one may also have been shaded by a leaf causing the lower temperatures. Movement or fluttering of the leaf could have contributed to the surface variability.



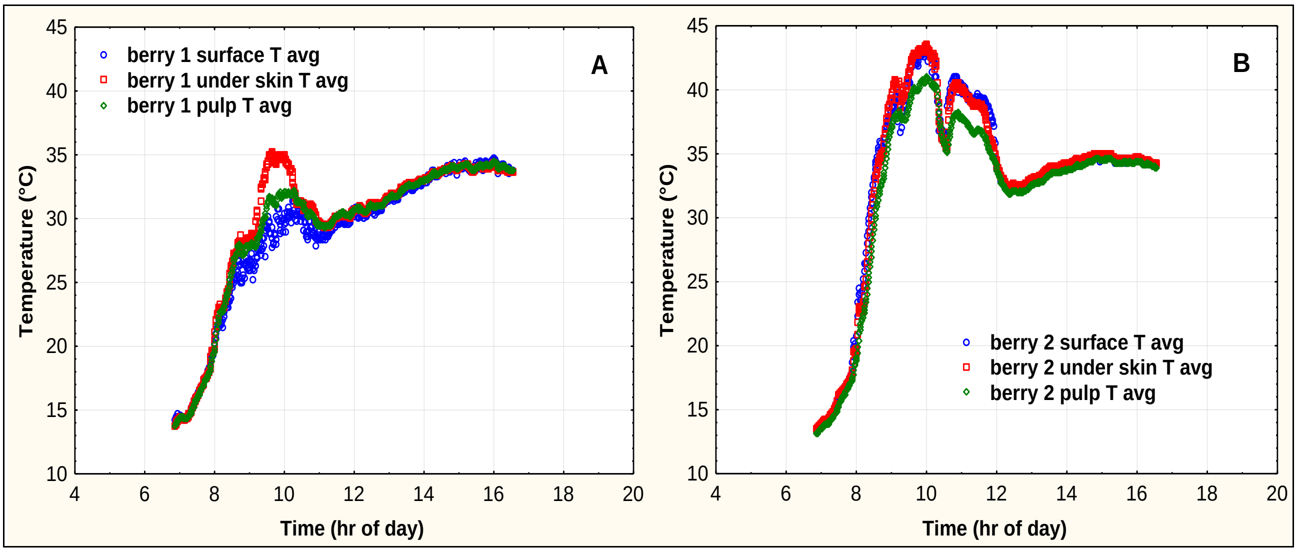


Figure 66 Temperatures on the surface of the skin, under the skin and in the pulp of berries one (A) and two (B) on day cycle four in Robertson on the east side.

On day cycle three on the west side of the canopy, differences between berry two and three were observed. The surface and under skin temperatures of berry two, situated at the bottom of the bunch, were higher than pulp temperature for the period 15:30 to 17:30 (Figure 67). This was as a result of the direct sun exposure received by the bunch in the afternoon period (Addendum A, Figure 72c). Berry three situated at the back of the bunch had slightly warmer temperatures in the pulp compared to the surface and under skin temperatures (from around 15:00), which may have been as a result of the relative placement of the pulp sensor in an exposed section of the berry as seen in the image (Figure 67). The sensors placed on the surface and under the skin, may have been placed on a more shaded part of the berry.

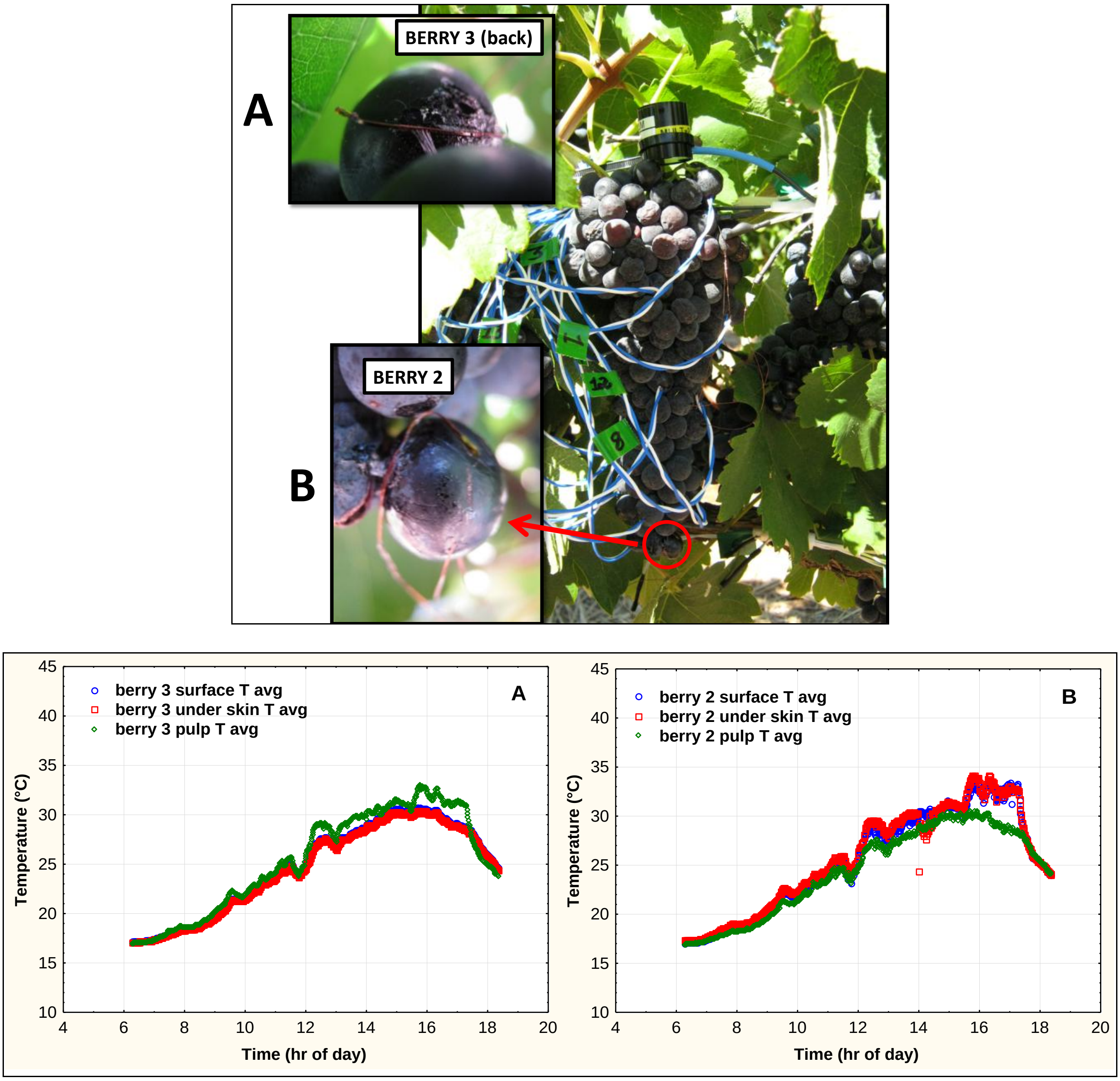


Figure 67 Temperatures on the surface of the skin, under the skin and in the pulp of berries two and three (measured by thermocouples) on day cycle three in Robertson on the west side.

3.5 Conclusions

Differences in macro- and mesoclimates were observed between Robertson and Stellenbosch as a result of the distance from the sea. Seasonal daily ambient temperatures in Robertson were higher than those in Stellenbosch. Stellenbosch reached peak temperatures around 12:00, after which it decreased. This coincided with the increase in wind speed from the southwest as well as an increase in relative humidity. Ambient temperatures in Robertson reached a peak in the late afternoon. These diurnal temperature trends in Robertson and Stellenbosch were also recognised in bunch and berry temperatures, specifically shaded berries. Bunch surface temperatures in Robertson reached higher temperatures (higher maximum and dominant class). In Stellenbosch bunch surface temperatures in the afternoon were lower compared to the morning temperatures, which coincided with the abovementioned sea breeze. The suppressing effect of the sea breeze may have also contributed to the reduced differences in thermal accumulation in berry temperature between the east and west sides in Stellenbosch.

The training system was found to have an impact on bunch surface and berry temperature. The Ballerina training system in Stellenbosch created a variable canopy which consisted of a high gap fraction that allowed for the filtering of light through the canopy. This caused double peaks (morning and afternoon) in canopy temperature, PAR and berry temperature, specifically for the berry situated at the back of the bunch on the upper, west side of the canopy. The overall bunch surface temperature increased above ambient temperature in the morning on the west side with no notable increase in variability. This overall increase in surface temperature of the visible side of the bunch may have been the effect of conduction through the bunch (i.e. berry to berry heat transfer), which was one of the mentioned components contributing to the energy balance of spherical fruits in a study by Smart & Sinclair (1976). The thin canopy in Stellenbosch may have contributed to the reduced differences in temperature accumulation between the east and west sides as well as the rapid increase in temperature of berries on the west side of the canopy. In a more uniform canopy, such as was observed in Robertson, bunches/berries on the east and west sides showed single peaks in radiation and temperature due to the higher number of leaf layers and shoot positioning.

With regard to the upper and lower ripening zones of the Ballerina system, only a single peak in canopy temperature and PAR was observed in the lower ripening zone, possibly due to a higher number of leaf layers through which the light had to travel. Slightly higher bunch surface temperatures and higher on-bunch temperature variability were observed in the lower ripening zone(s) when bunches were directly radiated as the sun approached solar noon. This could have been as a result of the absence of upper canopy protection of the lower bunches during this period, whereas bunches in the upper ripening zone were protected by the overhanging shoots as a result of no tipping/topping.

There was a tendency for bunch surface temperatures to be higher on the east side in Robertson and Stellenbosch, which is contrary to what many grape producers believe for a north-south row orientation. In Robertson, despite higher ambient temperatures in the afternoon when west-facing bunches were exposed to direct radiation, more temperature units were accumulated on the east side. This was due to the rapidly increasing berry and bunch surface temperatures in the morning on the east side that were maintained in the afternoon as a result of the increasing ambient temperatures. However, there was a higher occurrence of bunch surface temperatures above 40°C on the west side, albeit for a short period, thus increasing the risk of sunburn. However, this was not observed in Stellenbosch, which suggests that it could be site-specific. In Stellenbosch, the higher bunch surface and berry temperatures on the east side compared to the west, were as a result of the rapidly increasing ambient temperatures in the morning that cooled down towards the afternoon as a result of the sea breeze, also leading to a decrease in bunch surface and berry temperatures.

With regard to intra-berry temperatures, no notable differences were observed between the surface, under skin and pulp sections of the berry. This may have been as a result of the timing of measurements which were performed after véraison when the ability of the berry to transpire has reduced (Blanke & Leyhe, 1987; Ollat *et al.*, 2002). Differences in intra-berry temperatures may thus occur during the early stages of development. The small differences that were observed on rare occasions were due to the technicalities related to sensor placement.

In terms of spatial and diurnal variability observed in Robertson and Stellenbosch, an increase in variability occurred with an increase in direct radiation exposure of berries and bunches. Diffuse conditions may thus be more favourable with regard to less variability in grape composition within a bunch. High on-bunch variability in bunch surface temperature was observed for a mostly exposed bunch, where on one occasion, temperatures of 30-35°C to 50-55°C were observed at peak radiation. Such a large range in temperatures may have negative implications for grape berry composition. Large diurnal variability was observed in the morning in Stellenbosch as a result of the combined effect of increasing global radiation and rapidly increasing ambient temperatures. Such a rapid increase in bunch surface and berry temperatures may also affect certain components relating to berry quality, and it may also induce negative morphological effects such as sunburn. Variability between bunches on the same day in Robertson was as a result of the relative positioning of the bunches within the canopy. Bunches further out of the canopy or closer to the soil surface seem to experience higher temperatures and increased temperature variability.

3.6 References

Amerine, M.A. & Winkler, A.J., 1944. Composition and quality of musts and wines of California grapes. Hilgardia 15, 493-675.

Barbagallo, M., Guidoni, S. & Hunter, J., 2011. Berry size and qualitative characteristics of *Vitis vinifera* L. cv. Syrah. S Afr J Enol Vitic 32.

Bergqvist, J., Dokoozlian, N. & Ebisuda, N., 2001. Sunlight exposure and temperature effects on berry growth and composition of Cabernet Sauvignon and Grenache in the Central San Joaquin Valley of California. Am J Enol Vitic 52 (1), 1-7.

Blanke, M.M. & Leyhe, A., 1987. Stomatal activity of the grape berry cv. Riesling, Müller-Thurgau and Ehrenfelser. J Plant Physiol 127 (5), 451-460.

Bonnardot, V., Carey, V., Planchon, O. & Cautenet, S., 2001. Sea breeze mechanism and observations of its effects in the Stellenbosch wine producing area. Wineland 107-113.

Buttrose, M., Hale, C. & Kliewer, W.M., 1971. Effect of temperature on the composition of'Cabernet Sauvignon'berries. Am J Enol Vitic 22 (2), 71-75.

Gladstones, J., 1992. Viticulture and environment. Winetitles, Adelaide.

Grant, O.M., Tronina, Ł., Jones, H.G. & Chaves, M.M., 2007. Exploring thermal imaging variables for the detection of stress responses in grapevine under different irrigation regimes. J Exp Bot 58 (4), 815-825.

Haselgrove, L., Botting, D., Heeswijck, R., Høj, P., Dry, P., Ford, C. & Land, P., 2000. Canopy microclimate and berry composition: The effect of bunch exposure on the phenolic composition of Vitis vinifera L cv. Shiraz grape berries. Aust J Grape Wine Res 6 (2), 141-149.

Hunter, J., Archer, E. & Volschenk, C.G., 2010. Vineyard management for environment valorisation. In: Proc. Eighth International Terrior Conference, Soave, Italy. pp. 3-15.

Jones, H.G., 1999. Use of infrared thermometry for estimation of stomatal conductance as a possible aid to irrigation scheduling. Agric For Meteorol 95 (3), 139-149.

Jones, H.G., 2004. Application of thermal imaging and infrared sensing in plant physiology and ecophysiology. Adv Bot Res 41, 107-163.

Kliewer, W.M. & Torres, R.E., 1972. Effect of controlled day and night temperatures on grape coloration. Am J Enol Vitic 23 (2), 71-77.

Melo, M.S., 2011. Berry size implications for phenolic composition and wine quality of Vitis vinifera L. cv. Syrah. thesis, University of Applied Sciences, Geisenheim, Germany.

Moncur, M., Rattigan, K., Mackenzie, D. & Mc Intyre, G., 1989. Base temperatures for budbreak and leaf appearance of grapevines. Am J Enol Vitic 40 (1), 21-26.

Mullins, M.G., Bouquet, A. & Williams, L.E., 1992. Biology of the grapevine. Press Syndicate, University of Cambridge.

Ollat, N., Diakou-Verdin, P., Carde, J., Barrieu, F., Gaudillere, J.P. & Moing, A., 2002. Grape berry development: a review. J Int Sci Vigne Vin 36.

Smart, R.E., 1985. Principles of grapevine canopy microclimate manipulation with implications for yield and quality. A review. Am J Enol Vitic 36 (3), 230-239.

Smart, R.E. & Sinclair, T.R., 1976. Solar heating of grape berries and other spherical fruits. Agric Meteorol 17 (4), 241-259.

Van Zyl, J., 1986. Canopy temperature as a water stress indicator in vines. S Afr J Enol Vitic 7 (2), 53-60.

Van Zyl, J. & Van Huyssteen, L., 1980. Comparative studies on wine grapes on different trellising systems: II. Microclimatic studies, grape composition, and wine quality. S Afr J Enol Vitic 1 (1), 15.

Williams, D., L E, W., Barnett, W., Kelley, K. & McKenry, M., 1985. Validation of a model for the growth and development of the Thompson Seedless grapevine. I. Vegetative growth and fruit yield. Am J Enol Vitic 36 (4), 275-282.

Williams, L., 1987. The effect of cyanamide on budbreak and vine development of Thompson Seedless grapevines in the San Joaquin Valley of California. Vitis 26, 107-113.

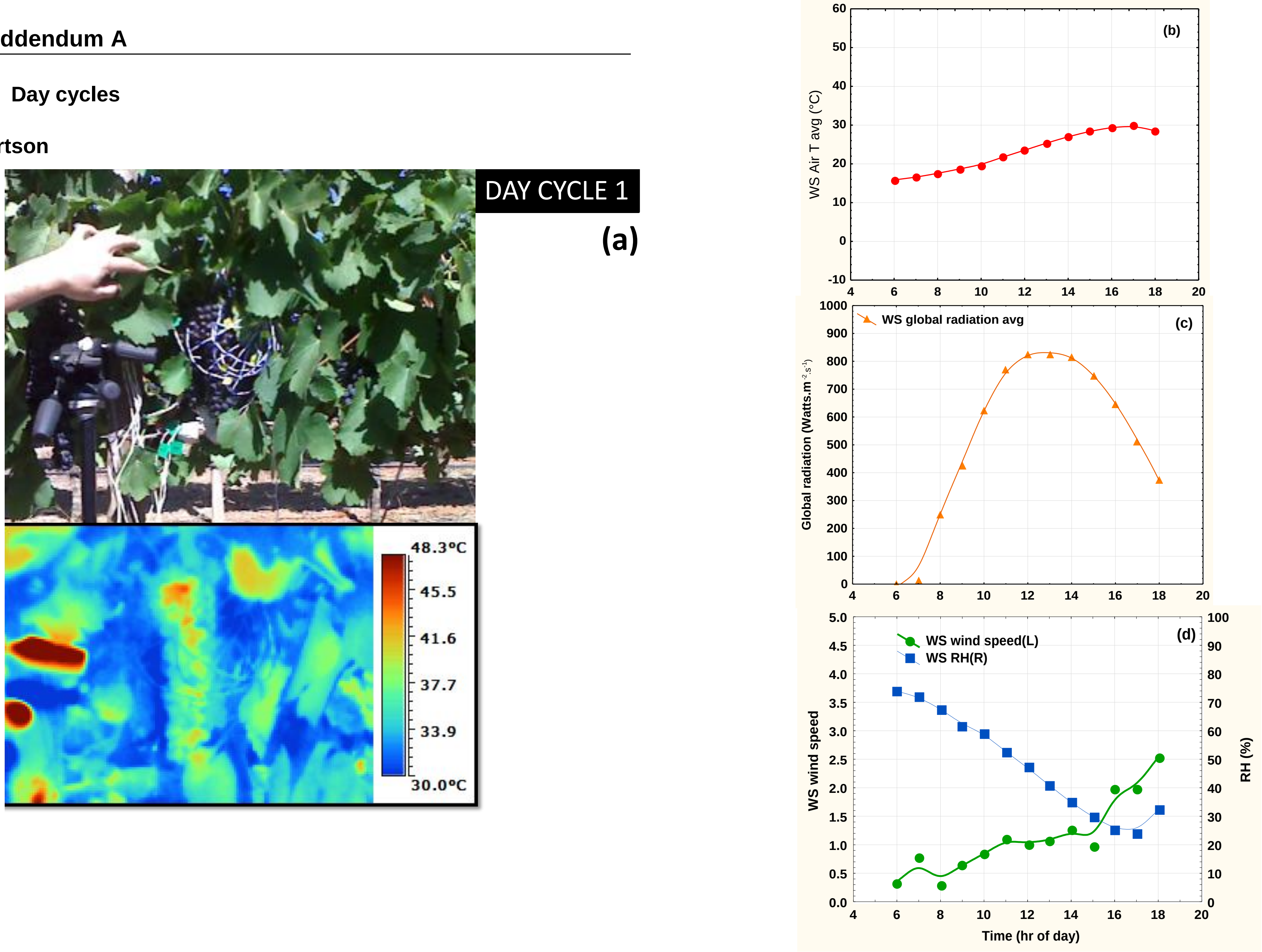
Winkler, A.J., 1965. General viticulture. Univ of California Press, University of California, Berkeley.

Zorer, R., Rocchini, D., Delucchi, L., Zottele, F., Meggio, F. & Neteler, M., 2011. Use of multi-annual modis land surface temperature data for the characterization of the heat requirements for grapevine varieties. In: Proc. 6th International Workshop on the Analysis of Multi-temporal Remote Sensing Images (Multi-Temp), pp. 225-228.

3.7 Addendum A

3.7.1 Day cycles

Robertson



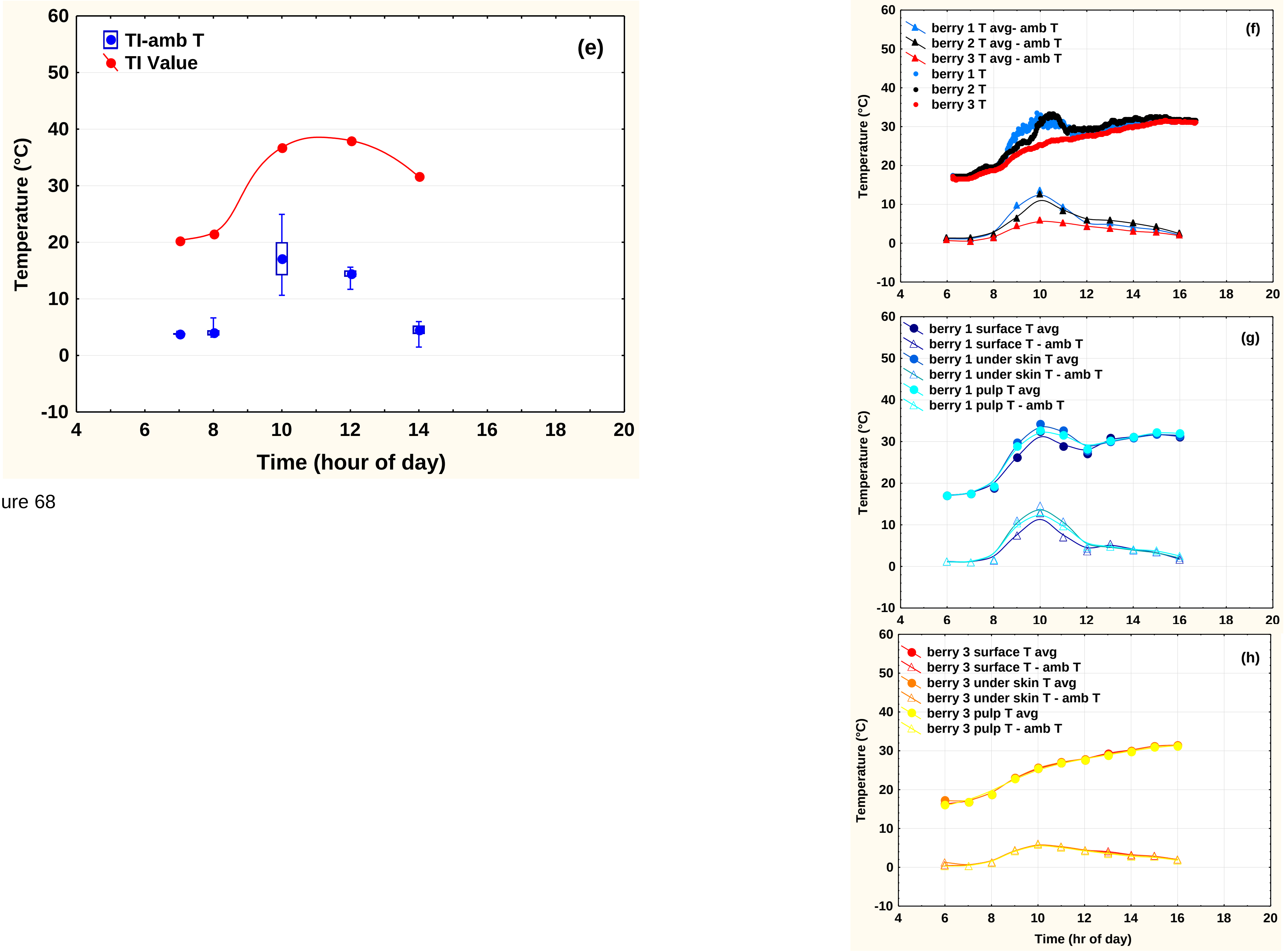
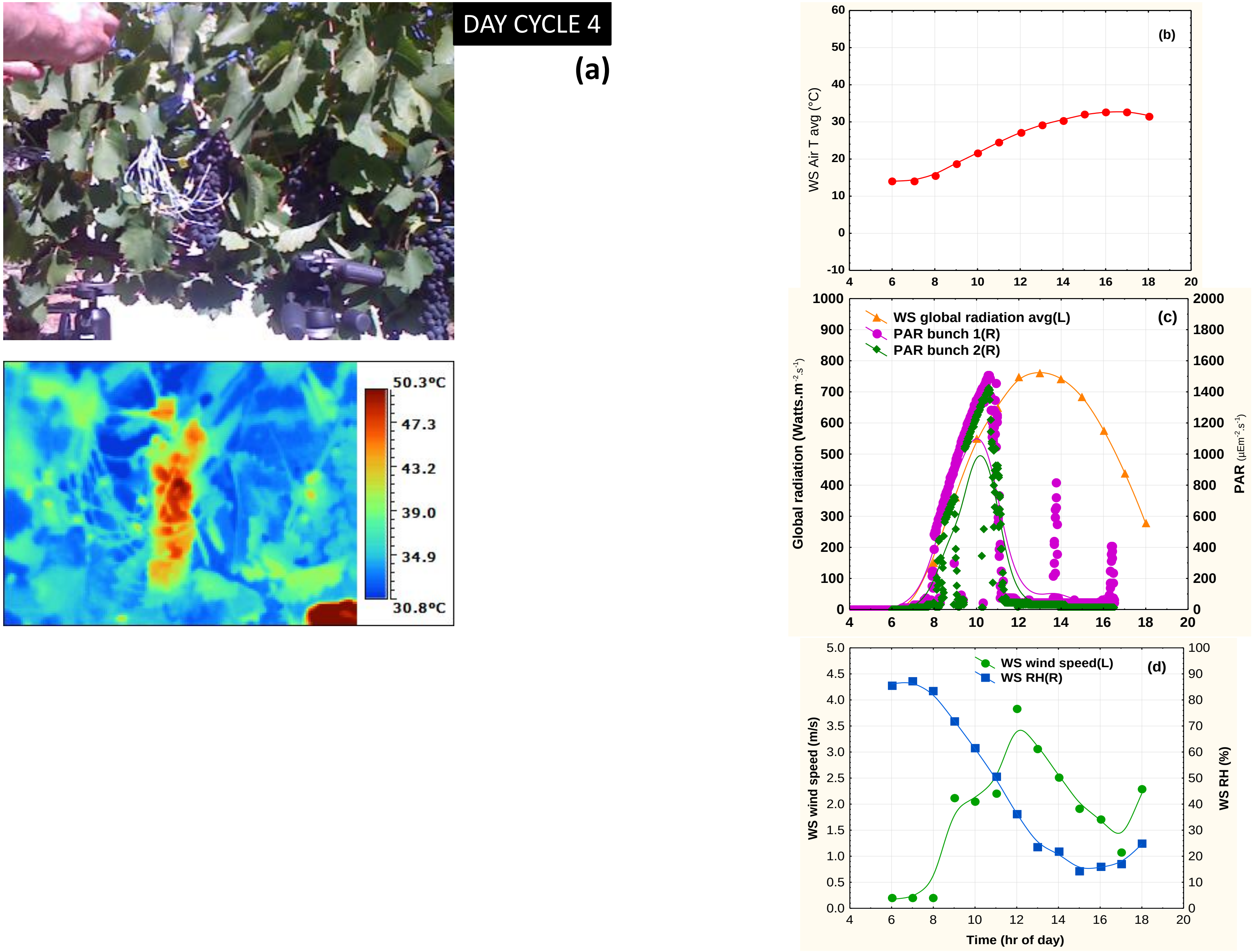

(e)
TI-amb T
TI Value
Temperature (°C)
Time (hour of day)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
(f)
berry 1 T avg- amb T
berry 2 T avg - amb T
berry 3 T avg - amb T
berry 1 T
berry 2 T
berry 3 T
(g)
berry 1 surface T avg
berry 1 surface T - amb T
berry 1 under skin T avg
berry 1 under skin T - amb T
berry 1 pulp T avg
berry 1 pulp T - amb T
(h)
berry 3 surface T avg
berry 3 surface T - amb T
berry 3 under skin T avg
berry 3 under skin T - amb T
berry 3 pulp T avg
berry 3 pulp T - amb T
Time (hr of day)

Figure 68


DAY CYCLE 4
(a)
50.3°C
47.3
43.2
39.0
34.9
30.8°C
(b)
WS Air T avg (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
(c)
WS global radiation avg(L)
PAR bunch 1(R)
PAR bunch 2(R)
Global radiation (Watts.m-2.s-1)
1000
900
800
700
600
500
400
300
200
100
0
PAR (μEm-2.s-1)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
(d)
WS wind speed(L)
WS RH(R)
WS wind speed (m/s)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
WS RH (%)
100
90
80
70
60
50
40
30
20
10
0
Time (hr of day)

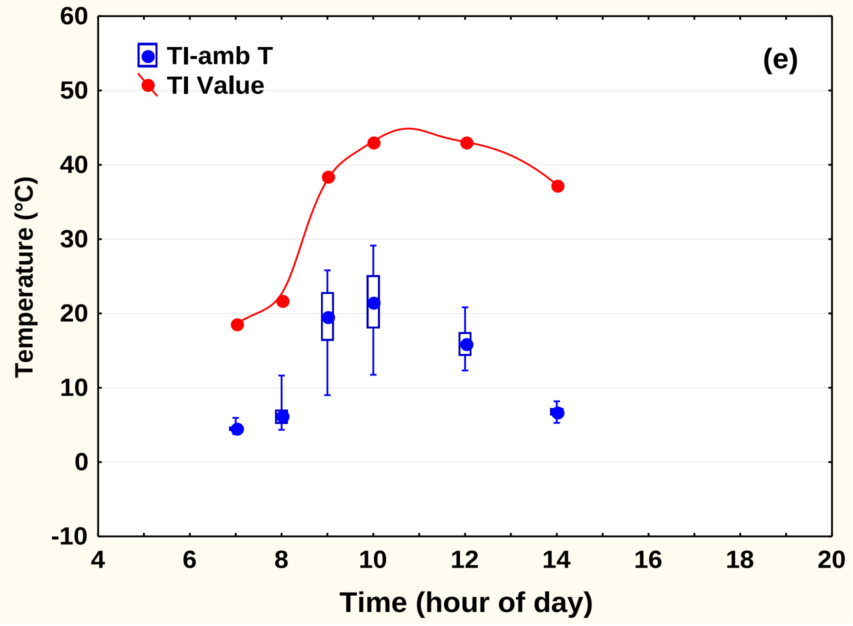
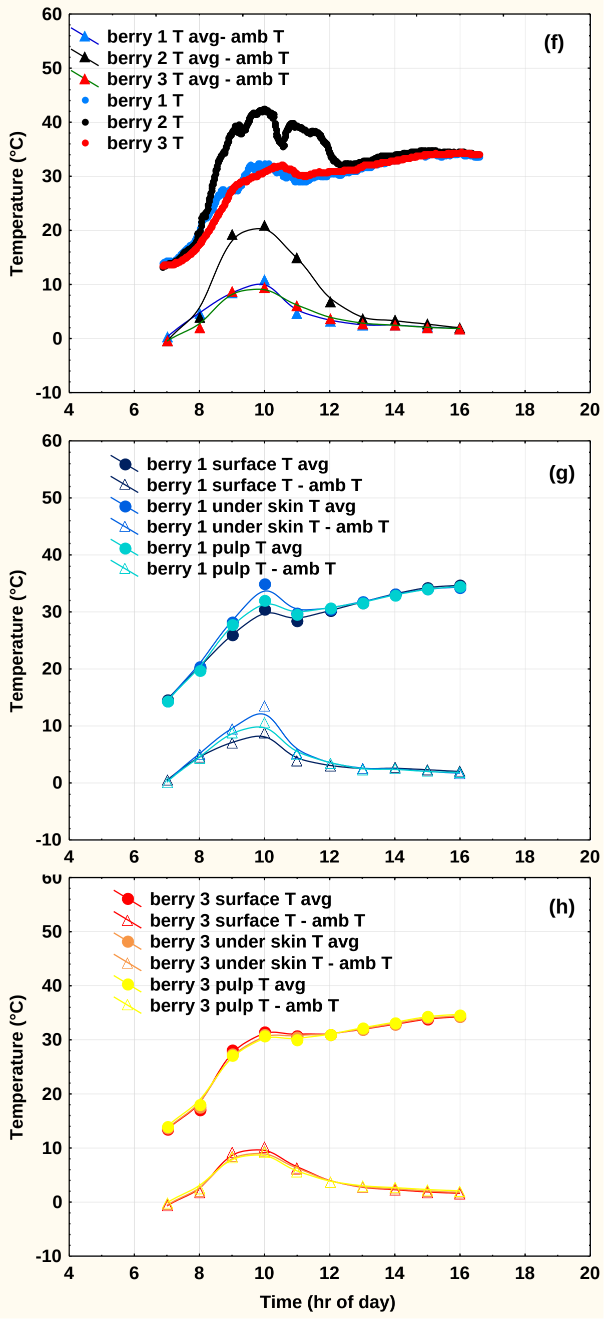
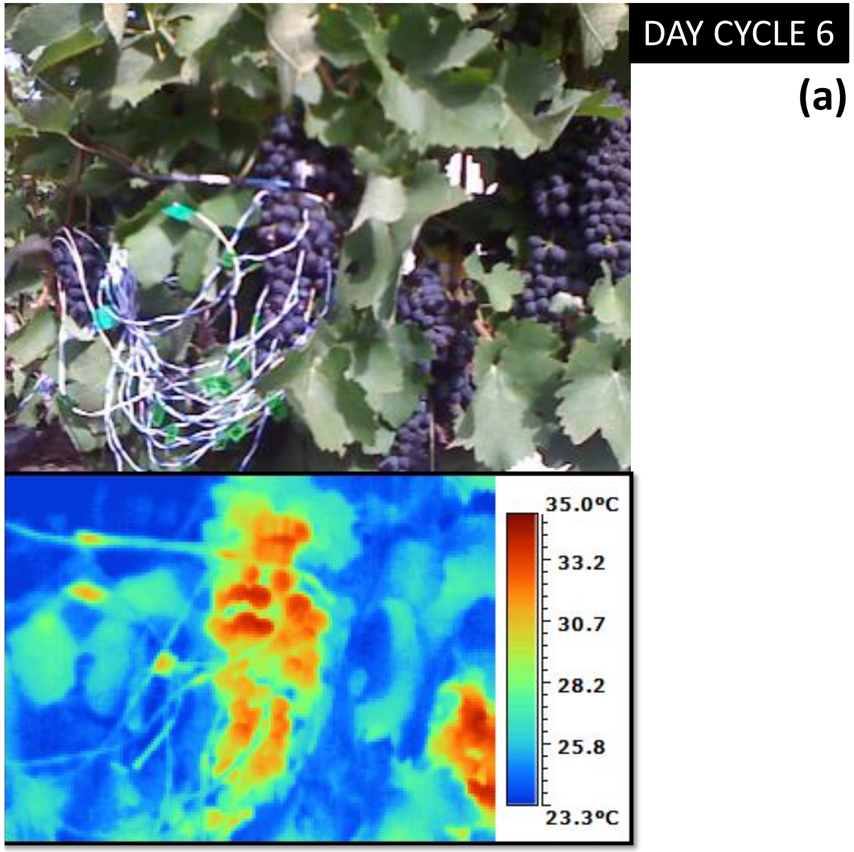
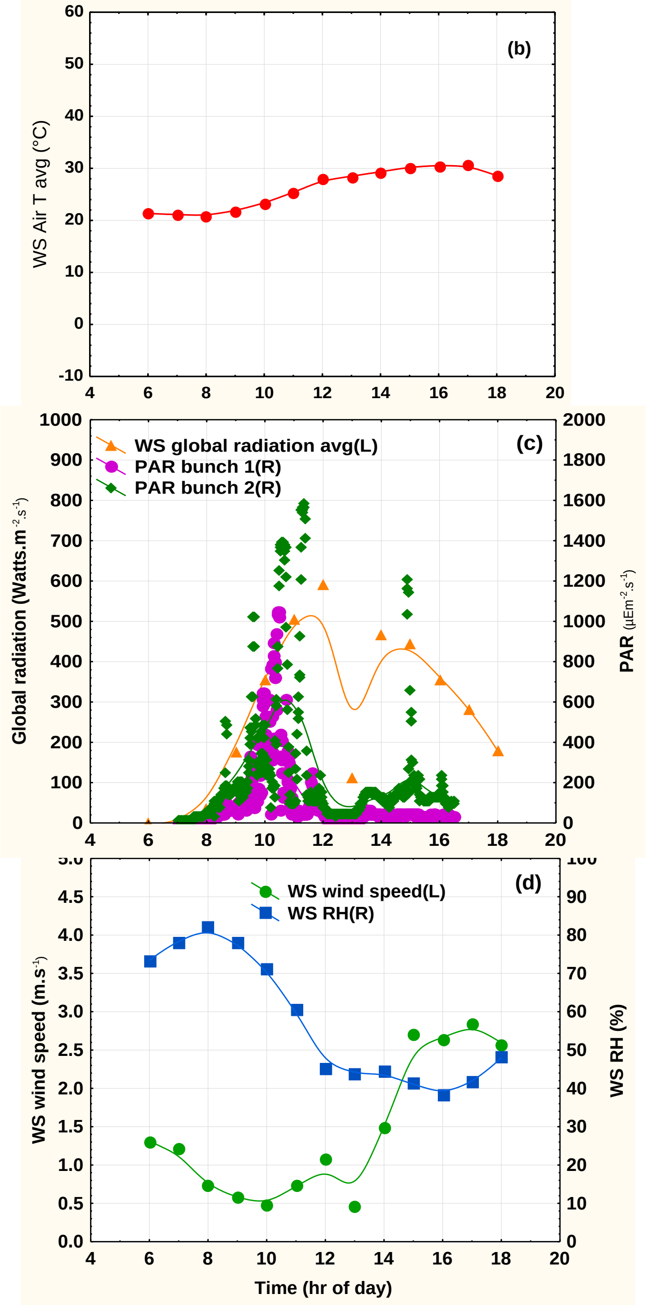

TI-amb T
TI Value
(e)
Temperature (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
Time (hour of day)

Figure 69


berry 1 T avg- amb T
berry 2 T avg - amb T
berry 3 T avg - amb T
berry 1 T
berry 2 T
berry 3 T
(f)
Temperature (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
berry 1 surface T avg
berry 1 surface T - amb T
berry 1 under skin T avg
berry 1 under skin T - amb T
berry 1 pulp T avg
berry 1 pulp T - amb T
(g)
Temperature (°C)
berry 3 surface T avg
berry 3 surface T - amb T
berry 3 under skin T avg
berry 3 under skin T - amb T
berry 3 pulp T avg
berry 3 pulp T - amb T
(h)
Temperature (°C)
Time (hr of day)


DAY CYCLE 6
(a)
35.0°C
33.2
30.7
28.2
25.8
23.3°C


(b)
WS Air T avg (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
(c)
WS global radiation avg(L)
PAR bunch 1(R)
PAR bunch 2(R)
Global radiation (Watts.m-2.s-1)
PAR (μEm-2.s-1)
1000
900
800
700
600
500
400
300
200
100
0
2000
1800
1600
1400
1200
1000
800
600
400
200
0
(d)
WS wind speed(L)
WS RH(R)
WS wind speed (m.s-1)
WS RH (%)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
100
90
80
70
60
50
40
30
20
10
0
Time (hr of day)

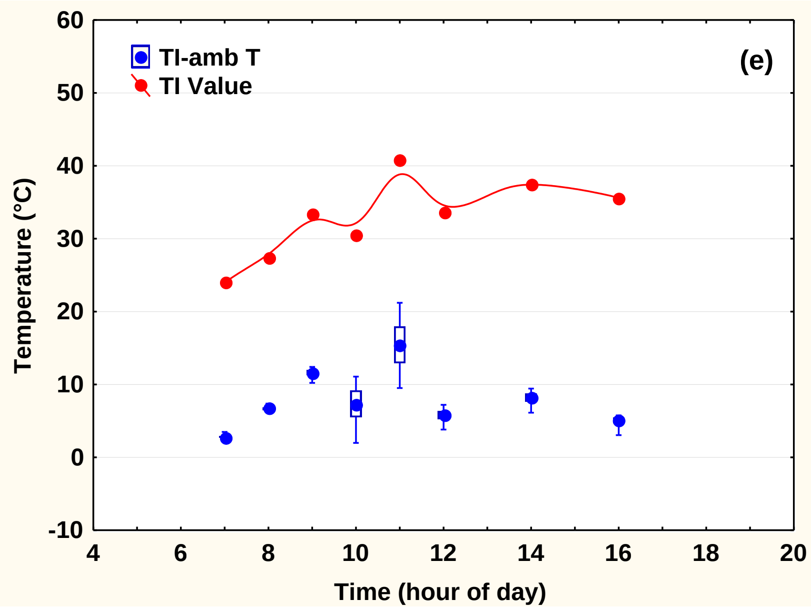
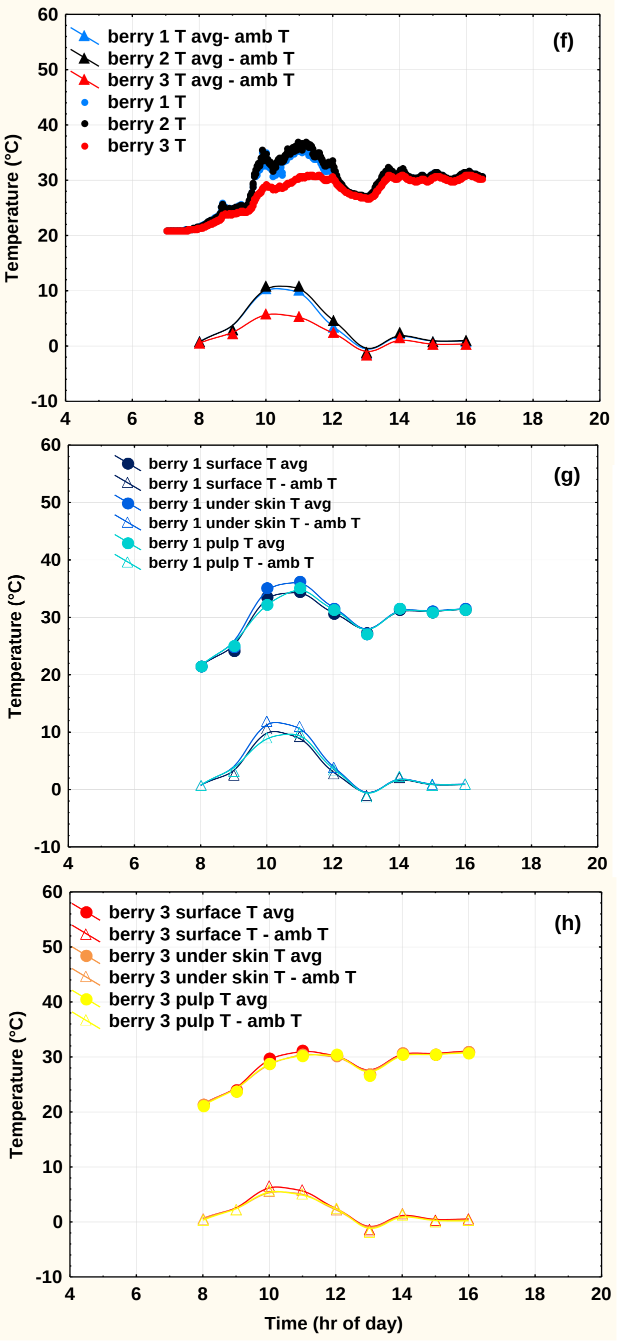
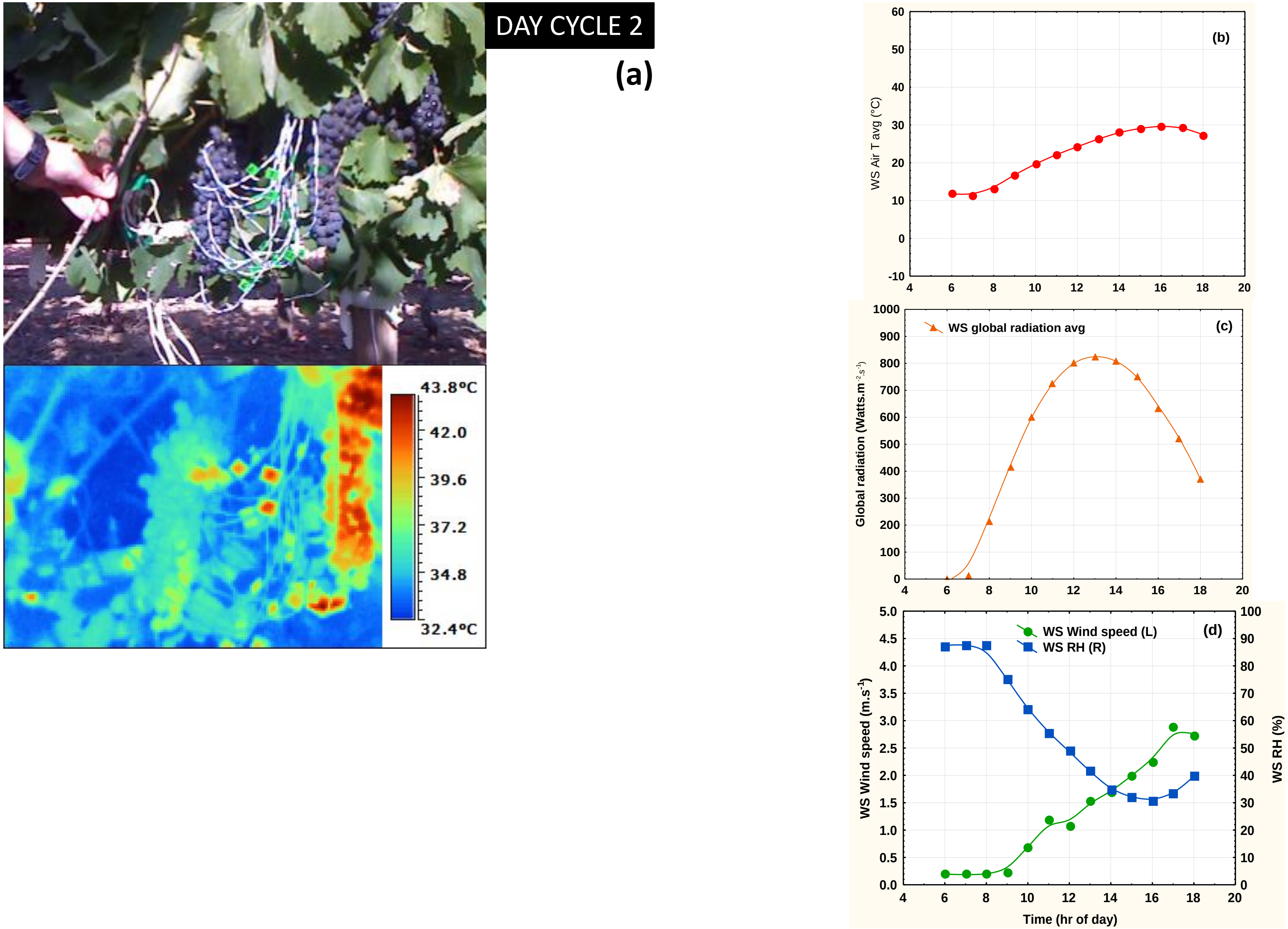

60
50
40
30
20
10
0
-10
Temperature (°C)
TI-amb T
TI Value
(e)
4
6
8
10
12
14
16
18
20
Time (hour of day)

Figure 70


(f)
berry 1 T avg- amb T
berry 2 T avg - amb T
berry 3 T avg - amb T
berry 1 T
berry 2 T
berry 3 T
Temperature (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
(g)
berry 1 surface T avg
berry 1 surface T - amb T
berry 1 under skin T avg
berry 1 under skin T - amb T
berry 1 pulp T avg
berry 1 pulp T - amb T
Temperature (°C)
(h)
berry 3 surface T avg
berry 3 surface T - amb T
berry 3 under skin T avg
berry 3 under skin T - amb T
berry 3 pulp T avg
berry 3 pulp T - amb T
Temperature (°C)
Time (hr of day)


DAY CYCLE 2
(a)
43.8°C
42.0
39.6
37.2
34.8
32.4°C
(b)
WS Air T avg (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
WS global radiation avg
(c)
Global radiation (Watts.m^{-2}.s^{-1})
1000
900
800
700
600
500
400
300
200
100
0
WS Wind speed (L)
WS RH (R)
(d)
WS Wind speed (m.s^{-1})
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
WS RH (%)
100
90
80
70
60
50
40
30
20
10
0
Time (hr of day)

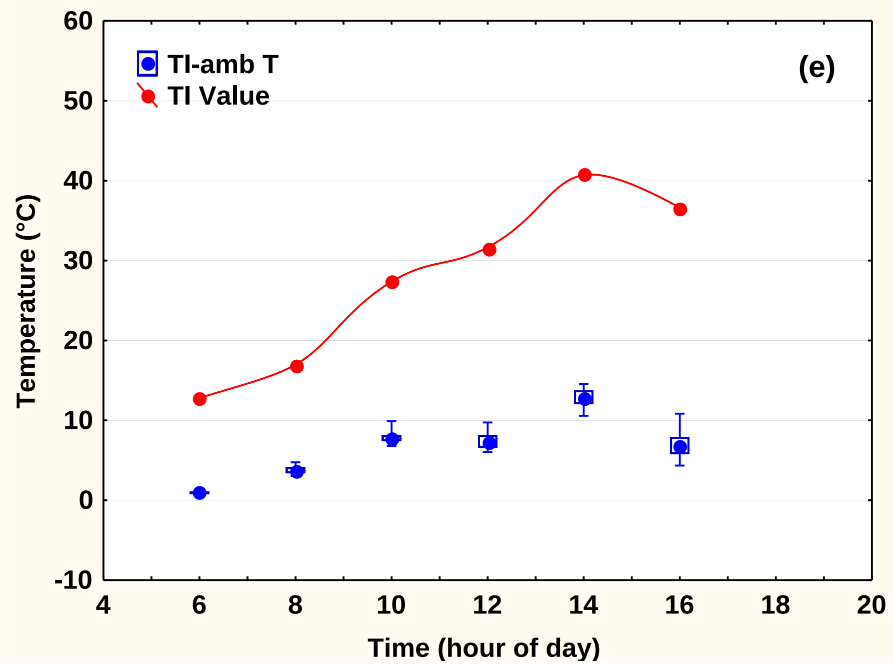
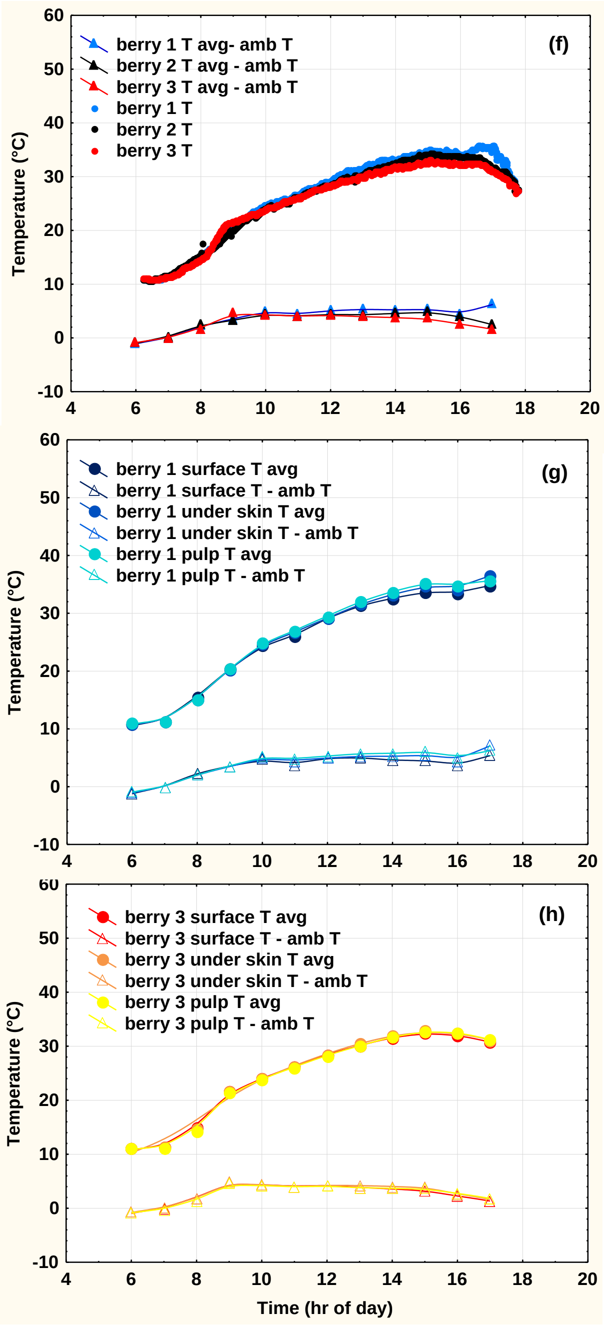
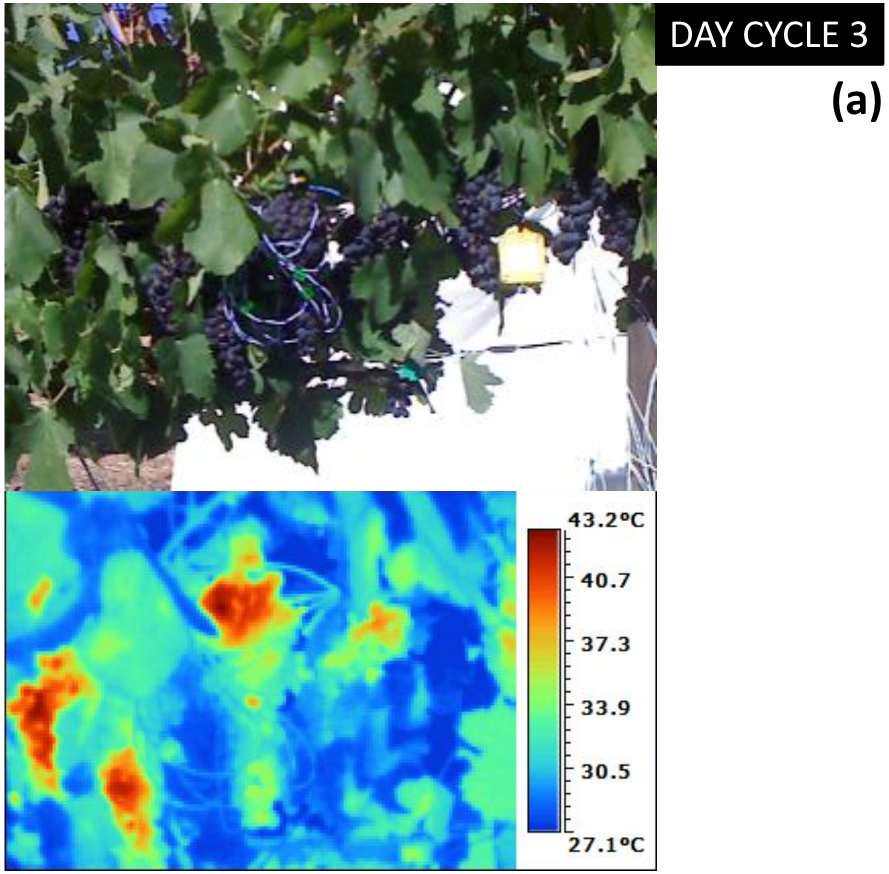
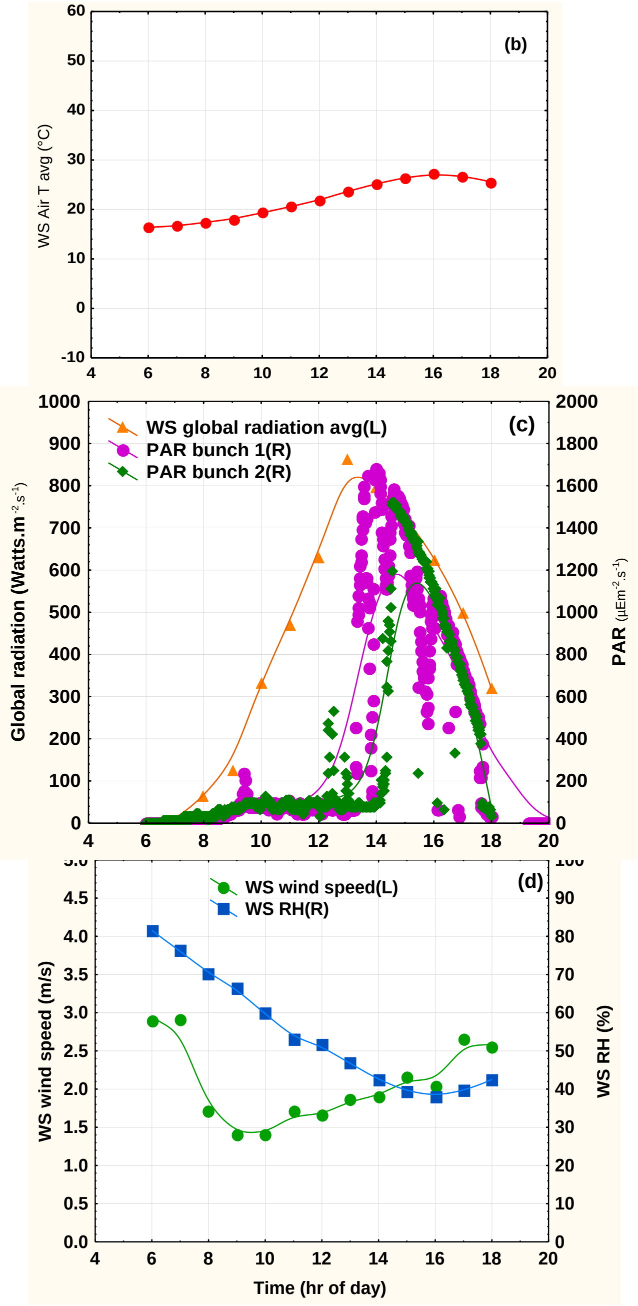

TI-amb T
TI Value
(e)
Temperature (°C)
Time (hour of day)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20

Figure 71


(f)
berry 1 T avg- amb T
berry 2 T avg - amb T
berry 3 T avg - amb T
berry 1 T
berry 2 T
berry 3 T
Temperature (°C)
(g)
berry 1 surface T avg
berry 1 surface T - amb T
berry 1 under skin T avg
berry 1 under skin T - amb T
berry 1 pulp T avg
berry 1 pulp T - amb T
Temperature (°C)
(h)
berry 3 surface T avg
berry 3 surface T - amb T
berry 3 under skin T avg
berry 3 under skin T - amb T
berry 3 pulp T avg
berry 3 pulp T - amb T
Temperature (°C)
Time (hr of day)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20


DAY CYCLE 3
(a)
43.2°C
40.7
37.3
33.9
30.5
27.1°C


(b)
WS Air T avg (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
(c)
WS global radiation avg(L)
PAR bunch 1(R)
PAR bunch 2(R)
Global radiation (Watts.m⁻².s⁻¹)
1000
900
800
700
600
500
400
300
200
100
0
PAR (μEm⁻².s⁻¹)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
4
6
8
10
12
14
16
18
20
(d)
WS wind speed(L)
WS RH(R)
WS wind speed (m/s)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
WS RH (%)
100
90
80
70
60
50
40
30
20
10
0
4
6
8
10
12
14
16
18
20
Time (hr of day)

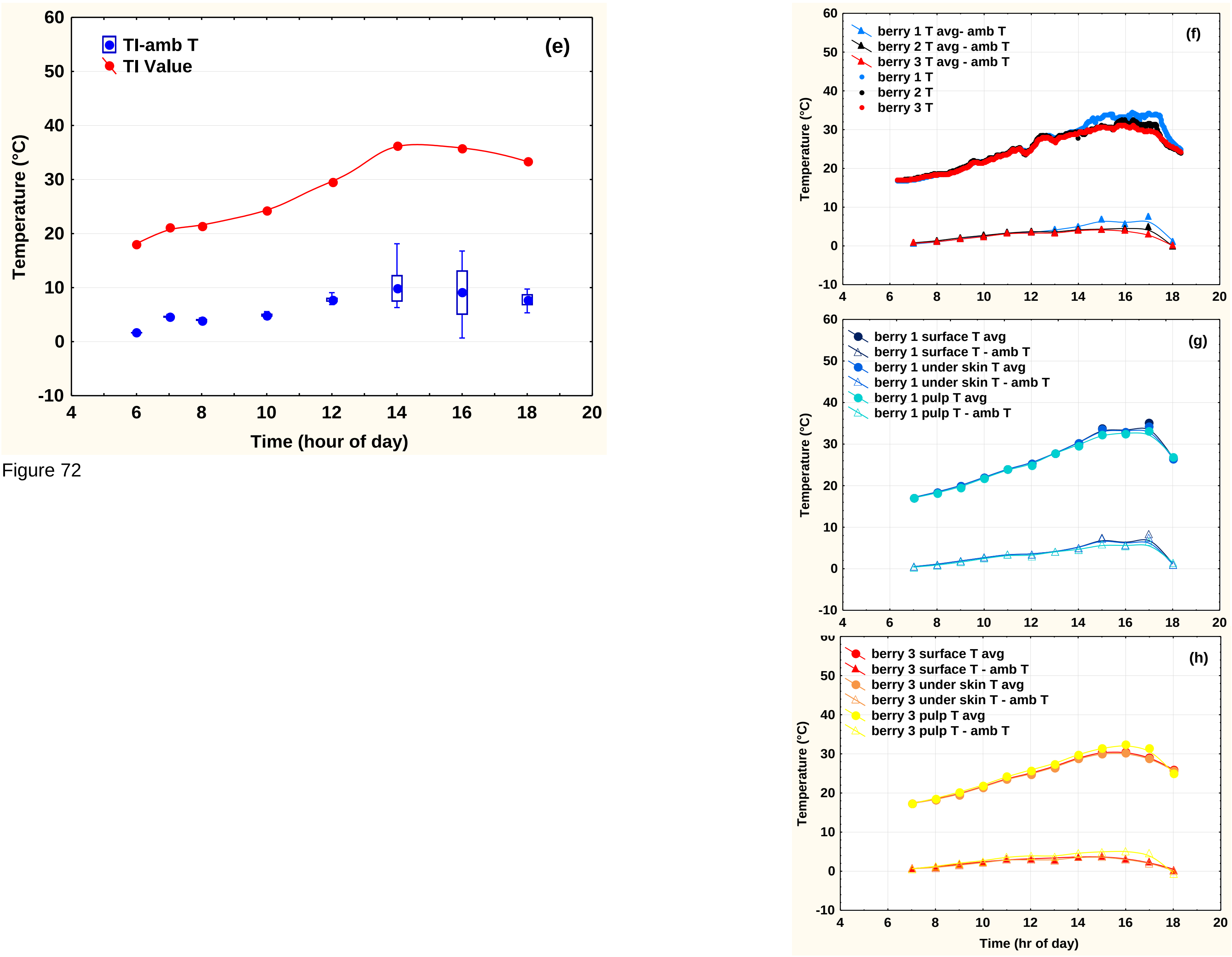
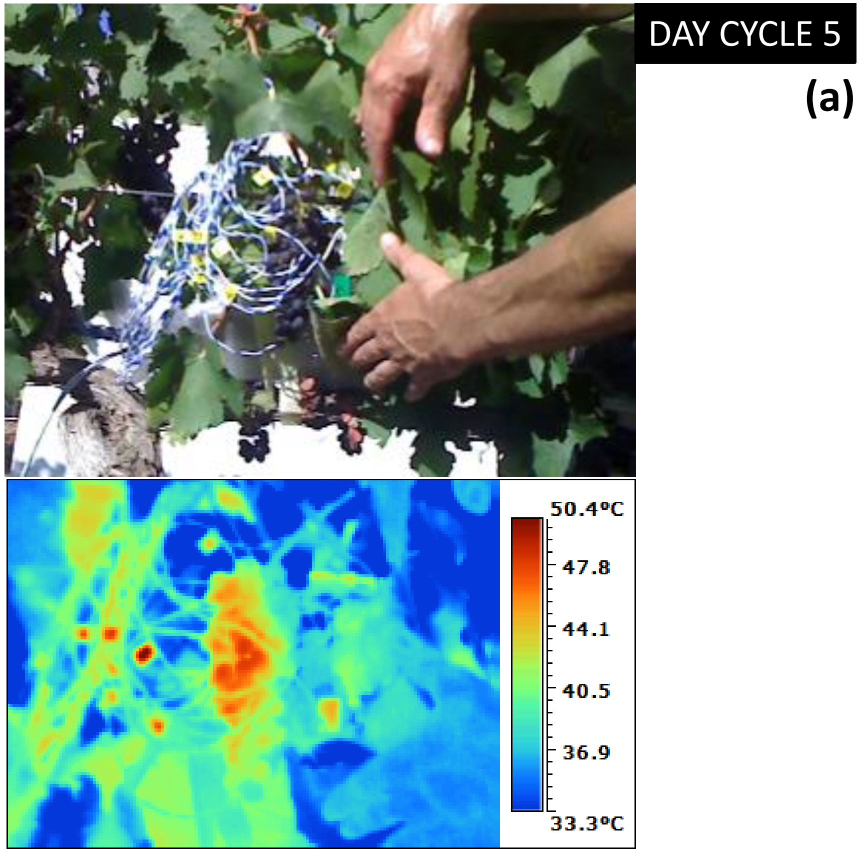
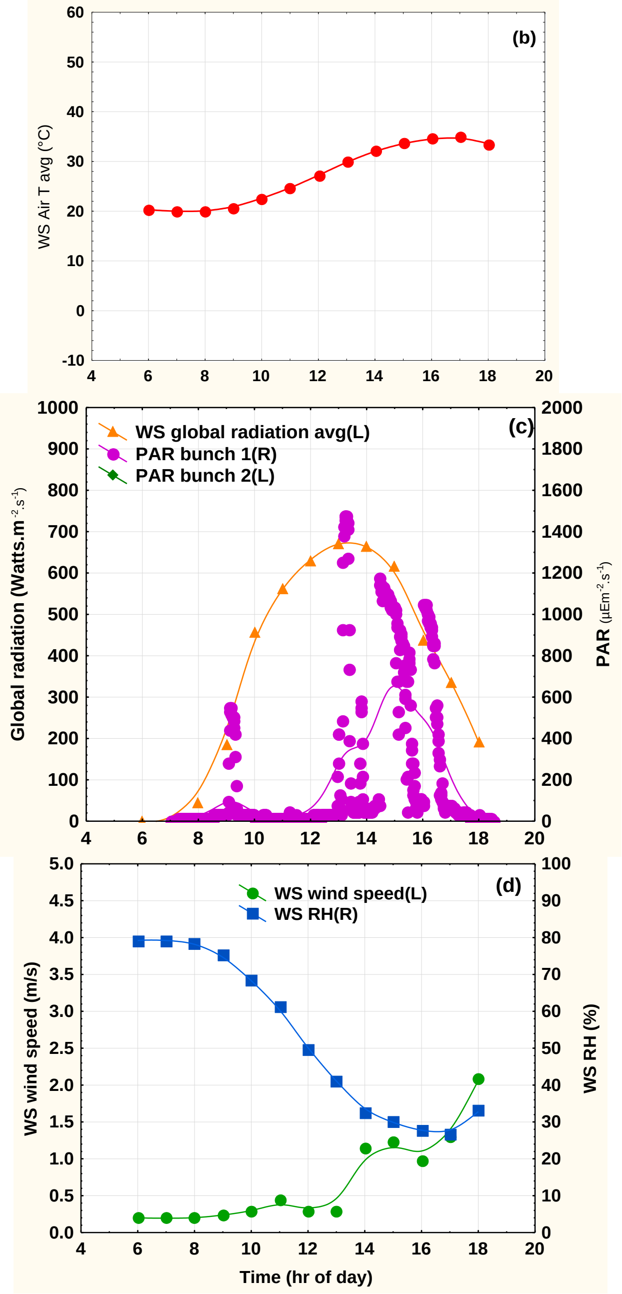

(e)
TI-amb T
TI Value
Temperature (°C)
Time (hour of day)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
(f)
berry 1 T avg- amb T
berry 2 T avg - amb T
berry 3 T avg - amb T
berry 1 T
berry 2 T
berry 3 T
(g)
berry 1 surface T avg
berry 1 surface T - amb T
berry 1 under skin T avg
berry 1 under skin T - amb T
berry 1 pulp T avg
berry 1 pulp T - amb T
(h)
berry 3 surface T avg
berry 3 surface T - amb T
berry 3 under skin T avg
berry 3 under skin T - amb T
berry 3 pulp T avg
berry 3 pulp T - amb T
Time (hr of day)

Figure 72


DAY CYCLE 5
(a)
50.4°C
47.8
44.1
40.5
36.9
33.3°C


(b)
WS Air T avg (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
(c)
WS global radiation avg(L)
PAR bunch 1(R)
PAR bunch 2(L)
Global radiation (Watts.m^{-2}.s^{-1})
PAR (µEm^{-2}.s^{-1})
1000
900
800
700
600
500
400
300
200
100
0
2000
1800
1600
1400
1200
1000
800
600
400
200
0
4
6
8
10
12
14
16
18
20
(d)
WS wind speed(L)
WS RH(R)
WS wind speed (m/s)
WS RH (%)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
100
90
80
70
60
50
40
30
20
10
0
4
6
8
10
12
14
16
18
20
Time (hr of day)

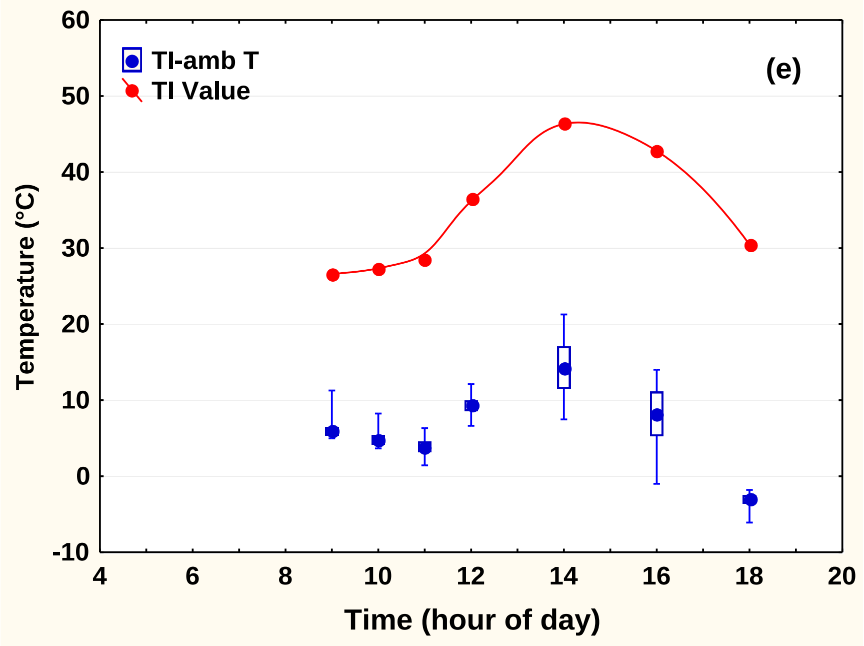
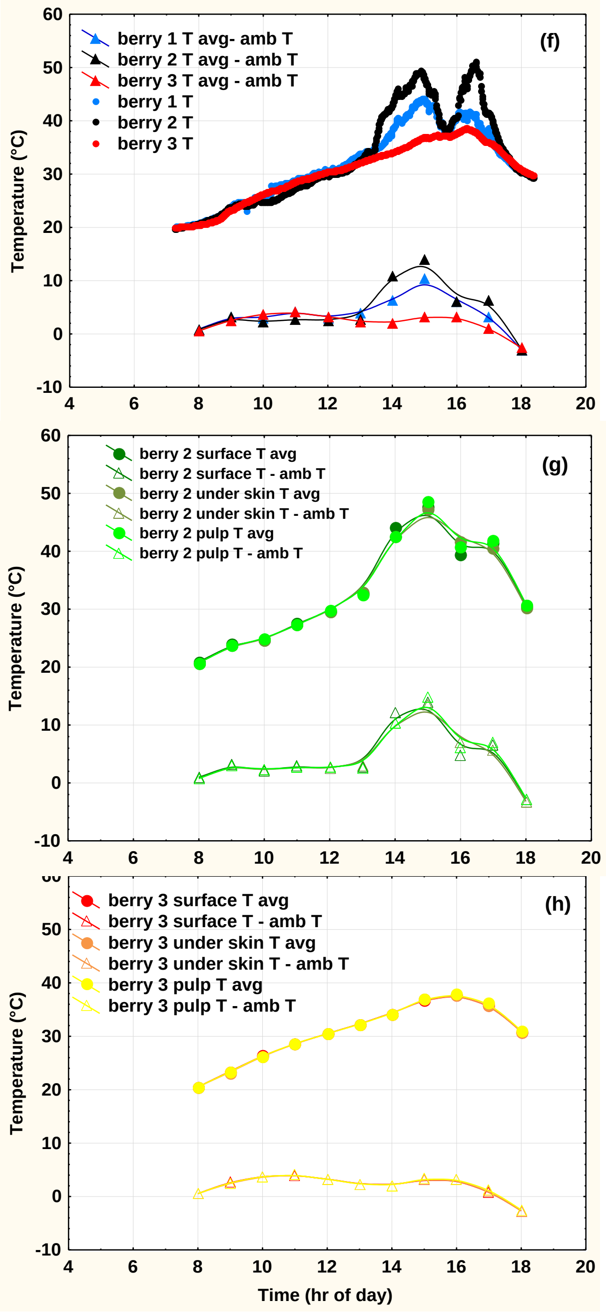
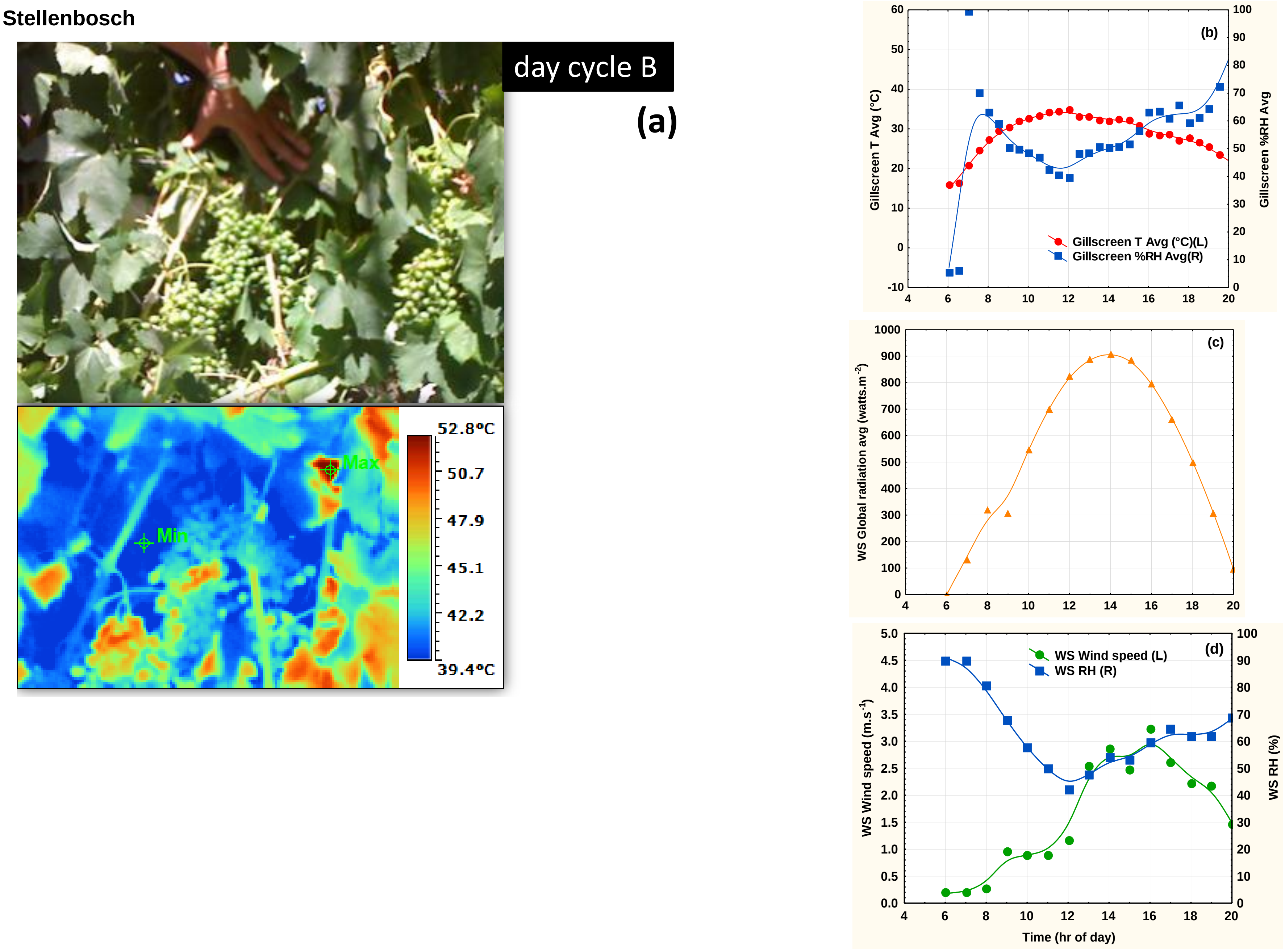

TI-amb T
TI Value
(e)
Temperature (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
Time (hour of day)

Figure 73


(f)
berry 1 T avg- amb T
berry 2 T avg - amb T
berry 3 T avg - amb T
berry 1 T
berry 2 T
berry 3 T
Temperature (°C)
(g)
berry 2 surface T avg
berry 2 surface T - amb T
berry 2 under skin T avg
berry 2 under skin T - amb T
berry 2 pulp T avg
berry 2 pulp T - amb T
Temperature (°C)
(h)
berry 3 surface T avg
berry 3 surface T - amb T
berry 3 under skin T avg
berry 3 under skin T - amb T
berry 3 pulp T avg
berry 3 pulp T - amb T
Temperature (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
Time (hr of day)

Stellenbosch



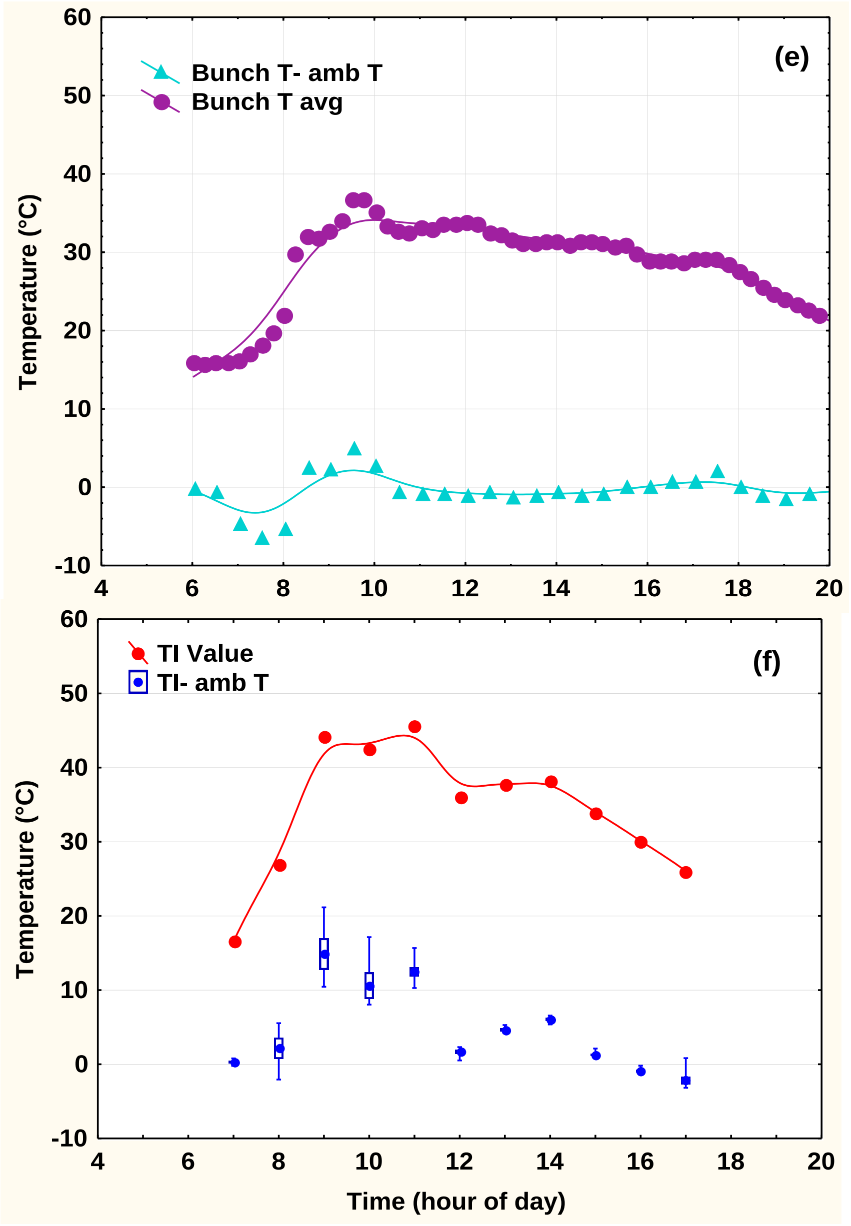
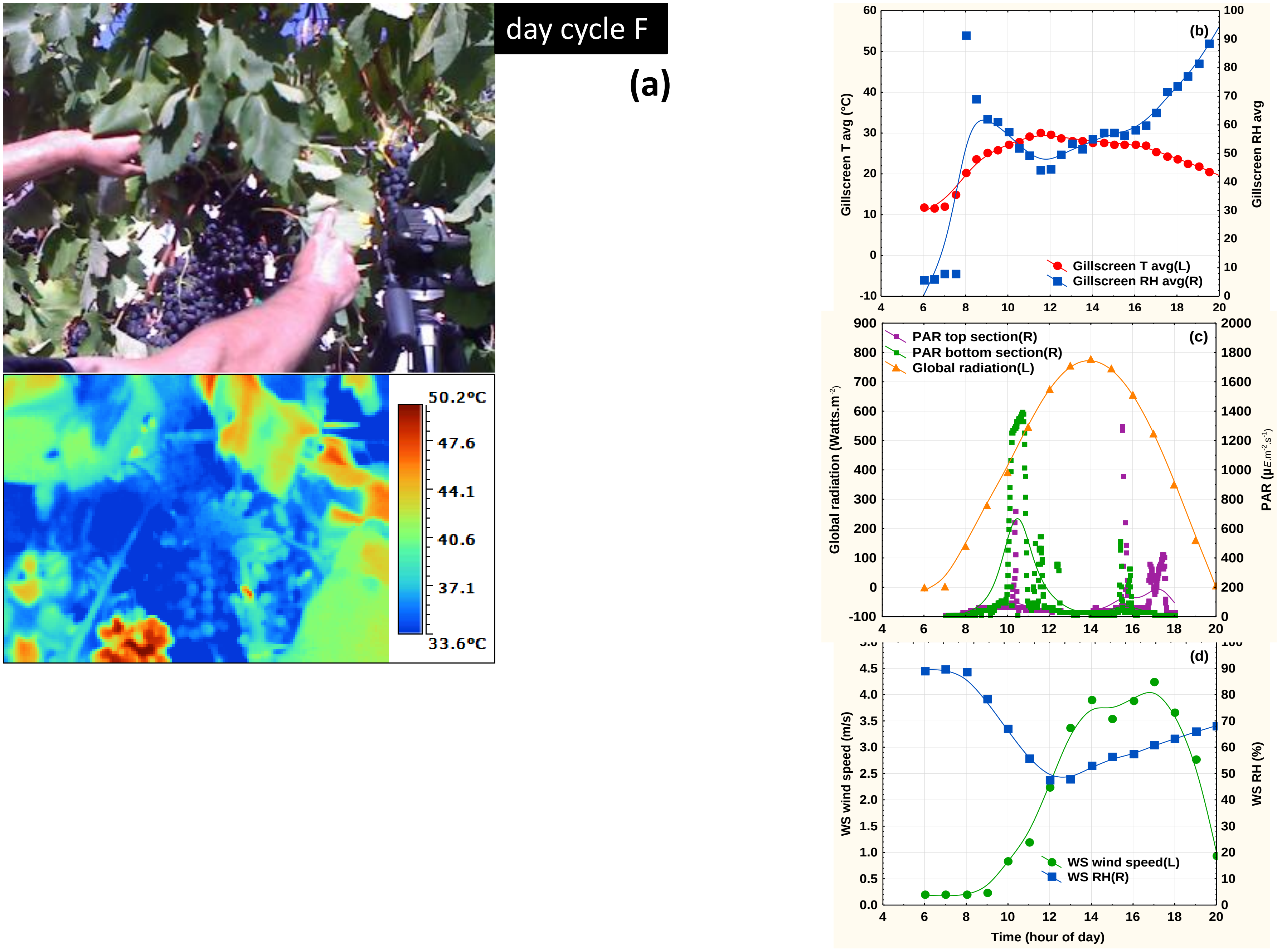

(e)
Bunch T- amb T
Bunch T avg
Temperature (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
(f)
TI Value
TI- amb T
Temperature (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
Time (hour of day)

Figure 74


day cycle F
(a)
50.2°C
47.6
44.1
40.6
37.1
33.6°C
(b)
Gillscreen T avg (°C)
Gillscreen RH avg
Gillscreen T avg(L)
Gillscreen RH avg(R)
60
50
40
30
20
10
0
-10
100
90
80
70
60
50
40
30
20
10
0
4
6
8
10
12
14
16
18
20
(c)
PAR top section(R)
PAR bottom section(R)
Global radiation(L)
Global radiation (Watts.m^{-2})
PAR (μE.m^{-2}.s^{-1})
900
800
700
600
500
400
300
200
100
0
-100
2000
1800
1600
1400
1200
1000
800
600
400
200
0
(d)
WS wind speed (m/s)
WS RH (%)
WS wind speed(L)
WS RH(R)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
90
80
70
60
50
40
30
20
10
0
Time (hour of day)

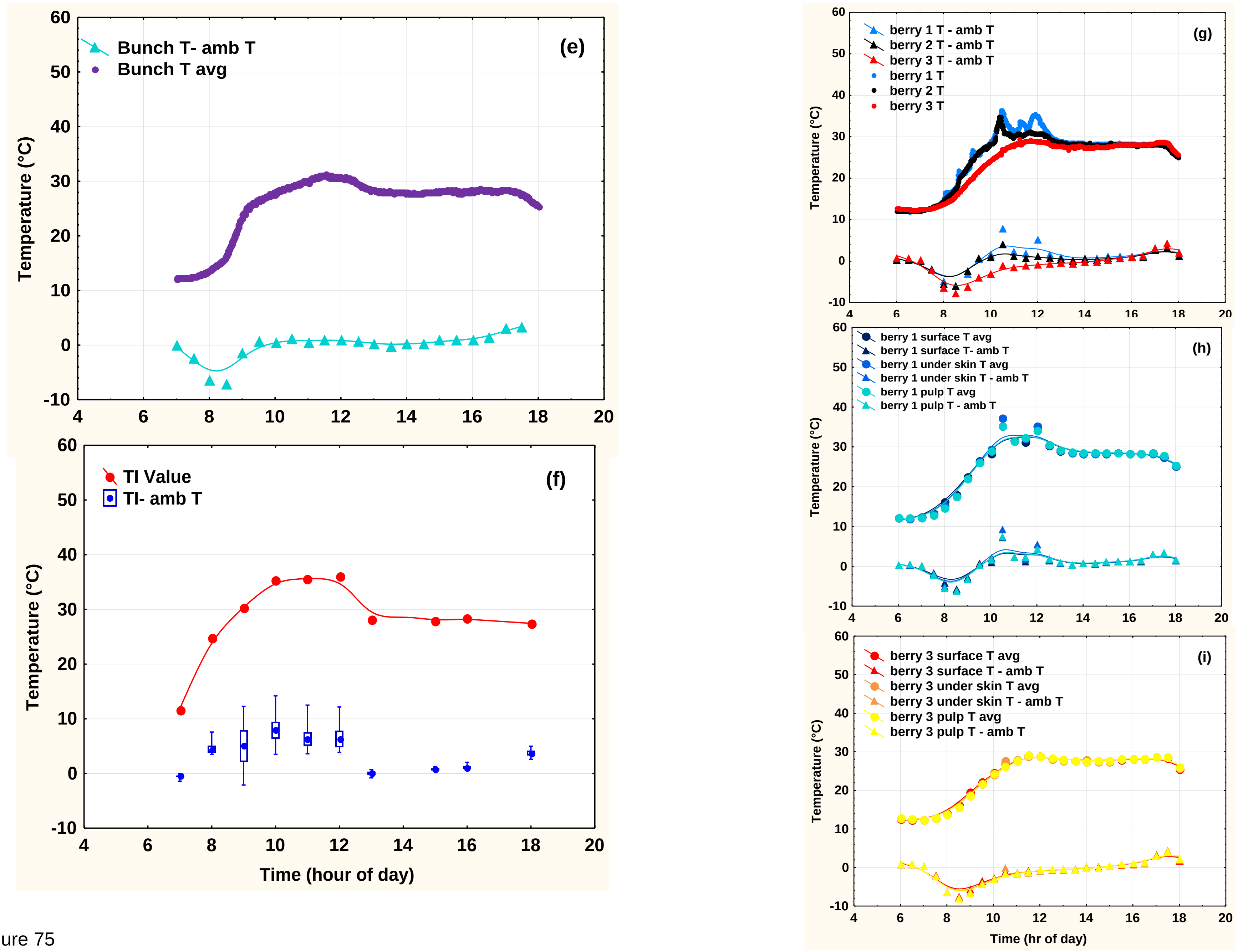
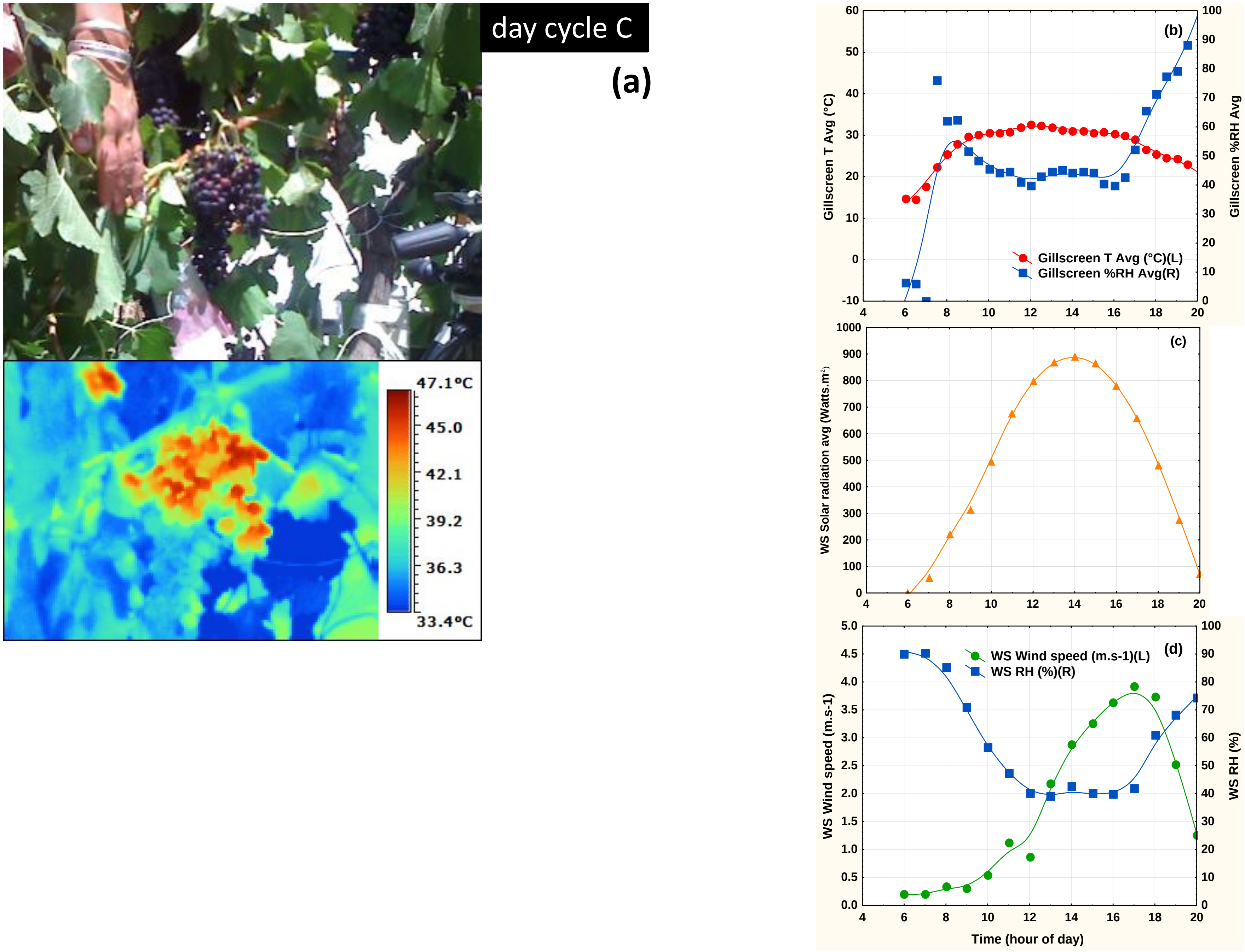

(e)
Bunch T- amb T
Bunch T avg
Temperature (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
(f)
TI Value
TI- amb T
Temperature (°C)
Time (hour of day)
(g)
berry 1 T - amb T
berry 2 T - amb T
berry 3 T - amb T
berry 1 T
berry 2 T
berry 3 T
Temperature (°C)
(h)
berry 1 surface T avg
berry 1 surface T- amb T
berry 1 under skin T avg
berry 1 under skin T - amb T
berry 1 pulp T avg
berry 1 pulp T - amb T
Temperature (°C)
(i)
berry 3 surface T avg
berry 3 surface T - amb T
berry 3 under skin T avg
berry 3 under skin T - amb T
berry 3 pulp T avg
berry 3 pulp T - amb T
Temperature (°C)
Time (hr of day)

Figure 75


day cycle C
(a)
47.1°C
45.0
42.1
39.2
36.3
33.4°C
(b)
Gillscreen T Avg (°C)
Gillscreen %RH Avg
Gillscreen T Avg (°C)(L)
Gillscreen %RH Avg(R)
60
50
40
30
20
10
0
-10
100
90
80
70
60
50
40
30
20
10
0
4
6
8
10
12
14
16
18
20
(c)
WS Solar radiation avg (Watts.m²)
1000
900
800
700
600
500
400
300
200
100
0
4
6
8
10
12
14
16
18
20
(d)
WS Wind speed (m.s-1)(L)
WS RH (%)(R)
WS Wind speed (m.s-1)
WS RH (%)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
100
90
80
70
60
50
40
30
20
10
0
4
6
8
10
12
14
16
18
20
Time (hour of day)

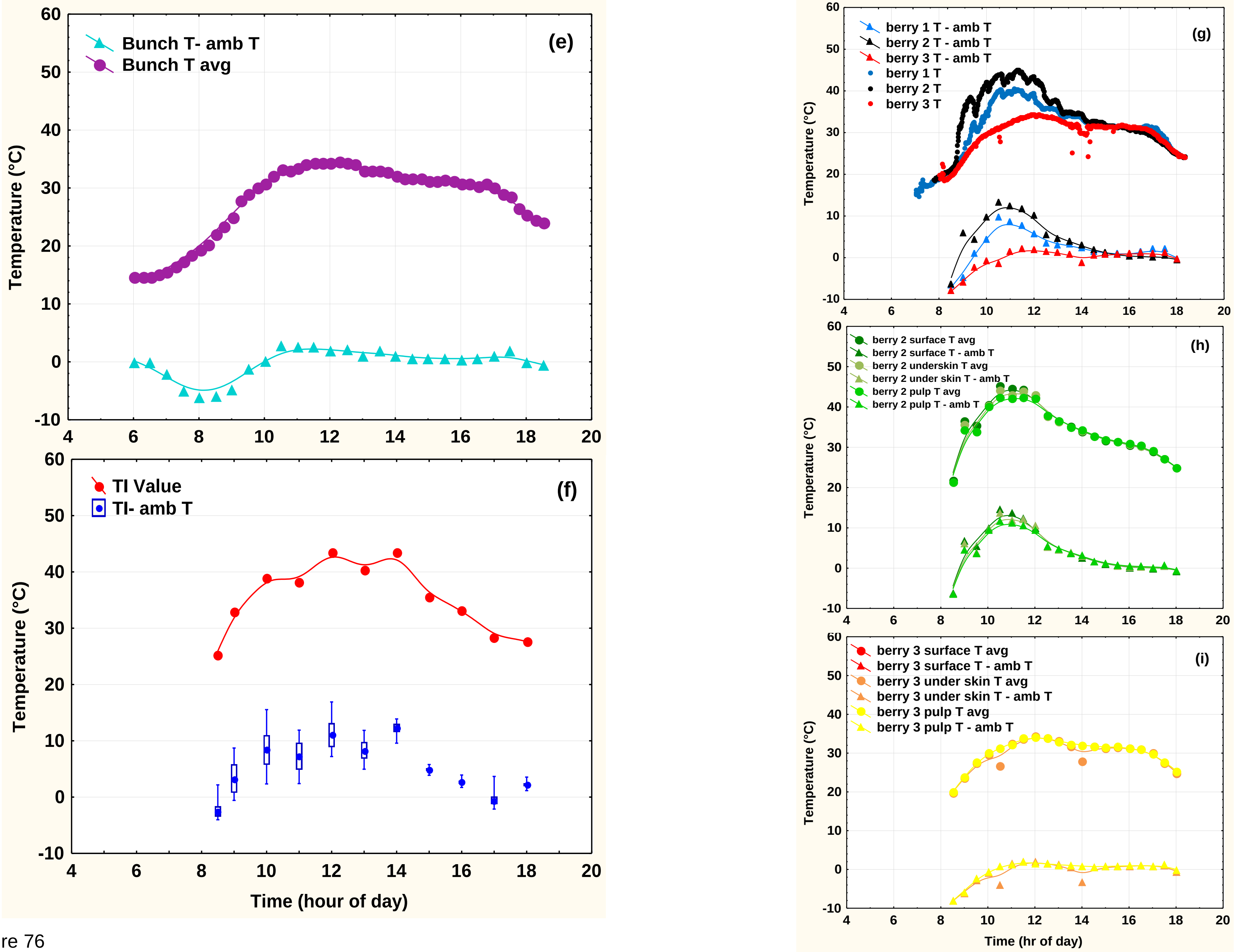
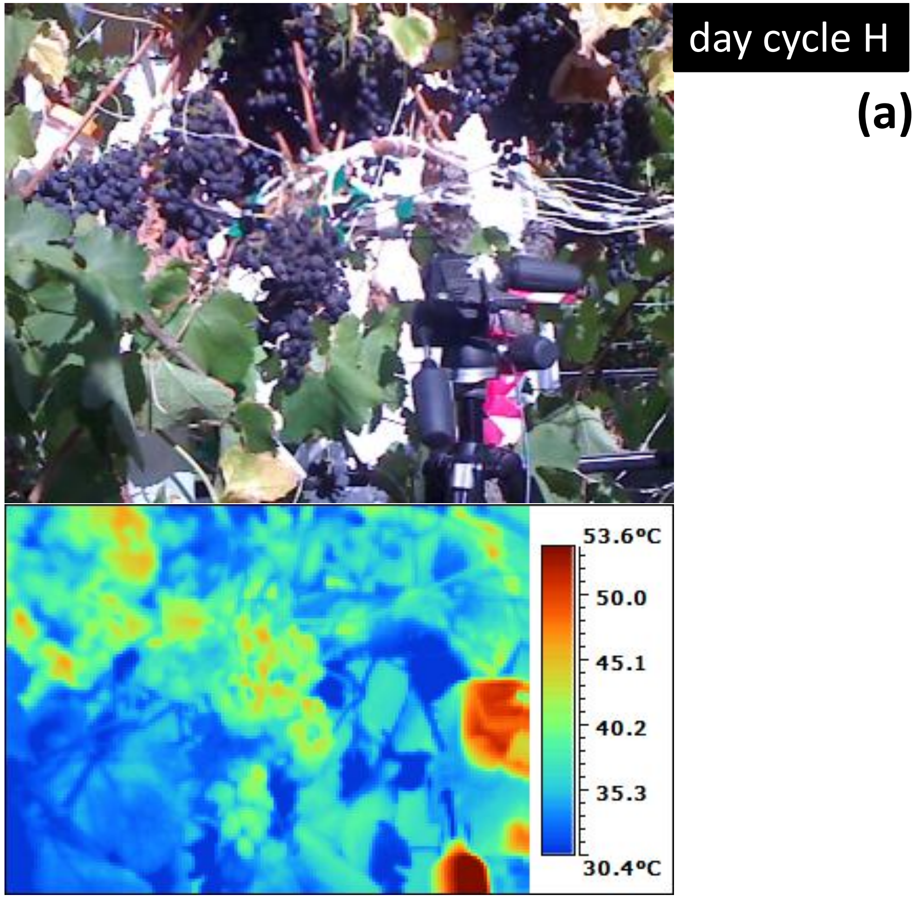
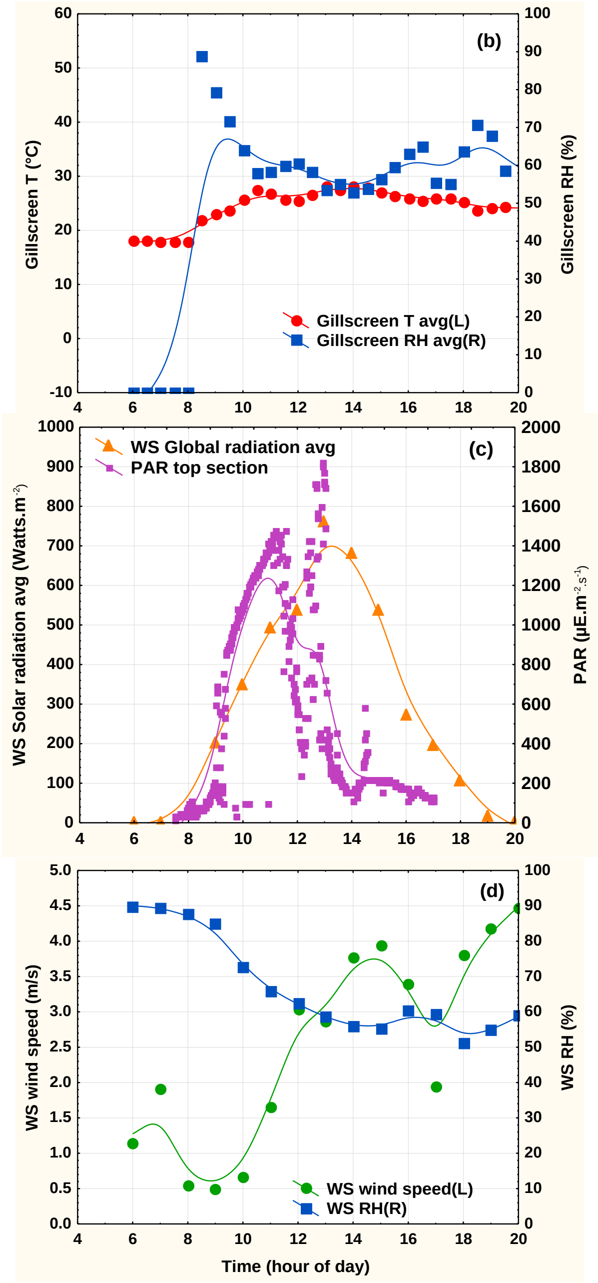
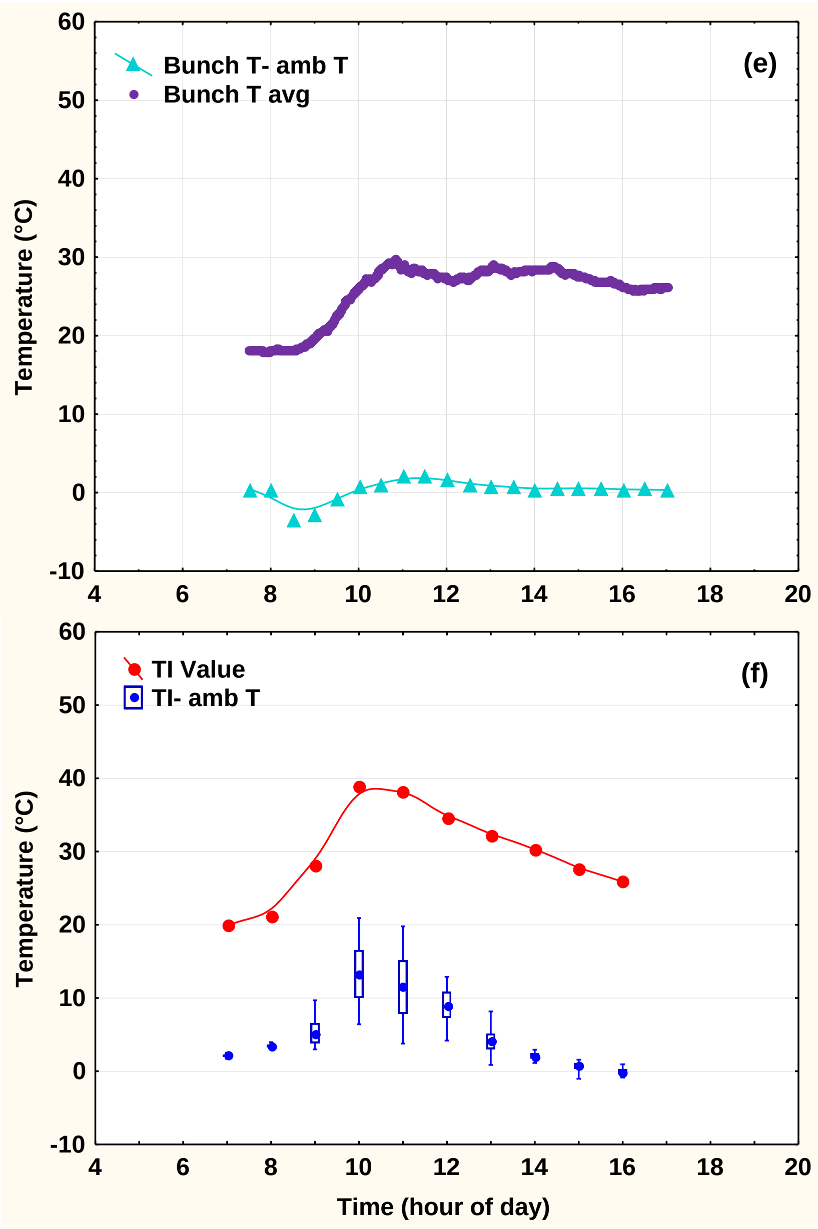

(e)
Bunch T- amb T
Bunch T avg
Temperature (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
(f)
TI Value
TI- amb T
Temperature (°C)
Time (hour of day)
(g)
berry 1 T - amb T
berry 2 T - amb T
berry 3 T - amb T
berry 1 T
berry 2 T
berry 3 T
Temperature (°C)
(h)
berry 2 surface T avg
berry 2 surface T - amb T
berry 2 underskin T avg
berry 2 under skin T - amb T
berry 2 pulp T avg
berry 2 pulp T - amb T
Temperature (°C)
(i)
berry 3 surface T avg
berry 3 surface T - amb T
berry 3 under skin T avg
berry 3 under skin T - amb T
berry 3 pulp T avg
berry 3 pulp T - amb T
Temperature (°C)
Time (hr of day)

Figure 76


day cycle H
(a)
53.6°C
50.0
45.1
40.2
35.3
30.4°C


(b)
Gillscreen T (°C)
Gillscreen RH (%)
Gillscreen T avg(L)
Gillscreen RH avg(R)
60
50
40
30
20
10
0
-10
100
90
80
70
60
50
40
30
20
10
0
4
6
8
10
12
14
16
18
20
(c)
WS Global radiation avg
PAR top section
WS Solar radiation avg (Watts.m^{-2})
PAR (µE.m^{-2}.s^{-1})
1000
900
800
700
600
500
400
300
200
100
0
2000
1800
1600
1400
1200
1000
800
600
400
200
0
(d)
WS wind speed (m/s)
WS RH (%)
WS wind speed(L)
WS RH(R)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Time (hour of day)


(e)
Bunch T- amb T
Bunch T avg
Temperature (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
(f)
TI Value
TI- amb T
Temperature (°C)
Time (hour of day)

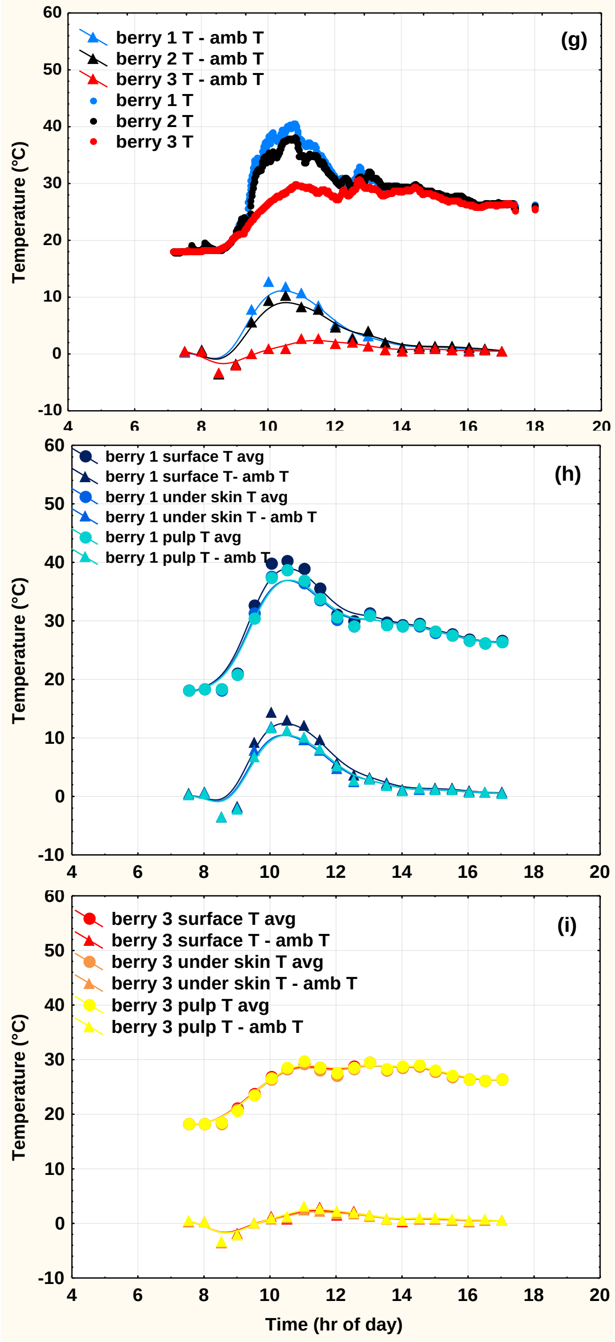
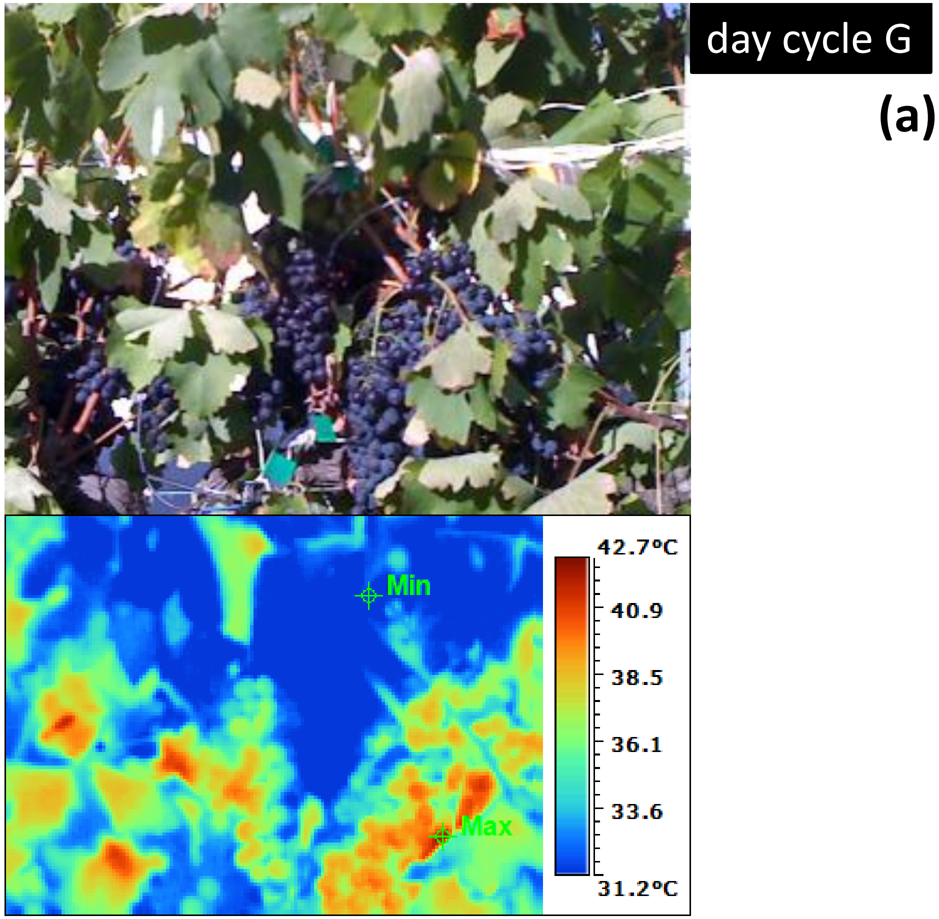
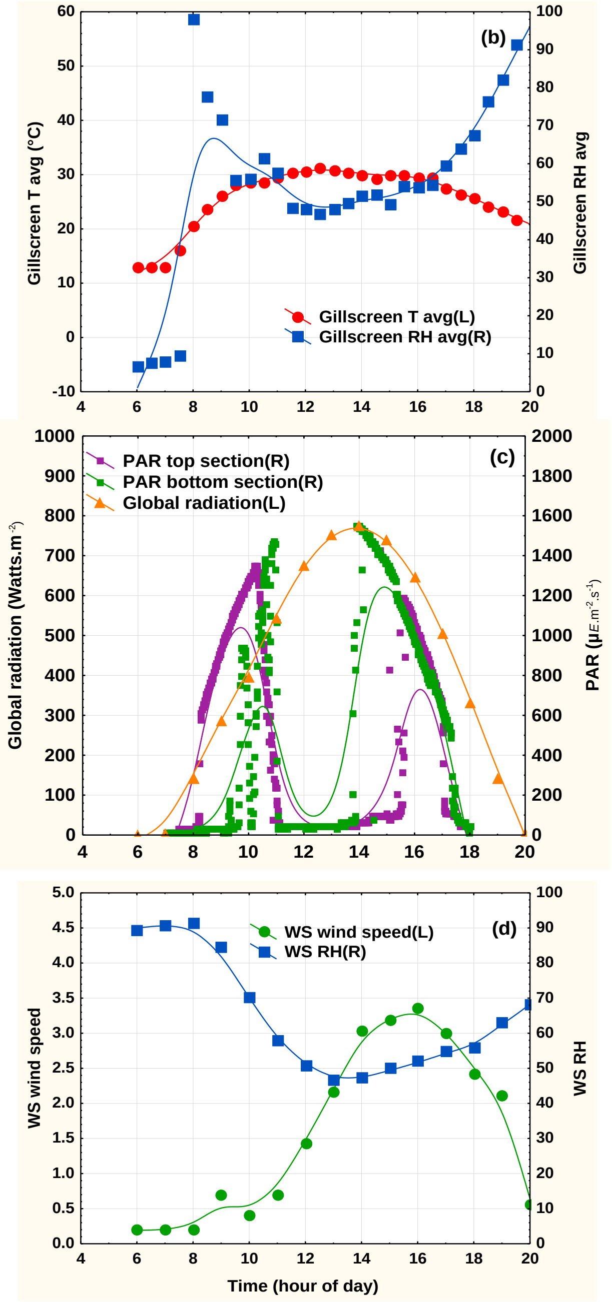

(g)
berry 1 T - amb T
berry 2 T - amb T
berry 3 T - amb T
berry 1 T
berry 2 T
berry 3 T
Temperature (°C)
(h)
berry 1 surface T avg
berry 1 surface T- amb T
berry 1 under skin T avg
berry 1 under skin T - amb T
berry 1 pulp T avg
berry 1 pulp T - amb T
Temperature (°C)
(i)
berry 3 surface T avg
berry 3 surface T - amb T
berry 3 under skin T avg
berry 3 under skin T - amb T
berry 3 pulp T avg
berry 3 pulp T - amb T
Temperature (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
Time (hr of day)

Figure 77


day cycle G
(a)
Min
Max
42.7°C
40.9
38.5
36.1
33.6
31.2°C


(b)
Gillscreen T avg (°C)
Gillscreen RH avg
Gillscreen T avg(L)
Gillscreen RH avg(R)
60
50
40
30
20
10
0
-10
100
90
80
70
60
50
40
30
20
10
0
4
6
8
10
12
14
16
18
20
(c)
PAR top section(R)
PAR bottom section(R)
Global radiation(L)
Global radiation (Watts.m-2)
PAR (µE.m-2.s-1)
1000
900
800
700
600
500
400
300
200
100
0
2000
1800
1600
1400
1200
1000
800
600
400
200
0
4
6
8
10
12
14
16
18
20
(d)
WS wind speed(L)
WS RH(R)
WS wind speed
WS RH
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
100
90
80
70
60
50
40
30
20
10
0
4
6
8
10
12
14
16
18
20
Time (hour of day)

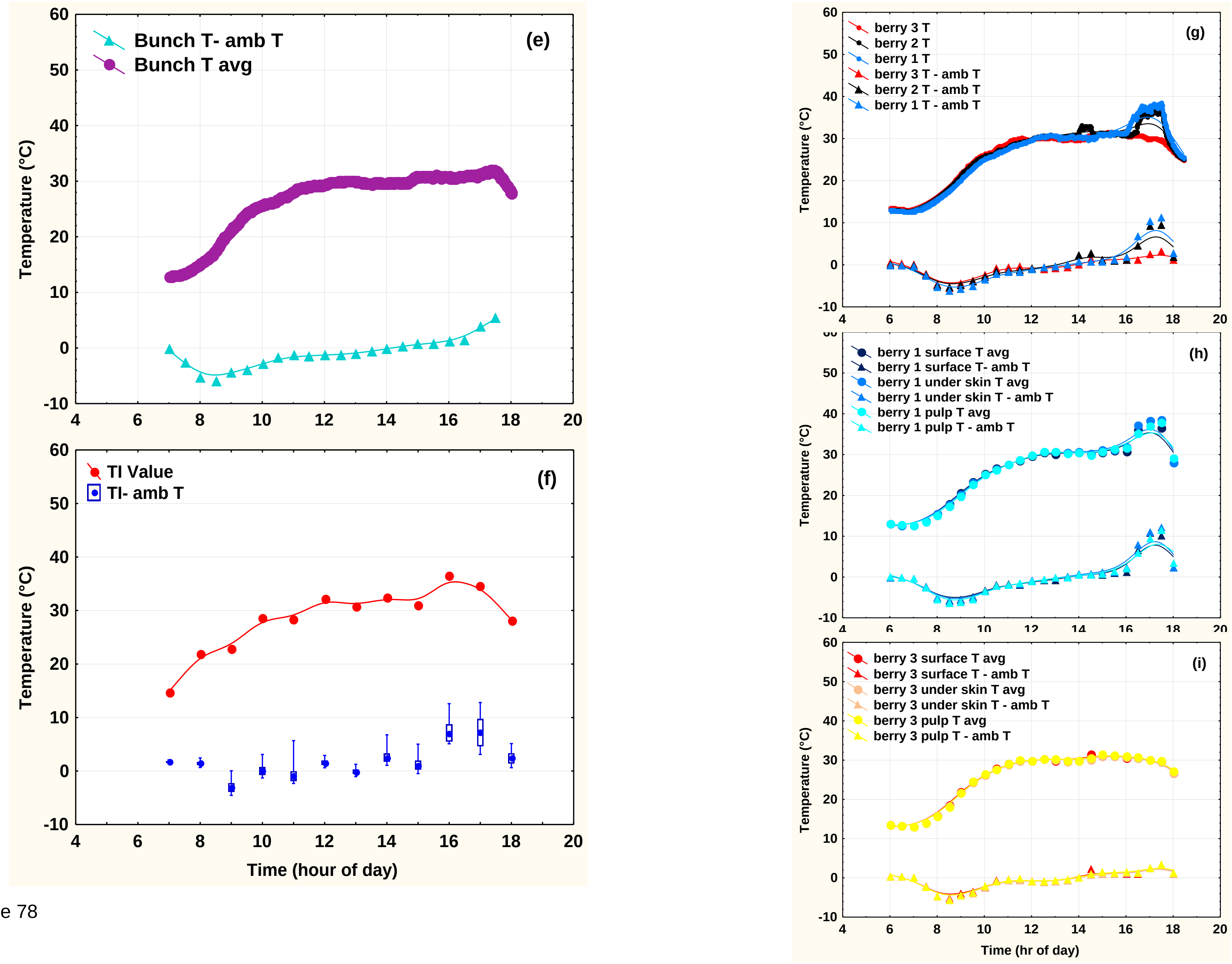
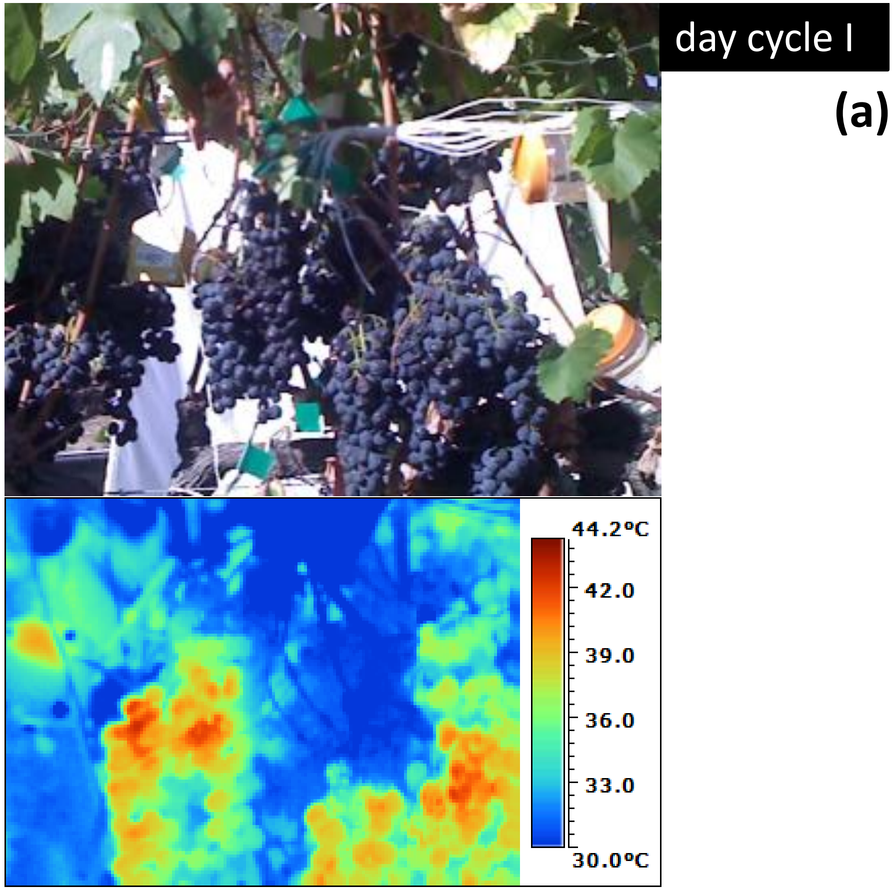
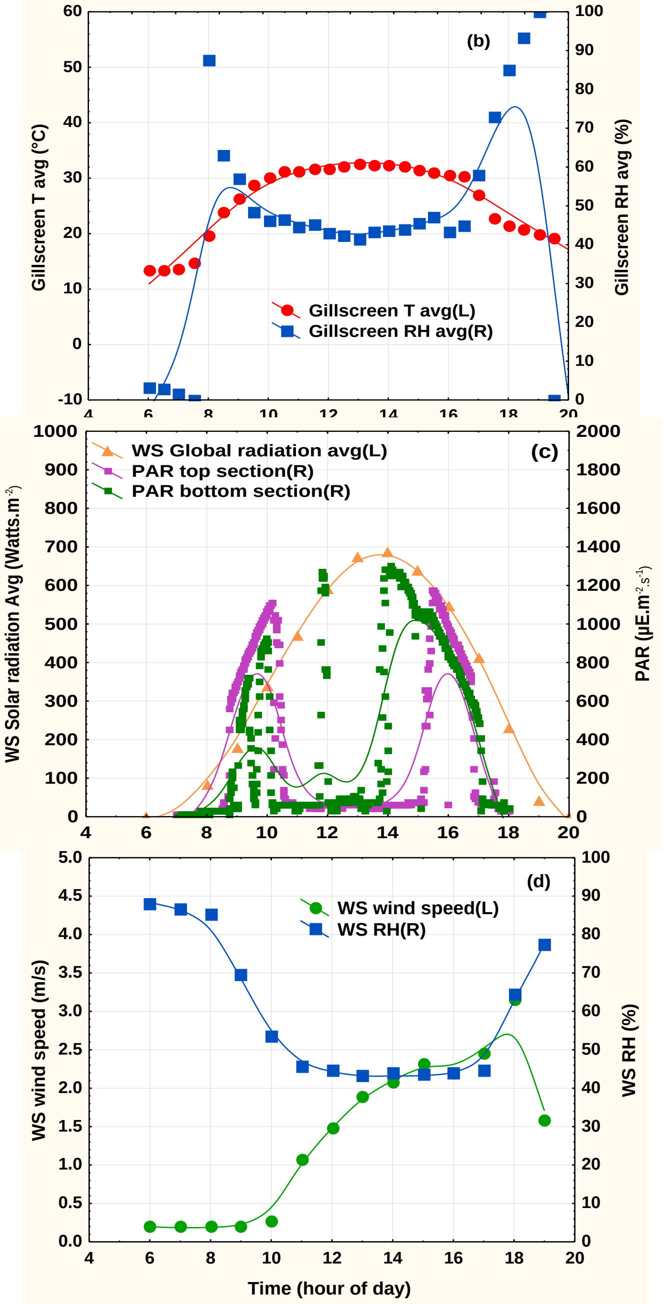

(e)
Bunch T- amb T
Bunch T avg
Temperature (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
(f)
TI Value
TI- amb T
Temperature (°C)
Time (hour of day)
(g)
berry 3 T
berry 2 T
berry 1 T
berry 3 T - amb T
berry 2 T - amb T
berry 1 T - amb T
Temperature (°C)
(h)
berry 1 surface T avg
berry 1 surface T- amb T
berry 1 under skin T avg
berry 1 under skin T - amb T
berry 1 pulp T avg
berry 1 pulp T - amb T
Temperature (°C)
(i)
berry 3 surface T avg
berry 3 surface T - amb T
berry 3 under skin T avg
berry 3 under skin T - amb T
berry 3 pulp T avg
berry 3 pulp T - amb T
Temperature (°C)
Time (hr of day)

Figure 78


day cycle I
(a)
44.2°C
42.0
39.0
36.0
33.0
30.0°C


(b)
Gillscreen T avg (°C)
Gillscreen RH avg (%)
Gillscreen T avg(L)
Gillscreen RH avg(R)
60
50
40
30
20
10
0
-10
100
90
80
70
60
50
40
30
20
10
0
4
6
8
10
12
14
16
18
20
(c)
WS Global radiation avg(L)
PAR top section(R)
PAR bottom section(R)
WS Solar radiation Avg (Watts.m^{-2})
PAR (µE.m^{-2}.s^{-1})
1000
900
800
700
600
500
400
300
200
100
0
2000
1800
1600
1400
1200
1000
800
600
400
200
0
4
6
8
10
12
14
16
18
20
(d)
WS wind speed(L)
WS RH(R)
WS wind speed (m/s)
WS RH (%)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
100
90
80
70
60
50
40
30
20
10
0
4
6
8
10
12
14
16
18
20
Time (hour of day)

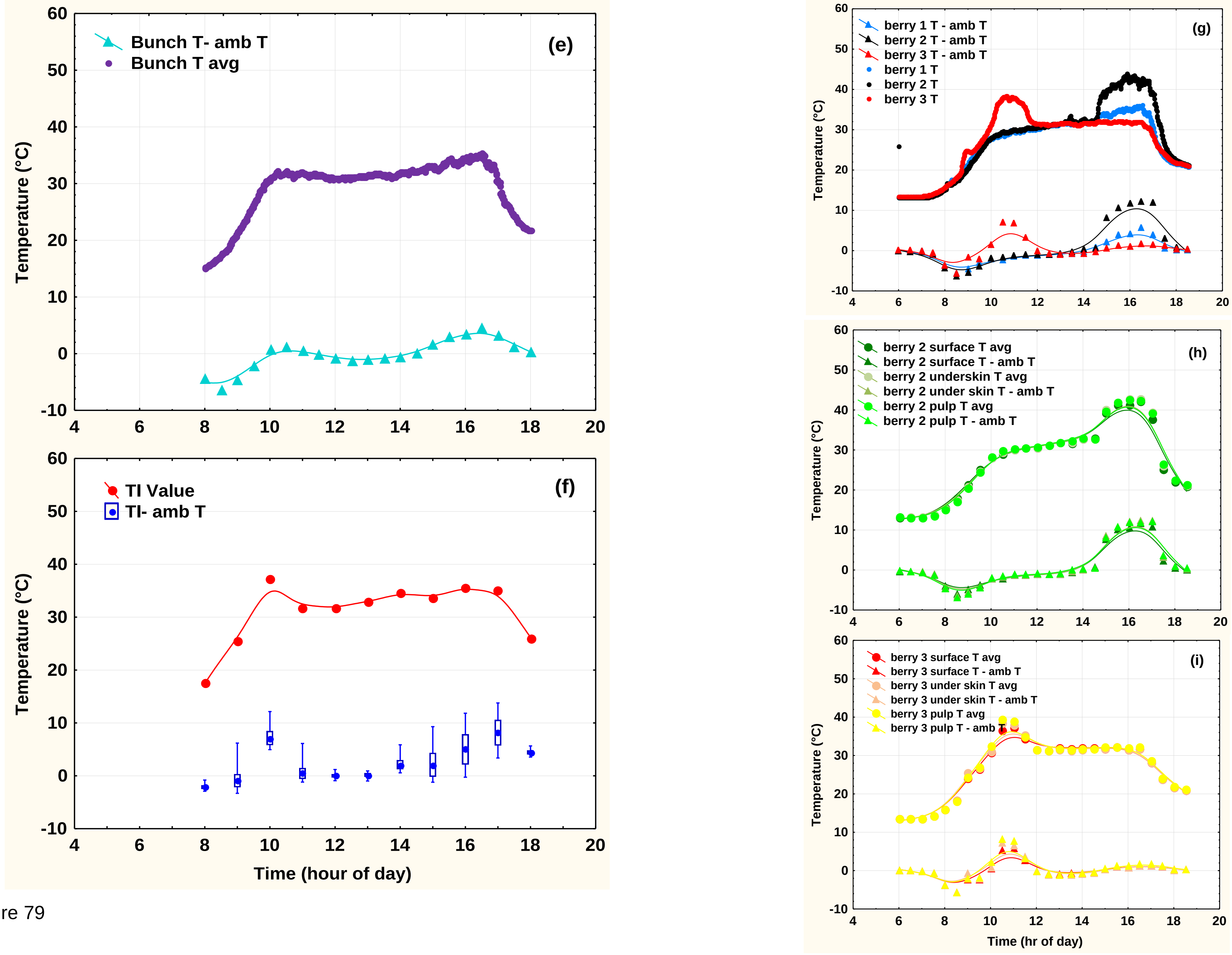
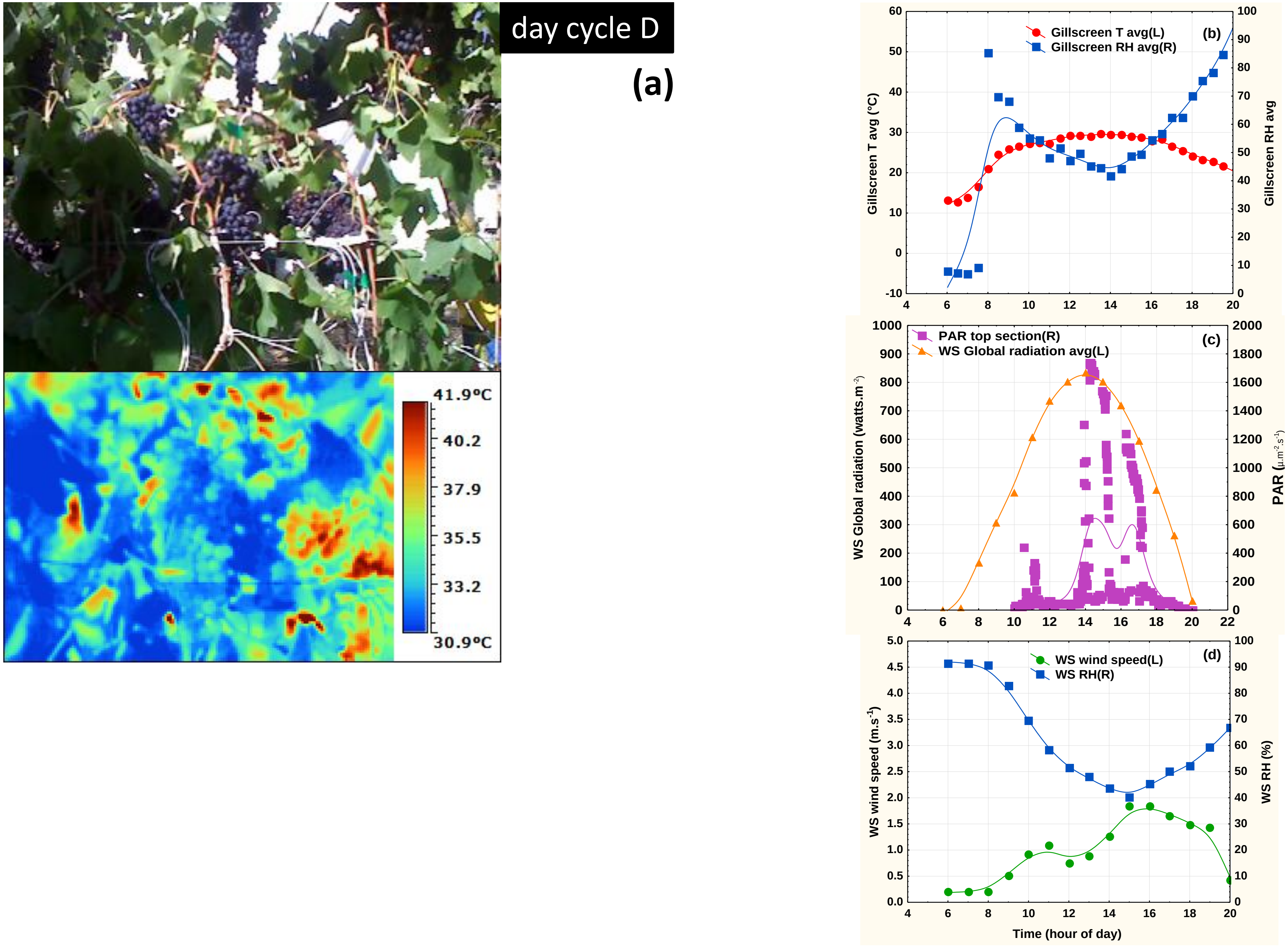

(e)
Bunch T- amb T
Bunch T avg
Temperature (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
(f)
TI Value
TI- amb T
Temperature (°C)
Time (hour of day)
(g)
berry 1 T - amb T
berry 2 T - amb T
berry 3 T - amb T
berry 1 T
berry 2 T
berry 3 T
Temperature (°C)
(h)
berry 2 surface T avg
berry 2 surface T - amb T
berry 2 underskin T avg
berry 2 under skin T - amb T
berry 2 pulp T avg
berry 2 pulp T - amb T
Temperature (°C)
(i)
berry 3 surface T avg
berry 3 surface T - amb T
berry 3 under skin T avg
berry 3 under skin T - amb T
berry 3 pulp T avg
berry 3 pulp T - amb T
Temperature (°C)
Time (hr of day)

Figure 79


day cycle D
(a)
41.9°C
40.2
37.9
35.5
33.2
30.9°C
(b)
Gillscreen T avg(L)
Gillscreen RH avg(R)
Gillscreen T avg (°C)
Gillscreen RH avg
(c)
PAR top section(R)
WS Global radiation avg(L)
WS Global radiation (watts.m^{-2})
PAR (μ.m^{-2}.s^{-1})
(d)
WS wind speed(L)
WS RH(R)
WS wind speed (m.s^{-1})
WS RH (%)
Time (hour of day)

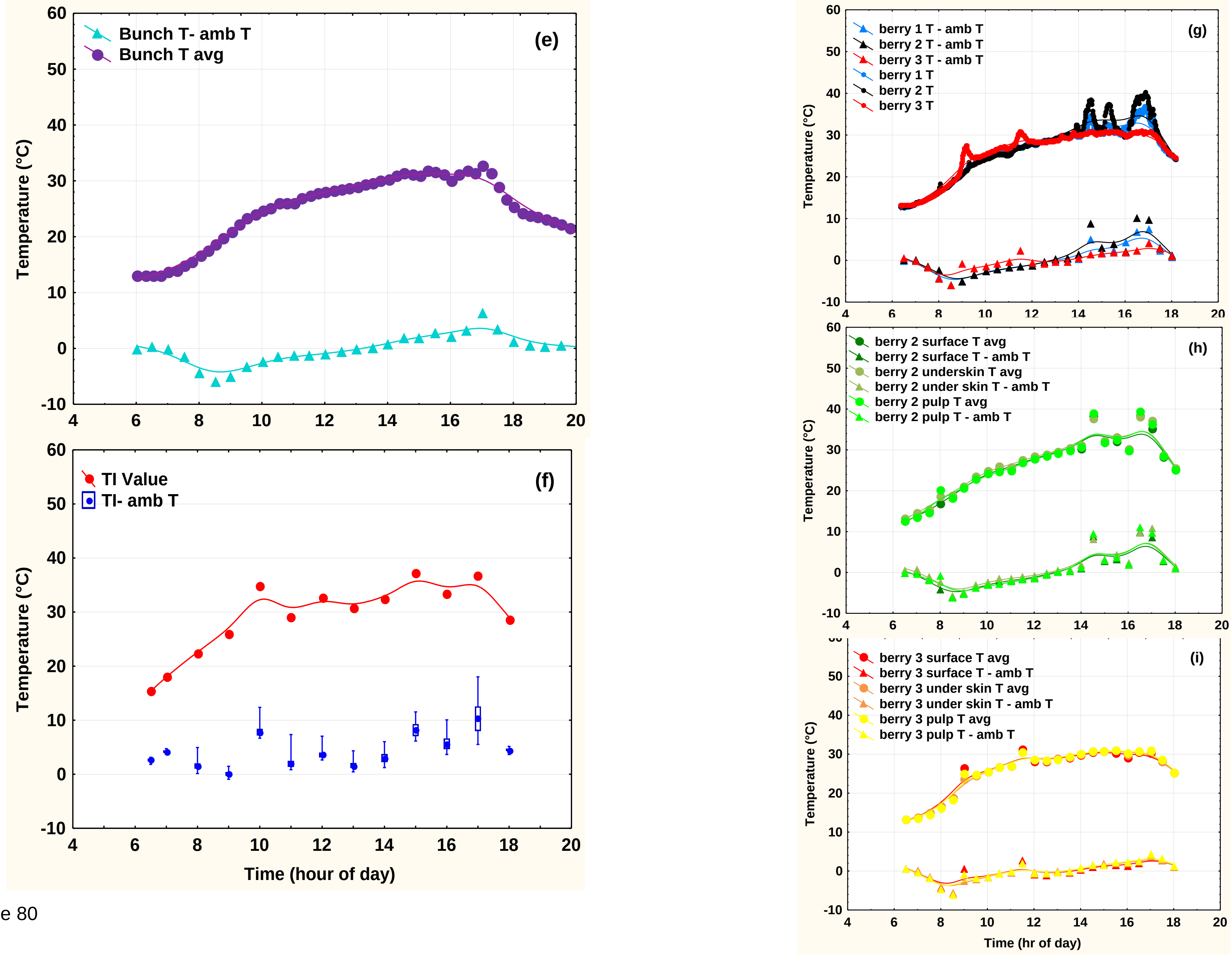
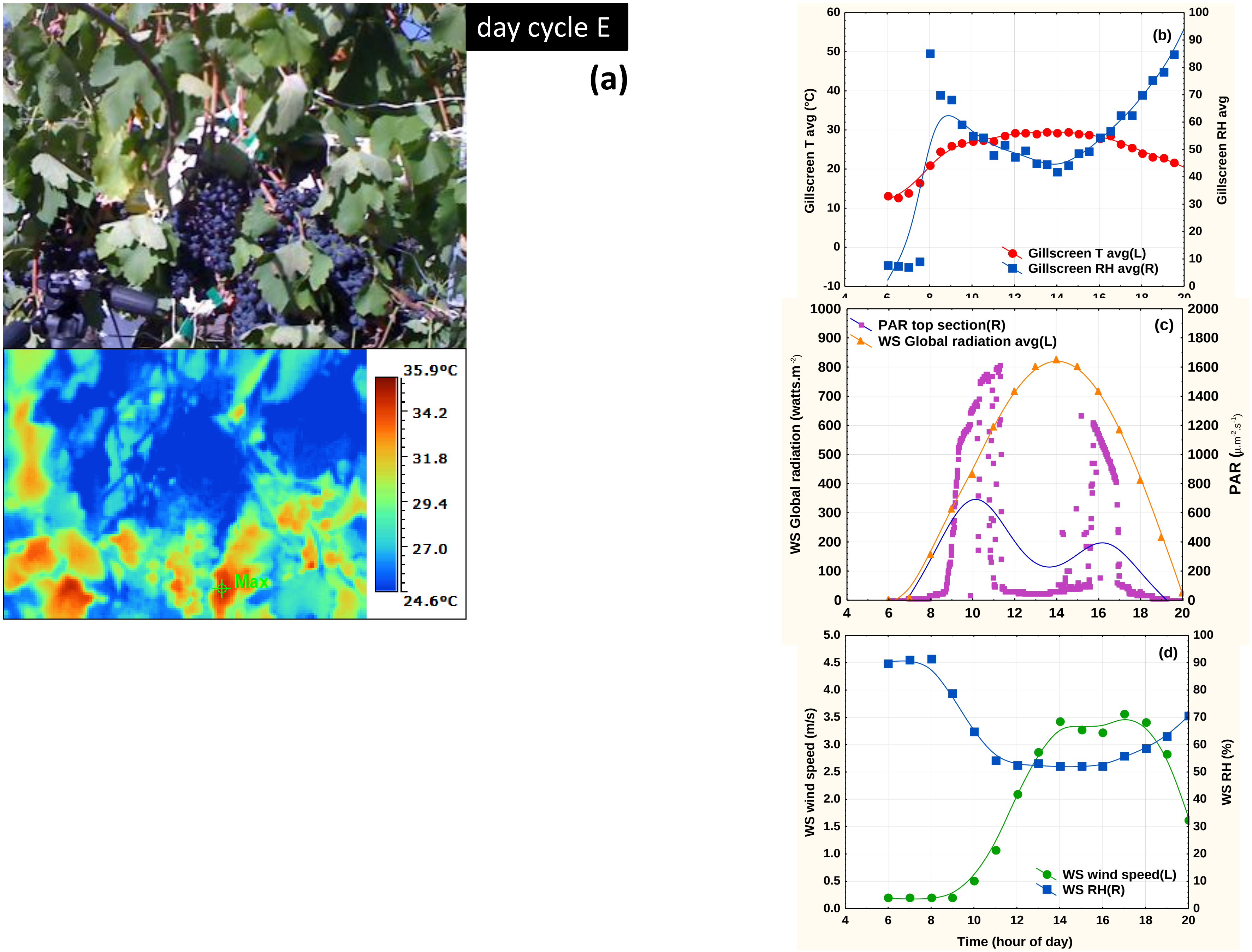

(e)
Bunch T- amb T
Bunch T avg
Temperature (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
(f)
TI Value
TI- amb T
Temperature (°C)
Time (hour of day)
(g)
berry 1 T - amb T
berry 2 T - amb T
berry 3 T - amb T
berry 1 T
berry 2 T
berry 3 T
Temperature (°C)
(h)
berry 2 surface T avg
berry 2 surface T - amb T
berry 2 underskin T avg
berry 2 under skin T - amb T
berry 2 pulp T avg
berry 2 pulp T - amb T
Temperature (°C)
(i)
berry 3 surface T avg
berry 3 surface T - amb T
berry 3 under skin T avg
berry 3 under skin T - amb T
berry 3 pulp T avg
berry 3 pulp T - amb T
Temperature (°C)
Time (hr of day)

Figure 80


day cycle E
(a)
35.9°C
34.2
31.8
29.4
27.0
24.6°C
Max
(b)
Gillscreen T avg (°C)
Gillscreen RH avg
Gillscreen T avg(L)
Gillscreen RH avg(R)
60
50
40
30
20
10
0
-10
100
90
80
70
60
50
40
30
20
10
0
(c)
PAR top section(R)
WS Global radiation avg(L)
WS Global radiation (watts.m^{-2})
PAR (μ.m^{-2}.s^{-1})
1000
900
800
700
600
500
400
300
200
100
0
2000
1800
1600
1400
1200
1000
800
600
400
200
0
4
6
8
10
12
14
16
18
20
(d)
WS wind speed (m/s)
WS RH (%)
WS wind speed(L)
WS RH(R)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
100
90
80
70
60
50
40
30
20
10
0
4
6
8
10
12
14
16
18
20
Time (hour of day)

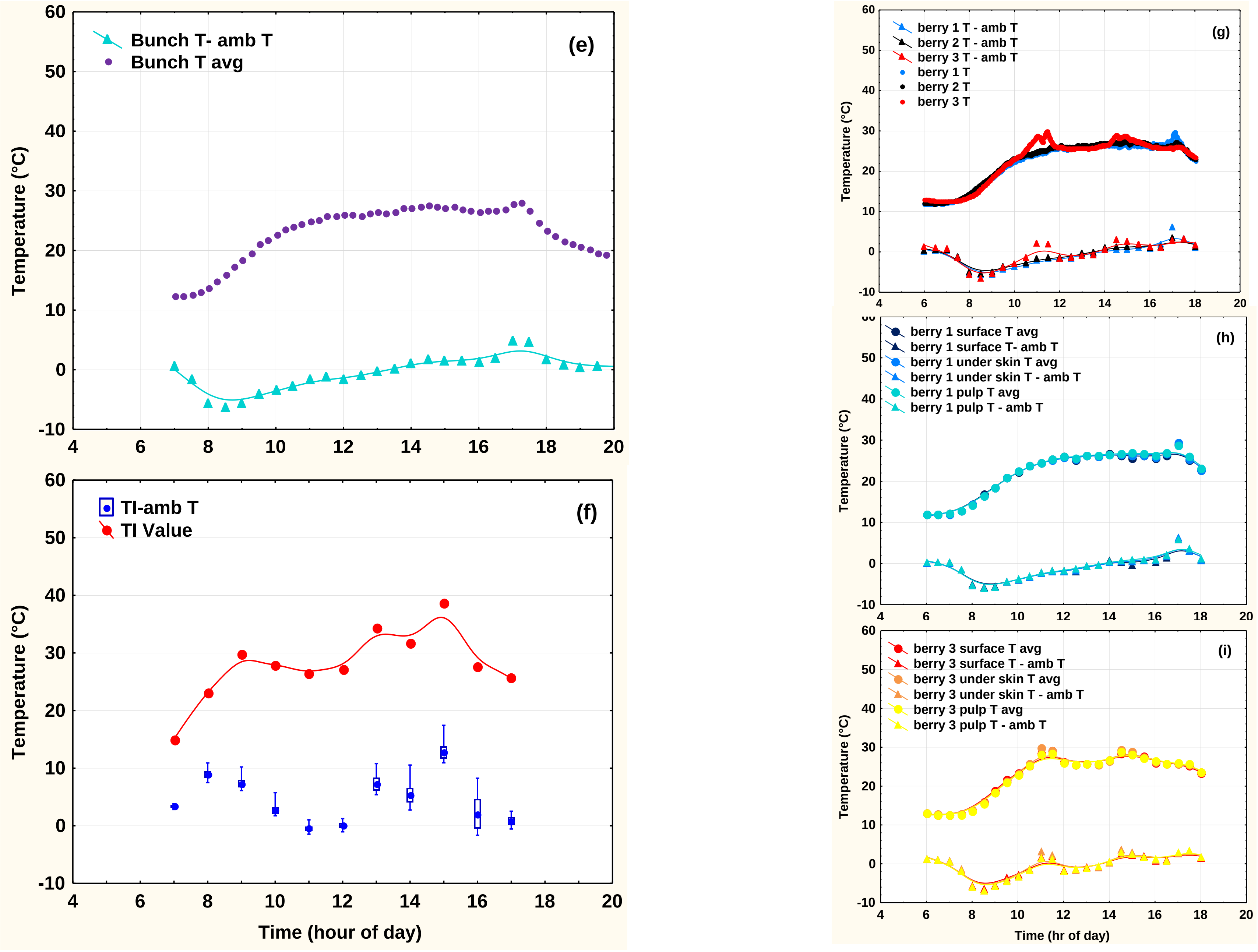

(e)
Bunch T- amb T
Bunch T avg
Temperature (°C)
60
50
40
30
20
10
0
-10
4
6
8
10
12
14
16
18
20
(f)
TI-amb T
TI Value
Temperature (°C)
Time (hour of day)
(g)
berry 1 T - amb T
berry 2 T - amb T
berry 3 T - amb T
berry 1 T
berry 2 T
berry 3 T
(h)
berry 1 surface T avg
berry 1 surface T- amb T
berry 1 under skin T avg
berry 1 under skin T - amb T
berry 1 pulp T avg
berry 1 pulp T - amb T
(i)
berry 3 surface T avg
berry 3 surface T - amb T
berry 3 under skin T avg
berry 3 under skin T - amb T
berry 3 pulp T avg
berry 3 pulp T - amb T
Time (hr of day)

Figure 81

3.8 List of figures (day cycles)

Figure 68 (a)-(h) represents distance-weighted least squares scatterplots of specific measurements on day cycle one in Robertson on the east side of the canopy.

(a) Bitmap and thermal images of bunch one.

(b) Hourly air/ambient temperature measured by the weather station in the vineyard.

(c) Hourly solar radiation measured by the weather station in the vineyard.

(d) Hourly wind speed and relative humidity (RH) measured by the weather station in the vineyard.

(e) The mean surface bunch temperature of the exposed side of bunch one, measured by the thermal imager (TI). The mean, minimum and maximum (whiskers) and standard deviation (box) of the difference between the surface temperature and the ambient temperature of the weather station is also illustrated.

(f) Average berry temperature for berries one, two (exposed side of the bunch) and three (backside of the bunch) with one minute intervals is illustrated. Average for each berry is computed from the surface, under skin and pulp temperatures. Hourly points of the difference between berry temperature for berries one, two and three and ambient temperature are illustrated.

(g) Hourly values of surface, under skin and pulp temperatures for berry one. Hourly points of the difference between surface, under skin and pulp temperatures of berry one and ambient temperature.

(h) Hourly values of surface, under skin and pulp temperatures for berry three. Hourly points of the difference between surface, under skin and pulp temperatures of berry three and ambient temperature.

Figure 69 (a)-(h) represents distance-weighted least squares scatterplots of specific measurements on day cycle four in Robertson on the east side of the canopy.

(a) Bitmap and thermal images of bunch one.

(b) Hourly air/ambient temperature measured by the weather station in the vineyard.

(c) Hourly solar radiation measured by the weather station in the vineyard as well as photosynthetically active radiation (PAR) measurements for bunch one and two.

(d) Hourly wind speed and relative humidity (RH) measured by the weather station in the vineyard (e) The mean surface bunch temperature of the exposed side of bunch one, measured by the thermal imager (TI). The mean, minimum and maximum (whiskers) and standard deviation (box) of the difference between the surface temperature and the ambient temperature of the weather station is also illustrated.

(e) Average berry temperature for berries one, two (exposed side of the bunch) and three (backside of the bunch) with one minute intervals is illustrated. Average for each berry is computed from the surface, under skin and pulp temperatures. Hourly points of the difference between berry temperature for berries one, two and three and ambient temperature are also illustrated.

(f) Hourly values of surface, under skin and pulp temperatures for berry one. Hourly points of the difference between surface, under skin and pulp temperatures of berry one and ambient temperature.

(g) Hourly values of surface, under skin and pulp temperatures for berry three.

(h) Hourly points of the difference between surface, under skin and pulp temperatures of berry three and ambient temperature.

Figure 70 (a)-(h) represents distance-weighted least squares scatterplots of specific measurements on day cycle six in Robertson on the east side of the canopy.

(a) Bitmap and thermal images of bunch one.

(b) Hourly air/ambient temperature measured by the weather station in the vineyard.

(c) Hourly solar radiation measured by the weather station in the vineyard as well as photosynthetically active radiation (PAR) measurements for bunch one and two.

(d) Hourly wind speed and relative humidity (RH) measured by the weather station in the vineyard.

(e) The mean surface bunch temperature of the exposed side of bunch one, measured by the thermal imager (TI). The mean, minimum and maximum (whiskers) and standard deviation (box) of the difference between the surface temperature and the ambient temperature of the weather station is also illustrated.

(f) Average berry temperature for berries one, two (exposed side of the bunch) and three (backside of the bunch) with one minute intervals is illustrated. Average for each berry was computed from the surface, under skin and pulp temperatures. Hourly points of the difference between berry temperature for berries one, two and three and ambient temperature are illustrated.

(g) Hourly values of surface, under skin and pulp temperatures for berry one. Hourly points of the difference between surface, under skin and pulp temperatures of berry one and ambient temperature.

(h) Hourly values of surface, under skin and pulp temperatures for berry three. Hourly points of the difference between surface, under skin and pulp temperatures of berry three and ambient temperature.

Figure 71 (a)-(h) represents distance-weighted least squares scatterplots of specific measurements on day cycle two in Robertson on the west side of the canopy.

(a) Bitmap and thermal images of bunch one.

(b) Hourly air/ambient temperature measured by the weather station in the vineyard.

(c) Hourly solar radiation measured by the weather station in the vineyard.

(d) Hourly wind speed and relative humidity (RH) measured by the weather station in the vineyard.

(e) The mean surface bunch temperature of the exposed side of bunch one, measured by the thermal imager (TI). The mean, minimum and maximum (whiskers) and standard deviation (box) of the difference between the surface temperature and the ambient temperature of the weather station is also illustrated.

(f) Average berry temperature for berries one, two (exposed side of the bunch) and three (backside of the bunch) with one minute intervals is illustrated. Average for each berry was computed from the surface, under skin and pulp temperatures. Hourly points of the difference between berry temperature for berries one, two and three and ambient temperature are illustrated.

(g) Hourly values of surface, under skin and pulp temperatures for berry one. Hourly points of the difference between surface, under skin and pulp temperatures of berry one and ambient temperature.

(i) Hourly values of surface, under skin and pulp temperatures for berry three. Hourly points of the difference between surface, under skin and pulp temperatures of berry three and ambient temperature.

Figure 72 (a)-(h) represents distance-weighted least squares scatterplots of specific measurements on day cycle three in Robertson on the west side of the canopy.

(a) Bitmap and thermal images of bunch one.

(b) Hourly air/ambient temperature measured by the weather station in the vineyard.

(c) Hourly solar radiation measured by the weather station in the vineyard as well as photosynthetically active radiation (PAR) measurements for bunch one and two.

(d) Hourly wind speed and relative humidity (RH) measured by the weather station in the vineyard.

(e) The mean surface bunch temperature of the exposed side of bunch one, measured by the thermal imager (TI). The mean, minimum and maximum (whiskers) and standard deviation (box) of the difference between the surface temperature and the ambient temperature of the weather station is also illustrated.

(f) Average berry temperature for berries one, two (exposed side of the bunch) and three (backside of the bunch) with one minute intervals is illustrated. Average for each berry was computed from the surface, under skin and pulp temperatures. Hourly points of the difference between berry temperature for berries one, two and three and ambient temperature are illustrated.

(g) Hourly values of surface, under skin and pulp temperatures for berry one. Hourly points of the difference between surface, under skin and pulp temperatures of berry one and ambient temperature.

Figure 73 (a)-(i) represents distance-weighted least squares scatterplots of specific measurements on day cycle five in Robertson on the west side of the canopy.

(a) Bitmap and thermal images of bunch one.

(b) Hourly air/ambient temperature measured by the weather station in the vineyard.

(c) Hourly solar radiation measured by the weather station in the vineyard as well as photosynthetically active radiation (PAR) measurements for bunch one and two.

(d) Hourly wind speed and relative humidity (RH) measured by the weather station in the vineyard.

(e) The mean surface bunch temperature of the exposed side of bunch one, measured by the thermal imager (TI). The mean, minimum and maximum (whiskers) and standard deviation (box) of the difference between the surface temperature and the ambient temperature of the weather station is also illustrated.

(f) Average berry temperature for berries one, two (exposed side of the bunch) and three (backside of the bunch) with one minute intervals is illustrated. Average for each berry was computed from the surface, under skin and pulp temperatures. Hourly points of the difference between berry temperature for berries one, two and three and ambient temperature are illustrated.

(g) Hourly values of surface, under skin and pulp temperatures for berry two. Hourly points of the difference between surface, under skin and pulp temperatures of berry two and ambient temperature.

(h) Hourly values of surface, under skin and pulp temperatures for berry three as well as hourly points of the difference between surface, under skin and pulp temperatures of berry three and ambient temperature.

Figure 74 (a)-(f) represents distance-weighted least squares scatterplots of specific measurements on day cycle B in Stellenbosch on the east side of the canopy in the upper ripening zone.

(a) Bitmap and thermal images of bunch.

(b) Air/ambient temperature and relative humidity (RH) measured by a Tinytag® covered with a radiation shield, placed above the canopy, with a 30 minute interval.

(c) Hourly solar radiation measured by the weather station in Heritage garden.

(d) Hourly wind speed and relative humidity (RH) measured by the weather station in Heritage garden.

(e) Interior bunch temperature measured using a thermocouple with a 15 minute interval. The difference between bunch and ambient temperature (gill screen) is also illustrated.

(f) The mean surface bunch temperature of the exposed side of bunch one, measured by the thermal imager (TI). The mean, minimum and maximum (whiskers) and standard deviation (box) of the difference between the surface temperature and the ambient temperature of the weather station is also illustrated.

Figure 75 (a)-(i) represents distance-weighted least squares scatterplots of specific measurements on day cycle F in Stellenbosch on the east side of the canopy in the upper ripening zone.

(a) Bitmap and thermal images of bunch.

(b) Air/ambient temperature and relative humidity (RH) measured by a Tinytag® covered with a radiation shield, placed above the canopy, with a 30 minute interval.

(c) Hourly solar radiation measured by the weather station in Heritage garden as well as photosynthetically active radiation (PAR) for the top and bottom sections of the bunch.

(d) Hourly wind speed and relative humidity (RH) measured by the weather station in Heritage garden.

(e) Interior bunch temperature measured using a thermocouple with a one minute interval. The difference between bunch and ambient temperature (gill screen) is also illustrated.

(f) The mean surface bunch temperature of the exposed side of bunch one, measured by the thermal imager (TI). The mean, minimum and maximum (whiskers) and standard deviation (box) of the difference between the surface temperature and the ambient temperature of the weather station is also illustrated.

(g) Average berry temperature for berries one, two (exposed side of the bunch) and three (backside of the bunch) with one minute intervals is illustrated. Averages for each berry were computed from the surface, under skin and pulp temperatures. Hourly points of the difference between berry temperature for berries one, two and three and ambient temperature are illustrated.

(h) Hourly values of surface, under skin and pulp temperatures for berry one. Hourly points of the difference between surface, under skin and pulp temperatures of berry one and ambient temperature.

(i) Hourly values of surface, under skin and pulp temperatures for berry three. Hourly points of the difference between surface, under skin and pulp temperatures of berry three and ambient temperature.

Figure 76 (a)-(i) represents distance-weighted least squares scatterplots of specific measurements on day cycle C in Stellenbosch on the east side of the canopy in the lower ripening zone.

(a) Bitmap and thermal images of bunch.

(b) Air/ambient temperature and relative humidity (RH) measured by a Tinytag® covered with a radiation shield, placed above the canopy, with a 30 minute interval.

(c) Hourly solar radiation measured by the weather station in Heritage garden.

(d) Hourly wind speed and relative humidity (RH) measured by the weather station in Heritage garden.

(e) Interior bunch temperature measured using a thermocouple with a 15 minute interval. The difference between bunch and ambient temperature (gill screen) is also illustrated.

(f) The mean surface bunch temperature of the exposed side of bunch one, measured by the thermal imager (TI). The mean, minimum and maximum (whiskers) and standard deviation (box) of the difference between the surface temperature and the ambient temperature of the weather station is also illustrated.

(g) Average berry temperature for berries one, two (exposed side of the bunch) and three (backside of the bunch) with one minute intervals is illustrated. Averages for each berry were computed from the surface, under skin and pulp temperatures. Hourly points of the difference between berry temperature for berries one, two and three and ambient temperature are illustrated.

(h) Hourly values of surface, under skin and pulp temperatures for berry two. Hourly points of the difference between surface, under skin and pulp temperatures of berry two and ambient temperature.

(i) Hourly values of surface, under skin and pulp temperatures for berry three. Hourly points of the difference between surface, under skin and pulp temperatures of berry three and ambient temperature.

Figure 77 (a)-(i) represents distance-weighted least squares scatterplots of specific measurements on day cycle H in Stellenbosch on the east side of the canopy in the lower ripening zone.

(a) Bitmap and thermal images of bunch.

(b) Air/ambient temperature and relative humidity (RH) measured by a Tinytag® covered with a radiation shield, placed above the canopy, with a 30 minute interval.

(c) Hourly solar radiation measured by the weather station in Heritage garden as well as photosynthetically active radiation (PAR) for the top section of the bunch.

(d) Hourly wind speed and relative humidity (RH) measured by the weather station in Heritage garden.

(e) Interior bunch temperature measured using a thermocouple with a one minute interval. The difference between bunch and ambient temperature (gill screen) is also illustrated.

(f) The mean surface bunch temperature of the exposed side of bunch one, measured by the thermal imager (TI). The mean, minimum and maximum (whiskers) and standard deviation (box) of the difference between the surface temperature and the ambient temperature of the weather station is also illustrated.

(g) Average berry temperature for berries one, two (exposed side of the bunch) and three (backside of the bunch) with one minute intervals is illustrated. Averages for each berry were computed from the surface, under skin and pulp temperatures. Hourly points of the difference between berry temperature for berries one, two and three and ambient temperature are illustrated.

(h) Hourly values of surface, under skin and pulp temperatures for berry one. Hourly points of the difference between surface, under skin and pulp temperatures of berry one and ambient temperature.

(i) Hourly values of surface, under skin and pulp temperatures for berry three. Hourly points of the difference between surface, under skin and pulp temperatures of berry three and ambient temperature.

Figure 78 (a)-(i) represents distance-weighted least squares scatterplots of specific measurements on day cycle G in Stellenbosch on the west side of the canopy in the upper ripening zone.

(a) Bitmap and thermal images of bunch.

(b) Air/ambient temperature and relative humidity (RH) measured by a Tinytag® covered with a radiation shield, placed above the canopy, with a 30 minute interval.

(c) Hourly solar radiation measured by the weather station in Heritage garden as well as photosynthetically active radiation (PAR) for the top section of the bunch.

(d) Hourly wind speed and relative humidity (RH) measured by the weather station in Heritage garden.

(e) Interior bunch temperature measured using a thermocouple with a one minute interval. The difference between bunch and ambient temperature (gill screen) is also illustrated.

(f) The mean surface bunch temperature of the exposed side of bunch one, measured by the thermal imager (TI). The mean, minimum and maximum (whiskers) and standard deviation (box) of the difference between the surface temperature and the ambient temperature of the weather station is also illustrated.

(g) Average berry temperature for berries one, two (exposed side of the bunch) and three (backside of the bunch) with one minute intervals is illustrated. Averages for each berry were computed from the surface, under skin and pulp temperatures. Hourly points of the difference between berry temperature for berries one, two and three and ambient temperature are illustrated.

(h) Hourly values of surface, under skin and pulp temperatures for berry one. Hourly points of the difference between surface, under skin and pulp temperatures of berry one and ambient temperature.

(i) Hourly values of surface, under skin and pulp temperatures for berry three. Hourly points of the difference between surface, under skin and pulp temperatures of berry three and ambient temperature.

Figure 79 (a)-(i) represents distance-weighted least squares scatterplots of specific measurements on day cycle I in Stellenbosch on the west side of the canopy in the upper ripening zone.

(a) Bitmap and thermal images of bunch.

(b) Air/ambient temperature and relative humidity (RH) measured by a Tinytag® covered with a radiation shield, placed above the canopy, with a 30 minute interval.

(c) Hourly solar radiation measured by the weather station in Heritage garden as well as photosynthetically active radiation (PAR) for the top and bottom sections of the bunch.

(d) Hourly wind speed and relative humidity (RH) measured by the weather station in Heritage garden.

(e) Interior bunch temperature measured using a thermocouple with a one minute interval. The difference between bunch and ambient temperature (gill screen) is also illustrated.

(f) The mean surface bunch temperature of the exposed side of bunch one, measured by the thermal imager (TI). The mean, minimum and maximum (whiskers) and standard deviation (box) of the difference between the surface temperature and the ambient temperature of the weather station is also illustrated.

(g) Average berry temperature for berries one, two (exposed side of the bunch) and three (backside of the bunch) with one minute intervals is illustrated. Averages for each berry were computed from the surface, under skin and pulp temperatures. Hourly points of the difference between berry temperature for berries one, two and three and ambient temperature are illustrated.

(h) Hourly values of surface, under skin and pulp temperatures for berry two. Hourly points of the difference between surface, under skin and pulp temperatures of berry two and ambient temperature.

(i) Hourly values of surface, under skin and pulp temperatures for berry three. Hourly points of the difference between surface, under skin and pulp temperatures of berry three and ambient temperature.

Figure 80 (a)-(i) represents distance-weighted least squares scatterplots of specific measurements on day cycle D in Stellenbosch on the west side of the canopy in the lower ripening zone.

(a) Bitmap and thermal images of bunch.

(b) Air/ambient temperature and relative humidity (RH) measured by a Tinytag® covered with a radiation shield, placed above the canopy, with a 30 minute interval.

(c) Hourly solar radiation measured by the weather station in Heritage garden as well as photosynthetically active radiation (PAR) for the top section of the bunch.

(d) Hourly wind speed and relative humidity (RH) measured by the weather station in Heritage garden.

(e) Interior bunch temperature measured using a thermocouple with a one minute interval. The difference between bunch and ambient temperature (gill screen) is also illustrated.

(f) The mean surface bunch temperature of the exposed side of bunch one, measured by the thermal imager (TI). The mean, minimum and maximum (whiskers) and standard deviation (box) of the difference between the surface temperature and the ambient temperature of the weather station is also illustrated.

(g) Average berry temperature for berries one, two (exposed side of the bunch) and three (backside of the bunch) with one minute intervals is illustrated. Averages for each berry were computed from the surface, under skin and pulp temperatures. Hourly points of the difference between berry temperature for berries one, two and three and ambient temperature are illustrated.

(h) Hourly values of surface, under skin and pulp temperatures for berry two. Hourly points of the difference between surface, under skin and pulp temperatures of berry two and ambient temperature.

(i) Hourly values of surface, under skin and pulp temperatures for berry three. Hourly points of the difference between surface, under skin and pulp temperatures of berry three and ambient temperature.

Figure 81 (a)-(i) represents distance-weighted least squares scatterplots of specific measurements on day cycle E in Stellenbosch on the west side of the canopy in the upper ripening zone.

(a) Bitmap and thermal images of bunch.

(b) Air/ambient temperature and relative humidity (RH) measured by a Tinytag®

(c) covered with a radiation shield, placed above the canopy, with a 30 minute interval.

(d) Hourly solar radiation measured by the weather station in Heritage garden as well as photosynthetically active radiation (PAR) for the top section of the bunch.

(e) Hourly wind speed and relative humidity (RH) measured by the weather station in Heritage garden.

(f) Interior bunch temperature measured using a thermocouple with a 15 minute interval. The difference between bunch and ambient temperature (gill screen) is also illustrated.

(g) The mean surface bunch temperature of the exposed side of bunch one, measured by the thermal imager (TI). The mean, minimum and maximum (whiskers) and standard deviation (box) of the difference between the surface temperature and the ambient temperature of the weather station is also illustrated.

(h) Average berry temperature for berries one, two (exposed side of the bunch) and three (backside of the bunch) with one minute intervals is illustrated. Averages for each berry were computed from the surface, under skin and pulp temperatures. Hourly points of the difference between berry temperature for berries one, two and three and ambient temperature are illustrated.

(i) Hourly values of surface, under skin and pulp temperatures for berry one. Hourly points of the difference between surface, under skin and pulp temperatures of berry one and ambient temperature.

(j) Hourly values of surface, under skin and pulp temperatures for berry three. Hourly points of the difference between surface, under skin and pulp temperatures of berry three and ambient temperature.

Chapter 4

General discussion and conclusions

CHAPTER IV: GENERAL DISCUSSION AND CONCLUSIONS

4.1 Introduction

Variability in the grapevine microclimate is an inevitable feature in nature which requires further investigation and understanding. Variability in a bunch can affect sampling techniques for scientific studies related to berry composition and gene expression as well as the sampling required for the determination of harvest dates, which is of crucial importance in industry. Variability that exists in a bunch is a product of the macro-, meso- and microclimates.

A brief overview of the different macro- and mesoclimates of the two vineyards in Robertson and Stellenbosch was conducted. The proximity to the sea (and the influence of the mountain ranges impacting on wind velocity, direction and temperature) caused differences with regard to the diurnal and daily ambient temperatures as a result of the sea breeze, which picked up in the afternoon in Stellenbosch, but which was absent in Robertson. The sea breeze had a dominating effect on bunch surface and berry temperatures and e.g. caused west facing bunches/berries in Stellenbosch to decrease in temperature in the afternoon. This was specifically for a north-south row orientation and may be different for other row orientations where differences occur in the timing of bunch exposure to radiation and peak temperatures (Tarara *et al.*, 2005). The susceptibility of a bunch/berry to temperature changes as a result of wind will depend largely on the wind direction and row orientation.

The main focus of the study was the microclimate on and around the bunch as well as temperature on a finer level, i.e. intra-berry. A comparison of the existing technology used to measure bunch/berry temperature was performed. This focussed on aspects such as spatial and temporal variability, bunch exposure/orientation and training system. The technicalities related to the sensors were discussed.

4.2 Comparing existing technology used to measure bunch/berry temperature

4.2.1 Spatial (on the bunch/berry) and temporal (diurnal or seasonal) variability

Spatial and temporal variability on a bunch or berry decreased with a decrease in direct radiation. The berry situated at the back of the bunch experienced little or no variability as a result of the absence or minimal direct radiation. Conditions as experienced by berry three may thus be more desirable when it comes to composition. Ruffner *et al.* (1976) observed higher levels of malic acid under lower temperature regimes (20/15°C day/night) compared to the lower malic acid levels at higher day/night temperatures (30/25°C). This was as a result of the degradation that occurred under 30/25°C day/night temperatures. Mori *et al.* (2007) found half the amount of anthocyanins in berries exposed to day temperatures of 35°C (controlled by means of a phytotron) compared to the control with day temperatures of 25°C. Regulated studies performed under controlled conditions may not be a true representation of outside conditions. In the present study, the berry situated at the back of the bunch was below 35°C in Robertson and below 30°C in Stellenbosch, compared to temperatures of above 40°C observed on the front side of the bunch. This possibly suggests preferable conditions at the back of the bunch in terms of berry composition and thus wine quality. A possible suggestion to create such conditions for the entire bunch in order to reduce the variability and risk of extreme temperature conditions could be the use of a different trellising system that allows sufficient light penetration (in other words, an optimal light microclimate) for optimal photosynthesis, crucial for sugar accumulation and colour formation. Bunches should be mostly out of direct radiation, with few, randomly distributed gaps through which direct radiation can pass. Hunter (2000) observed higher yields and improved fruit composition in treatments where canopy management practices were applied (vertical shoot positioning trellis system) compared to the control with no management. These included shoot positioning, suckering, topping and leaf removal, which improved microclimate in terms of light and air flow. A berry situated deep in the canopy behind more leaf layers may experience little or no light, whereas a berry situated at the back of an exposed bunch, such as in this study, may have received diffuse light mostly on the bottom and sides as well as possible fluctuations of direct light through gaps in the canopy. Berry temperatures of 6-10°C above ambient temperature were observed in Robertson when the bunch was directly exposed, which may have been a combination of conduction through the bunch and diffuse radiation. In studies where bunches are shaded by the canopy, temperature conformed to ambient (Spayd *et al.*, 2002).

The negative connotations regarding bunch variability in composition may also be questioned. It could be argued that spatial variability may add to the complexity in wine which may be lost with even shading or exposure. It is nevertheless always better to have knowledge of the existing variability, in order to make decisions on how it could be managed. Spatial variability within and between bunches makes scientific studies with regard to berry composition a challenge, specifically when it comes to sampling, which is more commonly done in a random fashion.

The thermal imager was a useful tool in observing the spatial variability within and between bunches. Interestingly, on-bunch variability was not notably higher in the more variable canopy in Stellenbosch. Increased variability occurred for longer periods in Stellenbosch, but due to the different intervals (in Robertson and Stellenbosch) this may not be an accurate observation. Further studies should perform identical procedures in both canopies, thus making it easier to compare.

4.2.2 Bunch orientation/exposure and training system (canopy architecture)

Bunch orientation, the relative positioning of bunches within the canopy, as well as bunch structure contributed to the bunch/berry temperature regime. With regard to the bunch orientation, a difference in composition between east-facing and west-facing bunches may occur as a result of different trends, such as the rapid increase in berry temperature on the east side in the morning as opposed to the constant increase in berry temperature on the west side from the morning until approximately 17:00. The canopy surrounding the bunch and the structure of the bunch played an important role in on-bunch variability. For a bunch further out of the canopy, a larger portion of the bunch was exposed and the exposure occurred for a longer period. The top section of the bunch thus received intense direct radiation, which caused higher surface temperatures, such as above 40°C, and increased variability within the bunch. This was observed for the bunch situated in the lower ripening zone of the Ballerina training system with no canopy protection above the bunch. The structure of the bunch also contributed to the on-bunch variability as an overhanging top section was observed to create shading of the lower berries despite being fully exposed.

4.2.3 Intra-berry temperature differences

No notable differences were observed between temperatures within the berry, i.e. on the surface, under the skin and in the pulp. Where differences were observed, sensor positioning appeared to be the cause, specifically as issues arose with the surface probe. The thermal imager was useful in determining whether the berry surface temperatures of the thermocouples were anomalous to what was expected. This occurred as a result of the difficulty in positioning the sensor close to the skin. If surface temperatures of the thermocouples on the visible side of the bunch did not fall in the minimum-maximum range of the thermal image, the measurements were classified as abnormal. The temperature differences within a berry were not observed with the hourly data, emphasizing the importance of high resolution data (i.e. one minute intervals), which detects important detail which may be important with regard to composition. Fluctuations in berry temperature as a result of the movement of leaves were often missed with the hourly data. The rapid increase in berry and bunch surface temperature on the east side in the morning may also be of importance to the overall quality, which may be disregarded in longer interval data. It can be suggested for future research to incorporate earlier stages of berry development as well as to monitor the ambient temperature close to the berry surface.

4.2.4 Perspectives on the optimal measurement strategy of bunch/berry temperature

When it comes to selecting the appropriate method to measure temperature in a bunch or berry, it depends on the objective. If the idea is to quantify temperature of the whole bunch, the microclimate around it as well as its relative positioning within the canopy, will play an important role in determining what conditions the majority of the bunch is experiencing. Depending on the morphology of the bunch maybe only a small fraction on the visible side of the bunch is exposed to direct radiation, causing increased temperatures, which are not representative of the bunch. In this situation a sensor should be placed in a shaded situation. Berry shading could be different depending on the berry’s position relative to the bunch axis, with peripheral berries at the back of the bunch possibly receiving radiation from the other side of the canopy. The thermal imager could aid in selecting the appropriate area which is most representative of the bunch. A thin thermocouple placed in the pulp of a berry in the area selected would suffice. According to this study the specific placement within the berry during the ripening period was not of huge importance due to an absence of notable differences in the different portions of the berry. This suggests the beneficial use of the thermal camera for bunch or berry temperature, as surface temperature seems to represent the majority of the berry. However, this had not been investigated for the early berry developmental stages pre-véraison. The quality of the camera, i.e. the resolution, will also determine its ability to distinguish between berries. In this study, a relatively low cost camera was used, which did not allow for this, but in more detailed studies it could be possible to define a target area on the bunch and move the camera closer, effectively increasing the resolution.

The thermal camera posed as a useful tool for the assessment of spatial variability in a bunch; however, this was only investigated for the visible side of the bunch. Images of the top, bottom and sides may have added value to the overall variability. Temporal variability was better assessed with the thermocouples, which recorded temperatures at shorter intervals and observed quick changes in temperature, for which hourly data (thermal imaging) failed to account. Such rapid changes in temperature may be physiologically relevant.

Interior bunch temperature followed ambient and berry three (at back of the bunch) temperatures closely suggesting that it may be a valuable measurement, depending on the conditions which the majority of the bunch experiences. However, it fails to account for increased berry temperatures as a result of direct radiation as experienced by front side berries.

4.3 Assessing potential long-term (seasonal) differences in temperature related to thermal time accumulation.

Previous sections dealt with the reaction of bunches/berries on specific days within the ripening phase. It is also relevant to look at potential long-term seasonal impact of temperature accumulation. The thermocouples placed permanently in bunches in Stellenbosch illustrated that the west lower bunch showed significantly lower temperature accumulation than the east upper and lower bunches. Interestingly, no significant differences in temperature accumulation were observed between the upper and lower ripening zones, whereas on the specific measuring dates, bunch and berry temperatures appeared slightly higher in the lower ripening zone. The east side tended to accumulate more temperature units compared to the west, which was also observed for bunch and berry temperatures on the specific day cycles, concluded to have been as a result of the rapidly increasing ambient temperatures in the morning and cool sea breeze in the afternoon, mentioned previously. The highest variability was observed between sensors in a bunch, specifically on the lower east bunch as a result of canopy and bunch structure, which was also observed in the results of the thermal images. This again highlights the importance of bunch variability, which not only occurred on the specific dates but right through the ripening period. Differences in berry composition within a bunch would thus be probable.

A disadvantage related to thermal time accumulation, whether it was through the season or through the day, was the absence of detail observed in the absolute diurnal temperatures. Berries on the east and west sides in Stellenbosch showed no differences in thermal accumulation, whereas differences in the pattern of temperature, specifically the rate of temperature change, were notable. Such differences may be of importance, physiologically.

4.4 Technicalities related to the sensors

The *positioning of sensors* was of huge importance in this study and will continue to be of significant importance for future studies, especially with regard to effects of temperature on berry composition. The canopy sensor, which is used widely, is dependent on the position relative to the direct radiation, as it appears more reactive to direct sunlight. The use of a single sensor for characterising the canopy climate has to be questioned, in terms of the position it needs to be in to define canopy temperature adequately. A sensor placed in a gap in the canopy would increase to a higher temperature than a sensor shaded by leaves. Both of those situations occur in a canopy and thus both need to be quantified to capture canopy variability sufficiently. In addition, the material of the sensor has different thermal properties compared to air and thus may differ in reaction to temperature. Although these sensors are widely used in viticulture applications, they will be much more accurate without incidence or direct/diffuse radiation, as is the case for instance when they are used to monitor the temperature within a cold room. Canopy air temperature therefore preferably needs to be quantified using a shielded sensor.

Similarly, with the *quantum sensor* a small change in its positioning can result in large differences in light intensity. In a situation where the sensor was placed above the bunch which was shaded by leaves, it received little or no radiation whereas the majority of the bunch was in direct sunlight, thus giving an inaccurate/inappropriate measurement for that bunch. The sensor should be placed as close as possible to the berry being measured.

Due to the variability existing on a bunch, *thermocouple positioning* is of huge importance. Large variability was observed in the thermal accumulation between sensors on a single bunch for February and March. It is thus important to select a berry or berries that adequately represent the bunch and that are not experiencing extremes in temperature, which only a small portion of the bunch may be experiencing. The use of the thermal imager in this regard may aid in determining which berries/area on the bunch is most representative.

Technicalities related to the use of the *thermal imager* occurred with regard to its positioning relative to the sun. Certain images gave temperatures anomalous to what was expected. This mostly occurred on the east side in the late afternoon when the sun was low. It was thus concluded that the cause was the direct rays of light entering the camera lens resulting in faulty images. It is advisable to use a screen when facing the sun to block out the rays when capturing an image. A summary of the positives, negatives and difficulties, which surrounded the sensors used in this study, is presented in Table 9.

4.5 Perspectives for future research

Further research on the effect of berry stage on temperature would be of interest to see how the colour (from green to red/black) and changing berry composition (accumulation of sugar and reduction of water) may affect berry temperatures. Radiation sensors placed on the berry being measured would aid in a better understanding of the relationship between direct radiation and berry temperature. A better understanding of the thermo-dynamics of a bunch with regard to bunch compaction and the contribution of conduction through the bunch is also of importance.

In this study, the driving factors of berry temperature were the ambient temperature and the solar flux density or direct radiation. Bunch or berry temperatures generally remained closer to ambient temperature when the bunch/berry was out of direct radiation. With direct exposure, berry temperatures of 20°C above ambient were observed. The sea breeze was also observed to have a dominating effect by suppressing bunch (surface and interior) and berry temperatures in Stellenbosch. Future studies could focus on the calibration of energy balance models such as developed by Cola *et al.* (2009) which allow for the consideration of the main driving factors of berry temperature (i.e. air temperature, relative humidity, solar short- and long-wave net radiation and wind speed).

This study was relevant for future development of berry temperature modelling. The variability in temperature observed within a bunch and in certain cases between bunches, emphasized the complexities surrounding berry or bunch temperature predictions. Consequently, studies developing models, manipulate the bunch environment, such as done by Cola *et al.* (2009) where leaves were removed, in order to reduce variability and improve the accuracy. The question is, what proportion of bunches are experiencing these conditions? In a commercial vineyard, there may be a great possibility that most bunches experience certain shaded and exposed portions, creating variability. It is thus imperative to measure the light environment around the bunch using techniques such as hemispherical photography or pyranometers placed as close as possible to the temperature sensor. The bunch variability observed in this study also highlights the importance of sensor placement when it comes to model development. In this situation, a berry most representative of the bunch should be selected.

Different sensors are required for analysis of spatial and temporal variability, and the technicalities related to their use must be noted. Variability on a microclimatic level is an important concept affecting wine quality and requires attention for the future development of berry temperature models.

Table 9 Positives, negatives and difficulties that arose with the different sensors used in this study

Sensor	Measurement (in study)	Positives	Negatives	Difficulties
Weather station	Ambient conditions (air temperature, relative humidity, rainfall, global radiation)	• Large data base therefore regular acquisition of data not required • More than two meteorological elements measured • Continuous measurements	• Costly maintenance • Lacking sufficient weather stations in complex terrains • Immobile	• Placement critically important, i.e. in an open area with no buildings or trees that may influence readings as well as high enough ground to avoid cooler temperature readings which occur in hollows
Sensor (Tinytag®) in radiation shield	Air temperature and relative humidity	• Efficient data acquisition • Simple setup • Less susceptible to increased temperatures due to direct radiation than unshielded sensor	• Due to body of the sensor (Tinytag®), higher maximum and minimum temperatures may be observed	• For more accurate ambient temperature measurement, smaller sensor is preferred which is less reactive to increased temperatures in the shield
Canopy sensor (Tinytag®)	Air temperature and relative humidity	• Efficient data acquisition • Simple setup • Continuous measurements	• Sensitive to direct radiation (increased air temperatures possibly due to yellow colour and size of the body)	• Variable canopy conditions (leaf distribution) and positioning for a representative measurement is difficult and a radiation shield is advisable
Quantum sensor	Photosynthetic active radiation (PAR)	• Small size allows for close positioning to the bunch/berry • Continuous measurements	• Costly • Large variability in canopy, therefore placement critical • Point measurement (spatially)	• Measurement largely dependent on sensor levelling and difficult to fix it to a permanent position (variable shoot angle) • For light quantification of canopy, Ceptometer may be preferable due to integrated measurement
Thermal imager	Bunch surface temperature	• Quantification of spatial variability • Non-destructive	• Time consuming setup (with tripod) • Overheating of instrument when left in the sun • Continuous imaging difficult due to short lifespan of battery • Difficulty in distinguishing berries visually on image 1m from the bunch • costly	• Faulty thermal images resulted when rays of light entered camera lens and therefore advisable to use a shield to block out sun when collecting images • Advisable to use a screen behind canopy to differentiate between gaps, soil and leaves

Table 10 (continued)

Sensor	**Measurement (in study)**	**Positives**	**Negatives**	**Difficulties**
Standard thermocouples	Interior bunch temperature	• Diurnal variability (continuous temperature measurement) • Possibly represents a considerable portion of bunch (depending on positioning of bunch within canopy) • Non destructive	• Not representative of exposed berries (smoothed curve) • Difficult to see if in air space or touching berry (may result in different temperatures)	• Insertion into compact bunches may be difficult, therefore advisable to insert in early stages of development, when bunch is loose (problems may arise in compact bunches, where berries grow, closing air spaces between them)
Thin thermocouples	Surface, under skin and pulp berry temperatures	• Small dimensions of sensor allows for berry temperature (pulp) measurements through the season (small entry wound) • More sensitive to temperature changes compared to standard thermocouple • Diurnal variability (continuous measurement)	• Data loggers are costly • Setup is time consuming for the different positions within the berry • Point measurement (spatially)	• In riper stage of berry development shorter measuring time (berry desiccates slightly faster) therefore for long term measurements, i.e. through season, it is advisable to insert in the green berry stage, as wound closes around the sensor • Due to surface point measurement, measurements can vary depending on exposure of berry, therefore placement important

4.6 Literature cited

Cola, G., Failla, O. & Mariani, L., 2009. BerryTone--A simulation model for the daily course of grape berry temperature. Agric For Meteorol 149 (8), 1215-1228.

Hunter, J., 2000. Implications of seasonal canopy management and growth compensation in grapevine. S Afr J Enol Vitic 21.

Mori, K., Goto-Yamamoto, N., Kitayama, M. & Hashizume, K., 2007. Loss of anthocyanins in red-wine grape under high temperature. J Exp Bot 58 (8), 1935-1945.

Ruffner, H.P., Hawker, J.S. & Hale, C.R., 1976. Temperature and enzymic control of malate metabolism in berries of *Vitis vinifera*. Phytochemistry 15 (12), 1877-1880.

Spayd, S.E., Tarara, J.M., Mee, D.L. & Ferguson, J., 2002. Separation of sunlight and temperature effects on the composition of *Vitis vinifera* cv. Merlot berries. Am J Enol Vitic 53 (3), 171-182.

Tarara, J., Ferguson, J., Hoheisel, G.A. & Perez Peña, J., 2005. Asymmetrical canopy architecture due to prevailing wind direction and row orientation creates an imbalance in irradiance at the fruiting zone of grapevines. Agric For Meteorol 135 (1), 144-155.