

Leaf Wetness Duration Measurements in a Citrus Canopy

By

Martin Tarisai Kudinha

A dissertation submitted to the Faculty of Natural and Agricultural Sciences

in partial fulfillment of the requirement for the degree of

Doctor of Philosophy

in Agricultural Meteorology

Promoter: Prof Sue Walker

University of the Free State

Bloemfontein, South Africa

2014

DECLARATION

I declare that the dissertation hereby submitted by me for the degree of Doctor of Philosophy at the University of the Free State is my own independent work, except where acknowledged, and has not previously been submitted by me at another university or faculty. I furthermore cede copyright of the dissertation in favour of the University of the Free State.

Martin Tarisai Kudinha

Date: 30 January 2014

Place: Bloemfontein, Republic of South Africa

ACKNOWLEDGEMENT

Foremost, I would like to express my most sincere thanks to my supervisor Professor Sue Walker, who patiently provided the vision, guidance, advice, valuable knowledge and unflagging encouragement throughout my studies. I most sincerely appreciate all her assistance and support for my research and life in general. Indeed, words only cannot express what I owe her. Her integrity, patience, passion for Agrometeorology as well as self-discipline will always be an inspiration to me. I truly appreciate her.

I also extend my special gratitude to the University of Stellenbosch for allowing me to use their Welgenvallen Experimental Farm for my field trials. I always ask myself what I would have done at night if there was no accommodation available during my night observations. My special thanks and appreciation go to Mr Van Kerwel for arranging accommodation for me and his continued hospitality during my field observations. I also wish to express my sincere thanks to Campbell Scientific Africa and particularly Charl Le Roux for their support by providing me with wetness sensor and datalogger software free of charge. I also acknowledge and appreciate the invaluable assistance and helpful suggestions in datalogger programming from Dr Dzikiti.

I should mention The Department of Soil, Crop and Climate Sciences for allowing me to be part of this great professional community. The Agrometeorology Section staff of Mrs. Ronelle, Mrs. Linda, Mr. Stephen and Mr. Daniel deserve my thanks, their friendship and assistance meant more to me than I can ever express. A special thanks goes to Mr. Wilhelm Hoffman, for providing the technical knowledge in equipment installation. The assistance and motivation from Dr Weldermichael and Dr Bello is highly acknowledged. My fellow Agromet students were sources of laughter, joy and support. I am very happy that, in many cases, my friendships with most of them have extended well beyond our shared time in Bloemfontein.

I wish to thank my family, Dumie and son Takudzwa. Their love and unconditional support provided my inspiration and was my driving force. Finally, I would like to thank My Lord Jesus Christ for the strength and life that he gives me daily.

TABLE OF CONTENTS

DECLARATION	i
ACKNOWLEDGEMENT	ii
LIST OF TABLES	vi
LIST OF FIGURES	viii
LIST OF SYMBOLS AND ABBREVIATIONS	xi
ABSTRACT.....	xiii
Chapter 1 : Literature Review	1
1.1 Leaf wetness and its importance	1
1.2 Devices for measuring leaf wetness.....	3
1.3 Protocol for measuring leaf wetness duration.....	6
1.3.1 Wetness sensor treatment	7
1.3.2 Canopy placement.....	9
1.3.3 Sensor orientation.....	10
1.3.4 Number of sensors.....	11
1.4 Modelling leaf wetness	12
1.4.1 Physical model	14
1.4.2 Empirical models.....	16
1.4.3 Validation of LWD models using field measurements	18
1.5 Conclusion	18
1.6 Justification for current study	20
1.7 Design limitations	20
1.8 Objectives of the study.....	21
1.9 Dissertation composition	21
Chapter 2 : Operation of leaf wetness sensors in a Satsuma Mandarin <i>Citrus unshiu</i> Marchovitch orchard canopy.....	22
2.1 Introduction.....	22
2.2 Materials and Methods.....	23
2.2.1 Field site description	23
2.2.2 Wetness sensors.....	23
2.2.3 Sensor placement in the citrus tree canopy	24

2.2.4	Visual observations of dew	26
2.2.5	Data Analysis	27
2.3	Temporal and spatial variation of leaf wetness in a citrus canopy	28
2.3.1	Variation of weather data on a dew day considering the upper canopy.....	28
2.3.2	Determination of wet/dry canopy index.....	38
2.3.3	Visual observations of occurrence of leaf wetness	38
2.3.4	Comparison of visually observed LWD at different canopy positions	40
2.3.5	Discussion of spatial variations.....	42
2.4	Performance of leaf wetness sensors	47
2.4.1	Wetness duration and weather conditions.....	47
2.4.2	Sensor testing	49
2.4.3	Sensor calibration.....	49
2.4.4	Mean and absolute errors of LWD measured by wetness sensors	55
2.5	Conclusion	59
Chapter 3 : Process of dew formation and dissipation in upper citrus canopy by considering a few typical days		60
3.1.	Introduction.....	60
3.2	Materials and Method	61
3.2.1	Site description.....	61
3.2.2	Data and Measurements	62
3.2.3	Data analysis	65
3.3	Frequency of occurrence of dew formation and dissipation.....	65
3.4	Comparison of dew onset and dry-off as measured by three different methods	69
3.5	Conditions necessary for dew formation	78
3.6	Conclusion	81
Chapter 4 : Leaf energy balance.....		82
4.1	Introduction.....	82
4.2	Theory.....	83
4.3	Materials and Methods.....	86
4.3.1	Field site description	86
4.3.2	Experimental procedure	87

4.3.3	Data Analysis	88
4.4	Results and Discussion	90
4.4.1	Leaf temperature deduction	90
4.4.2	Assessment of the Newton-Raphson method in leaf temperature determination .	94
4.5	Conclusion	102
 Chapter 5 : Determination of leaf wetness duration from simulation models		104
5.1	Introduction.....	104
5.2	Theory.....	105
5.3	Materials and Methods.....	107
5.3.1	Models' input data.....	107
5.3.2	Data Analysis	107
5.4	Results and Discussion	109
5.4.1	Analysis of hourly leaf wetness duration in the upper canopy for different wetness events	109
5.4.2	Analysis of observed leaf wetness duration in both upper and lower canopy levels	110
5.4.3	Analysis of daily leaf wetness duration.....	111
5.4.4	Frequency of errors	112
5.5	Conclusion	116
 Chapter 6 : General discussion and recommendations		117
 References		123

LIST OF TABLES

Table 2.1 Incidence of wetness in the upper during dew days only as well as occurrence of wetness in the lower eastern canopy	40
Table 2.2 Mean daily leaf wetness duration (LWD), in hours per day, in the three citrus canopy positions during different wetness events from 27 th July to 30 th November, 2013.....	41
Table 2.3 Categories of daily observed LWD according to their duration (X) in hours considering a period of 51 days when wetness occurred in the upper canopy level	41
Table 2.4 Categories of daily observed LWD according to their duration (X) in hours considering a period of 41 days when wetness occurred in the lower eastern canopy	42
Table 2.5 Categories of daily observed LWD according to their duration (X) in hours considering a period of 30 days when wetness occurred in the lower western canopy.....	42
Table 2.6 Average leaf and air nightly temperature measured from 27 th July to 30 th November 2012 during dew days (n=22)	43
Table 2.7 Average daily weather conditions (\pm SD) for different wetness categories during the period between 27 th July - 30 th November 2012 at Stellenbosch in the citrus orchard.....	47
Table 2.8 Coefficient of determination (R^2) for the meteorological variables effect on LWD by stepwise multiple regression model	49
Table 2.9 Wet/dry threshold value for Campbell sensors (R_1 and R_2) as well as Decagon sensors (D_1 and D_2).....	50
Table 2.10 Coefficient of determinations for the lower citrus canopy considering visually observed and measured LWD for different wetness days	55
Table 2.11 Mean errors between LWD measured by wetness sensors and observed at different canopy heights and sides of the bottom canopy.....	56
Table 2.12 Total leaf wetness duration (h) observed and measured during considering dew and dry days (n=34)	58
Table 3.1 Days when wetness with all the visual observations were performed (Dew refers to wetness on the upper canopy level)	63
Table 3.2 Time that dew deposition ended as well as the duration of the delay in evaporation after sunrise.....	69
Table 3.3 Time of first occurrence of dew onset according to visual, theoretical as well as according to sensor measurement in citrus canopy during 2012	72
Table 3.4 Mean values of weather parameters during the onset and end of condensation as well as when the leaf was completely dry (\pm SD) calculated for each of the 22 days.....	75
Table 3.5 Classification of weather variables during dew formation	78
Table 3.6 Occurrence of wetness at 15 minute interval based on air temperature and relative humidity variables categories	79

Table 4.1 Classification of weather parameters from automatic weather station at CPUT during May and June, 2010.....	89
Table 4.2 Coefficient of determination (R^2), mean error (ME), mean absolute error (MAE), agreement index (D) and the confidence index (C) for the leaf temperature and weather parameter measurements of the indigenous <i>A. praecox</i> from 6 th June to 11 th June 2010.....	99
Table 4.3 Coefficient of determination, mean error, mean absolute error, agreement index and the confidence index coefficient of indices for the leaf temperature measurements of the <i>S. nicolai</i> plant from 31 st May to 11 th June 2010.....	100
Table 4.4 Coefficient of determination, mean error, mean absolute error, agreement index and the confidence index coefficient of indices for the leaf temperature of the <i>F. microcarpa</i> at a distance from the station (2 m x 2 m) from 18 th May to 20 th May 2010.....	101
Table 5.1 Classification of hits, misses, false alarms and correct negatives.....	108
Table 5.2 Statistical indices comparing hourly visual observations of leaf wetness duration with both the SWEB and relative humidity models for different wetness events in the upper canopy.....	109
Table 5.3 Statistical indices comparing visual observations of leaf wetness duration with both the SWEB and relative humidity models for the lower and upper canopies using all data.....	110
Table 5.4 Coefficient of determination (R^2) between observed and model simulated leaf wetness duration.....	111

LIST OF FIGURES

Fig 2.1 A photo showing wetness sensors located in the upper positions of the citrus canopy at Welgenvallen Experimental Farm of the University of Stellenbosch from 27 th July until 30 th November, 2012.....	25
Fig 2.2 Variation of air temperature, leaf temperature, dew point temperature (DPT) and relative humidity (RH) at Welgenvallen Experimental Farm of the University of Stellenbosch from 17 th August, 2012 until the next day	30
Fig 2.3 Visually observed upper canopy wetness within a citrus canopy at Welgenvallen Experimental Farm of the University of Stellenbosch from 17 th August, 2012 until the next day.....	30
Fig 2.4 Wetness sensors' response (upper canopy level) to dew formation at Welgenvallen Experimental Farm of the University of Stellenbosch from 17 th August, 2012 until the next day.....	31
Fig 2.5 Variation of weather parameters at Welgenvallen Experimental Farm of the University of Stellenbosch from 17 th August, 2012 until the next day.....	33
Fig 2.6 Sensors' response to vapour pressure deficit at Welgenvallen Experimental Farm of the University of Stellenbosch from from 17 th August, 2012 until the next day.....	34
Fig 2.7 Sensors' response to relative humidity at Welgenvallen Experimental Farm of the University of Stellenbosch from 17 th August 2012 till the next day	35
Fig 2.8 Sensors' response to air temperature at Welgenvallen Experimental Farm of the University of Stellenbosch from 17 th August 2012 till the next day	36
Fig 2.9 Variation of sensors' output as a function of leaf temperature at Welgenvallen Experimental Farm of the University of Stellenbosch from 17 th August 2012 till the next day..	37
Fig 2.10 Relationship between LWD and weather parameters (temperature, relative humidity, net radiation and vapour pressure deficit) when the canopy was wet during dew days only (n=24).....	48
Fig 2.11 Relationship between visually observed and sensor measurement LWD in the upper canopy level considering only dew days (n=24, p<0.05) considering sensors R_1, R_2, D_3 and D_4.....	52
Fig 2.12 Relationship between visually observed and sensor measurement LWD in the upper canopy level during rainy days (n=27, p<0.05) considering sensors R_1, R_2, D_3 and D_4....	53
Fig 2.13 Relationship between visually observed and sensor measurement LWD in the upper considering all the wet day (n=51; p<0.05) considering sensors R_1, R_2, D_3 and D_4.....	54
Fig 2.14 Difference between daily measured and observed LWD considering the Decagon sensors for the upper canopy level sensors for the upper canopy level for dew days (n=24) when dew was visually observed from 27 th July to 30 th November, 2012	57

Fig 2.15 Difference between daily measured and observed LWD (daily error) considering the Campbell sensors for the upper canopy level for dew days (n=24) when dew was visually observed from 27 th July to 30 th November, 2012	57
Fig 3.1 Frequency of first occurrence of visual observations of dew formation from a citrus canopy during field experiment for the period 27 th July to 30 th November, 2012.....	66
Fig 3.2 Frequency of visual observations of dew dry-off from citrus orchard leaves for the period of 27 th July to 30 th November 2012	67
Fig 3.3 Time of the first occurrence of dew deposition based on visual observations (observed); sensors (one of the sensors) (D_1) and dew point temperature (theoretical method) for all the dew days during July to November 2012	70
Fig 3.4 Comparison of time of the first occurrence of dew deposition between visual observations, sensors and theoretical method considering all the dew days (n=23)	71
Fig 3.5 Dew dry-off time based on visual observations as well as one of the wetness sensors (D_1) for all the dew days during July to August 2012 in citrus orchard in Stellenbosch.....	73
Fig 3.6 Comparison of observed and sensor dry-off for the days that dew occurred (n=22) from 27 th July to 30 th November, 2012	74
Fig 3.7 Variation of meteorological parameters as well as the leaf temperature from 2 hours before dew deposition began until the canopy was dry, at 15 minute intervals showing all data for the 22 dew days at 15 time interval in a citrus canopy at Stellenbosch for the period from 27 th July to 30 th November 2012.....	77
Fig 3.8 Occurrence of leaf wetness in a citrus orchard at Stellenbosch from 27 th July to 30 th November 2012 (n=596).....	80
Fig 4.1 Diurnal variation of temperature with time of the day for <i>S. nicolai</i> for a period of 12 days as from 31 st May to 11 th June, 2010 from hourly data.....	95
Fig 4.2 Diurnal variation of temperature with time of the day for <i>A. praecox</i> from 11 th to 16 th June 2010 from hourly data	95
Fig 4.3 Comparison of calculated and measured leaf temperature when <i>F. microcarpa</i> leaf was 2 m away from an automatic weather station placed at height of 2 m (with wind speed replaced by 0.005 ms ⁻¹) for the period 18 th to 20 th May 2010 (n=332) based on 10 minute data.	96
Fig 4.4 Comparison of calculated and measured temperature when the <i>F. microcarpa</i> leaf was 2 m away at a height of 3 m on tree (with null wind speed replaced by 0.005 ms ⁻¹), for the period 27 th to 30 th May, 2010 (n=365) based on 10 minute data.....	97
Fig 4.5 Comparison of calculated and measured leaf temperature for <i>S. nicolai</i> for the period 31 st May to 11 th June, 2010 (n=263)	98
Fig 4.6 Comparison of calculated and measured leaf temperature for <i>A. praecox</i> (with wind speed of 0.005 ms ⁻¹) (n=135) for the period from 6 th June to 11 th June 2010	98
Fig 5.1 Frequency of errors in the top canopy from (a) SWEB model (b) relative humidity model for citrus orchard near Stellenbosch in 2012	113

Fig 5.2 Frequency of errors in the lower canopy from (a) SWEB model (b) relative humidity model at at Welgevallen Experimental Farm of the University of Stellenbosch for the citrus canopy 115

LIST OF SYMBOLS AND ABBREVIATIONS

a	leaf shortwave absorptivity
ARC-ISCW	Agricultural Research Council – Institute for Soil, Climate and Water
B_s	bias
C	confidence index
C_{SI}	correct success index
C_p	heat capacity of air (Jkg ⁰ C ⁻¹)
CS	Campbell Scientific
CWSI	Crop Water Stress Index
d	zero plane displacement (m)
D	Willmott agreement index
DOY	day of the year
DPD	dew point depression (°C)
e_a	vapour pressure of the air (kPa)
e_s	saturation vapour pressure (kPa)
F_c	correct estimate
F_{AR}	false alarm ratio
g_H	heat conductance (mol m ⁻² s ⁻¹)
g_v	vapour conductance (mol m ⁻² s ⁻¹)
G	conduction of flux via the soil surface (Wm ⁻²)
h_c	convective heat transfer coefficient for one side of the leaf (Wm ⁻² °C ⁻¹)
h_w	water vapour transfer coefficient for one side of the leaf (Wm ⁻²)
H	sensible heat flux (Wm ⁻²)
k	= 0.41, Von Karman constant
L_u	outgoing longwave radiation (Wm ⁻²)
L_d	incoming longwave radiation (Wm ⁻²)
LAI	leaf area index
LWD	leaf wetness duration (h)
LE	latent heat flux (Wm ⁻²)
L_{sky}	sky longwave radiation (Wm ⁻²)
M	metabolic heat flux (Wm ⁻²)
ME	mean error
MAE	mean absolute error

mV	millivolts
P	air pressure (Pa)
R²	coefficient of determination
R_d	incoming longwave radiation (Wm ⁻²)
R_u	outgoing longwave radiation (Wm ⁻²)
R_g	solar global radiation (Wm ⁻²)
R_n	net radiation (Wm ⁻²)
RH	relative humidity (%)
S	slope of the saturation vapour (Pa°C ⁻¹)
SD	standard deviation
SWEB	Surface Wetness Energy Budget
ΔS	is the net physical storage of energy (Wm ⁻²)
T_a	air temperature (°C)
T_l	leaf temperature (°C)
T_m	average of leaf and air temperature (°C)
$F^1(T_s^n)$	derivative of a function which is temperature dependent
$T_s^{n+1} = T_s^n$	iteration is stopped and T_s^n will be the required leaf temperature
u	wind speed (ms ⁻¹)
w	effective leaf length in the direction of the wind (m)
z_o	roughness coefficient (m)
λ	latent heat of vaporization (J kg ⁻¹)
α	surface albedo
Ω	Ohm, unit of resistance
ρ_a	molar density of air (mol m ⁻³)
σ	= 5.67×10 ⁻⁸ , (Wm ⁻² K ⁻⁴) Stefan Boltzmann constant
ε	leaf emissivity

ABSTRACT

Leaf Wetness Duration Measurements in a Citrus Canopy

Martin Tarisai Kudinha

Doctor of Philosophy in Agricultural Meteorology, University of the Free State,
Bloemfontein, South Africa, 2014

Leaf wetness duration (LWD) is a key component of most disease-warning systems which are designed to help growers to determine when to apply control measures to suppress plant diseases. Since LWD is a complex phenomenon due to its spatial and temporal variability, this can affect the performance of such systems. Despite the importance of LWD, it is not usually measured at most standard weather stations because of lack of standard sensor and protocol. This study was carried out to evaluate and characterize the spatial variability of LWD within a citrus canopy and also to evaluate the performance of two commercially available wetness sensors, namely the Campbell Scientific wetness sensor (Model 237) and the Decagon wetness sensor by comparing them with visual observation of water droplets on the leaves. A total of 6 sensors were installed in the upper and lower canopy levels of the citrus canopy to measure LWD at Welgenvallen Experimental Farm of the University of Stellenbosch from 27 July until 30 November 2012. A total of 62 days were visually observed for LWD. Four of the wetness sensors (2 of each type) were mounted at the upper canopy level (top two-thirds), whilst the other two were placed in the lower one-third of the canopy-one on either side. All the sensors were installed at 45° facing South. Other weather parameters such as air temperature, relative humidity, net radiation above the citrus canopy as well as the leaf temperature were measured by a nearby automatic weather station.

Visual observation of LWD showed the mean daily LWD in the upper canopy level was significantly ($p < 0.05$) longer, by about 1.7 h, in the upper canopy level than in the lower canopy level. However, no significant differences were noted between the lower eastern and western canopy levels, with a difference of only 24 minutes. When rain was the source of wetness, there was no significant difference between LWD at any of the canopy positions due to penetration of rainfall through canopy to lowest level. The mean daily LWD in the upper canopy was 15.5 h compared to 14.3 and 14.1 h in the lower eastern and western canopy positions. Based on these facts, it can then be concluded that the spatial variability of LWD

has to be considered if measurements of LWD are used as inputs to disease-warning system. The linear regression analysis between measured and visually observed LWD showed that the sensors installed in the upper canopy level provided higher accuracy than the sensors placed in the lower canopy level. Although some researchers recommend painting the Campbell sensors, these results showed that even the unpainted Campbell sensors installed in the upper canopy level of a citrus canopy can be used to measure LWD with acceptable accuracy. During dew days, the sensors at the upper canopy level had a MAE of about 1 h compared to more than 2 h for the sensors placed in the lower canopy.

An analysis of leaf and air temperature exhibited that in 96% of the nights when dew was observed, dew deposition in the citrus canopy commenced whenever the leaf temperature fell below the ambient dew point temperature. The first occurrence of dew deposition was mostly observed between 19h45 and 22h00, whilst dew dry-off took place more frequently between 8h45 and 10h30. On average, both the visually observed as well as the sensor predicted 'first onset of dew' was more than 30 minutes after the leaf temperature had fallen below the ambient dew point temperature. It then follows that leaf temperature together with the dew point temperature can be used as an indicator for the onset of dew deposition in citrus canopy.

A study was also conducted under field conditions to evaluate Newton-Raphson iterative method as an alternative approach in the indirect determination of leaf temperature from meteorological data. Three field experiments were performed at two different sites at Cape Peninsula University of Technology, Bellville Campus near Cape Town, using three different plants. Leaf temperatures predicted from the iteration method were compared with field measurements of leaf temperatures obtained from a *Ficus microcarpa* (local tree), potted *Strelitzia nicolai* flowering plant and *Agapanthus praecox*, another indigenous flowering plant growing at CPU nursery complex. The strongest relation, characterized by reasonable precision ($R^2 = 0.89$), high accuracy ($D = 0.96$) and a fairly high value of the confidence index ($C = 0.91$) was obtained when *A. praecox* was used, whilst *S. nicolai* yielded a poorer relationship ($R^2 = 0.71$; $D = 0.77$; $C = 0.64$), and *F. microcarpa* had the worst correlation. Leaf temperature computed by the iteration process showed a tendency of underestimation in all these experiments.

LWD can be also predicted from both empirical and physical models. Finally, a study was also undertaken with the objective to compare the performance of a physical model (SWEB) and an empirical model (RH) using the weather data for the 62 d of measurement. Both models exhibited a similar trend to that of the sensors, in that the accuracy was higher in the top of the canopy compared to the bottom of the canopy. The result also confirmed that models are poor estimators of LWD at the lower canopy levels. The RH model, however, performed better than the SWEB model with a higher fraction of correct estimates (F_c), correct success index (C_{SI}) and lower false alarm ratio (F_{AR}) when considering all the hours for both levels during wet and rainy events. An analysis of the distribution of the errors showed that whilst the SWEB showed a tendency to overestimate LWD, the converse was true for the RH model. Based on these results, it is concluded that if locally calibrated, the RH model can estimate LWD with acceptable accuracy. Consequently, citrus growers who cannot afford to install wetness sensors may therefore consider the use of RH model as part of their disease-warning system. Nevertheless a site-specific calibration is required prior to the use of the model.

Key words: leaf wetness duration, leaf wetness sensors, spatial variability, underestimation, overestimation, dew point temperature, iteration method, visual observation.

Chapter 1

Literature Review

1.1 Leaf wetness and its importance

Leaf wetness is defined as the presence of free water on a plant surface. It is caused by rainfall, fog, drizzle or dew. Depending on the tissue hygroscopicity and physical characteristics of the leaves, it may consist of individual drops or water films of thickness between a few nm and μm (Klemm et al., 2002). The period of time which the water is present on the leaf surfaces is defined as leaf wetness duration (LWD). Leaf wetness is of great importance to agriculture due to the requirement of a layer of free water for the infection processes of many plant pathogens. The longer the leaf surface is wet, the greater the risk of infection and the greater the number of infections per leaf (Hahn, 2009). In plants, pathogens can attack plant leaves or stems and feed on fruits and vegetables which can result in yield loss, lower quality of plant products and increased production costs.

In South Africa, citrus is a very important export product. The country is the second largest exporter of fresh citrus, with exports totalling 65% of total production (Gianessi and Williams, 2012). This important source of foreign exchange can be seriously threatened by restrictive quarantine regulations linked to a fruit disease known as citrus black spot (CBS) caused by the fungus *Guignardia citricarpa*. This disease occurs in citrus-growing regions of SA (Kotze, 1981). Disease symptoms are confined to the surface of the fruit and lesions may appear as a single spot or many spots per fruit. Symptoms on fruit do not significantly reduce yield, but spotted fruit are unacceptable to local or export fresh markets (Truter, 2010). Timely application of fungicides is essential to protect fruit, eradicate infections and prevent symptom development. These sprayings can be substantially reduced if reliable prognostic estimates can be made of actual leaf wetness duration. This would decrease farming input costs and also reduce the chemical load on the environment.

The availability of accurate and reliable leaf wetness data is a key requirement for the successful implementation of any disease warning system because leaf wetness duration is a critical input variable in many disease warning systems. Many phytopathological models use the leaf wetness

parameter in combination with other factors in order to assess the infection risk and pest severity and to manage disease control activities in an efficient way. Many efforts have also been made to model downy mildew (*Plasmopara viticola*) in grapevines. For example, the Metos software model was adapted for South African conditions in 1995 and 2006 to make it more accurate and user-friendly and named Donsige Skimmel Vroeg-Waarskuwingsmodel (DSVW) (Afrikaans for “Downy Mildew Early Warning Model”)(Haasbroek, 2006). According to the author, the DSVW model output now provides an indication (3 different colours - high, medium and low chance) of possible favourable periods for both primary and secondary infection occurrence. Leaf wetness duration, derived from simulation models, has been used as an input for epidemiological models such as PLASMO (Dalla Marta et al., 2005) and PERO to predict *P. viticola* development and intensity in grapevines Other disease warning systems include TOM-CAST, devised by Pitblado (1988) for early blight (pathogen: *Alternaria solani*), Septoria leaf spot (*Septoria lycopersici*) and anthracnose fruit rot of tomatoes (*Colletotrichum coccodes*) and Melcast for Alternaria leaf blight of muskmelon (*Alternaria cucumerina*) (Latina and Evans, 1996). Both TOM-CAST and Melcast advise on application of protective spray when the sum of daily disease-risk ratings, termed disease rating values for TOM-CAST and “environmental favourability indices” for Melcast, reaches a threshold value.

In citrus, the Alter-Rater model was developed for control of Alternaria brown spot, caused by *Alternaria alternata*, which results in serious yield losses in citrus. The Alter-Rater model predicts the need for fungicide applications based on the daily cumulative points that are designed on the basis of rainfall, LWD and temperature (Timmer et al., 2001). Bhatia et al. (2003) found that the Alter-Rater resulted in fewer sprays compared to a calendar spray schedule and its use results in better disease control. According to Timmer and Zitko (1996) model-based decisions on fungicide applications resulted in reduced disease, large increases in fruit production and elimination of unnecessary sprays.

Despite the importance of leaf wetness duration in plant disease epidemiology, the practical measurement and monitoring of leaf wetness is often problematic in an orchard/vineyard/field situation. Unlike most weather parameters, leaf wetness is a difficult variable to measure and

estimate because it is driven by both atmospheric conditions and their interactions with the crop canopy structure, including its composition and physiology. According to Nagel (1962) and Zangvil (1996), the difficulty of dew measurement is both in the definition of dew as well as in its actual measurement. The concept of leaf wetness has been poorly defined in literature with no precise spatial definition, although it has been variously applied to an individual drop, leaf or canopy. Normally it has been defined on the basis of an indirect measurement from either mechanical or electrical sensors (Huber and Gillespie, 1992), although it would be more appropriate to define the variable in physical terms. Qualitatively, it is possible to consider the presence of water that is visible to the human eye on a surface. Since traces of water may persist in the canopy for extended periods, it is necessary to find another approach that can give a precise and quantitative estimate of surface wetness. One possibility is to introduce a binary variable (wet or dry) based on the area, where the leaf wet surface area threshold is defined as 10% (Magarey, 1999; Dalla Marta et al., 2005). According to the authors, a leaf is considered to be wet when at least 10% of its surface area is visually observed to be wet.

Another possibility is to define a binary variable (wet or dry) based on time. According to Magarey (1999), an objective wet-surface-time threshold, below which the canopy is considered to be dry, has to be defined. An “hour” is considered wet if water is present for 12 minutes or more during that hour on a given surface. The 12-minute threshold is arbitrary but conservative, since it is better to overestimate than underestimate surface wetness for plant protection purposes (Magarey et al., 2005). The author considers that hours are a suitable unit because standard weather stations record weather data parameters at hourly time intervals. The use of a 0.2 h (12 minute) threshold can be problematic in that it is impossible to identify what part of that interval (time) was wet or dry. Another disadvantage of utilizing this binary variable is that it can create errors that are on average 0.5 h, which is not negligible for practical purposes.

1.2 Devices for measuring leaf wetness

Surface wetness has long been recognized as a quantifiable component of plant disease (Wallin, 1967), but the challenge of detecting and measuring moisture upon surfaces has intrigued scientists for many years. Numerous instruments have been designed and constructed over the

years in an attempt to quantify surface wetness (Gillespie and Kidd, 1978; Gillespie and Duan, 1987; Giesler et al., 1996; Sentelhas et al., 2004b). The history of these instruments began with the design of mechanical sensors (Hirst, 1954), which were later replaced by electronic grids. Mechanical sensors measure a change in sensor length, size or weight caused by moisture deposition. Typical examples of such instruments include the Wallin-Polhemus dew recorder and the De Witt leaf wetness recorder. The Wallin-Polhemus dew recorder utilized horse hair that was maintained under slight tension during exposure. As it became wetter or drier the horse hair would contract or relax, resulting in the movement of an attached ink-pen marker on a revolving paper chart (Wallin, 1963). The shortcomings of mechanical sensors include their incompatibility with modern, electronic digital weather station technology. Lomas and Shashoua (1970) also reported that these instruments give inconsistent results.

By 1980, mechanical leaf wetness duration (LWD) sensors and strip charts were superseded by electronic sensors which have become the predominant system used in measuring LWD in operational systems for plant disease monitoring (Getz, 1992; Kim et al., 2002). Another development with considerable promise is the use of infra-red thermometry to determine leaf wetness duration. The technique estimates surface wetness duration from the period during which the dew point or wet bulb temperature is greater than the canopy temperature. This method has the distinct advantage of measuring leaf wetness directly and then being able to calculate the duration from start and end times. The other advantage of this technique is that the infra-red thermometer measurement is representative of a larger area compared to an electronic sensor, and thus has the potential to be used in combination with remote sensing techniques.

The limitations of this technique include the high cost of the infra-red sensor, inaccurate estimation of the dry-off phase and calibration of the background temperature (Magarey et al., 2005). The last problem arises because the leaf and water are not perfect emitters, so they reflect a small amount of the sky radiation back to the thermometer (Fuchs and Tanner, 1966). However, determination of leaf wetness using infra-red thermometry was tested and found reliable for the conditions within dry bean canopies in Western Nebraska (Sadler, 1996). Recently another sensor, the optical wetness sensor, has been produced. A novel design, it is

based on the optical interaction of incident light with a surface to detect surface wetness. Laboratory and field testing of this optical wetness sensor have shown good conformity between recorded wetness and visually observed measurements, with an accuracy of 5% (Heusinkveld et al., 2008).

Literature shows that the most commonly cited and commercially available wetness sensor is the flat-plate, circuit printed sensor, referred to as the Campbell (Model 237) sensor. This sensor consists of a circuit board with interlacing gold-plated copper fingers at the surface. When dew or rain is deposited on the sensor's surface, the resistance between the fingers is lowered and measured by a data logger. The data logger compares the sensor excitation voltage and measured voltage to compute the resistance the sensor resistance (Campbell Scientific, 1998). Flat printed grids such as the Campbell sensor are widely used by researchers, consultants and growers to measure wetness duration because they are commercially available, inexpensive, durable and easy to use (Huband and Butler, 1984). According to Cosh et al. (2009) *in situ* Campbell leaf wetness sensors can provide quantitative leaf wetness information such as dew duration and amount. Studies conducted on this type of sensor have shown that the sensors have performed very well under field conditions, but certain differences have been observed that require attention to several details related to operational exposure (Sentelhas et al., 2004a,b; Wichink Kruit et al., 2008). Results of Pedro (1980) for apple, soyabean and maize, Lau et al. (2000) for tomatoes and Sentelhas et al. (2005) for turf grass and maize showed that the LWD difference between sensor measurement and visual observations were around 15-30 minutes, confirming the accuracy of the flat-plate sensors for measuring LWD in different crops.

A Decagon Dielectric wetness sensor is another flat-plate sensor design, which operates on the principle of electrical capacitance. This sensor measures leaf surface wetness by measuring the dielectric constant of the sensor's upper surface. As water builds up on the surface of the sensor, the measured dielectric constant increases. The sensor has a very high resolution and can detect very small amounts of water on the sensor surface (Decagon Devices, 2007). Water on the sensor does not need to bridge the electrode gap to be detected as is common with resistance based surface wetness sensors. Therefore this sensor requires no painting before use. Savage (2012)

investigated the estimation of LWD for a short-grass surface using sub-hourly measurements of dielectric sensors, infrared surface temperature, grass temperature, dew point temperature and relative humidity measurements. The results showed that the dielectric sensor was accurate and consistent in determining LWD, compared to grass and infra-red thermometer methods.

1.3 Protocol for measuring leaf wetness duration

Leaf wetness duration is a complex phenomenon, due to its spatial and temporal variability within a crop canopy. Attempts to directly detect surface wetness have been greatly hindered not only by the lack of a suitable sensor but also by the lack of a standard exposure protocol. Sensors were shown to give varying results when positioned outside or inside the crop canopy. Significant differences in leaf wetness duration from 6 up to 10 h have been observed at different locations in a canopy after the end of rainfall (Huber and Itier, 1990). In addition most sensors measure leaf wetness indirectly and have different physical properties. In order for a sensor to represent a particular crop, plant or organ or environment, the sensor should be calibrated with visual observations of leaf wetness. Unfortunately, the collection of visual observations is labour intensive and difficult. The absence of a measurement standard for surface wetness prompted the World Meteorological Organization (WMO) and the European and North American Plant Protection Organizations to jointly recommend the development of such a universal standard in 1990 (Anonymous, 1990). However, there is still no recognized standard method for making actual leaf wetness measurements. The absence of a standard prevents the exchange or interpretation of data obtained from different protocols or instruments (Magarey, 1999). To produce accurate LWD data, the use of sensors requires attention to details such as angle of deployment, orientation, calibration, number of sensors and surface conditions (e.g. painting) (Armstrong et al., 1993; Miranda et al., 2000; Madeira et al., 2002).

To date, there is no standardized protocol for measuring leaf wetness, due to lack of a standard instrument. Different instruments give different measurements under the same weather conditions. The absence of a standard has led to the inability to compare results among studies. Visual observations are considered to be the most accurate method and can therefore be used as the basis for the calibration of the sensors. However, the use of the visual observation requires

that the onset and dry-off be defined and it is also unknown how many samples are needed to be representative of the field. Despite the absence of a standard sensor, the performance of both Decagon and Campbell sensors, can be assessed by comparing them with visual observations of leaf wetness.

1.3.1 Wetness sensor treatment

Studies on the Campbell Scientific (Model 237) wetness sensor show that one of the generally accepted practices is to paint the sensors with latex paint and submit them to a heat treatment of 60 -70 °C for 12 hours in an oven. Latex paint reduces surface tension of the sensor and allows small amounts of water to spread uniformly across the sensor surface, allowing droplets smaller than the gaps within the grid to create a sensor response. It also reduces variability among the sensors. Another important influence is that it allows the sensor to mimic the thermal properties of the a leaf. According to Sentelhas et al. (2004b), the painting procedure is recommended for LWD sensors with typical electrode spacing of 1 mm, used in disease warning systems.

Gillespie and Kidd (1978) examined the effects of paint colour and sensor performance in an onion crop using custom resistance grid sensors. The sensors were painted using shades of off-white and three shades of gray. They found that paint colour had a significant effect on the performance of the sensors and that three coats of white paint worked well. Sensors of the colours other than white underestimated wetting in comparison with visual observation on real onion leaves. Over a full season, the authors recommend a light gray colour because it is less likely to be discoloured than off-white. While painted sensors may be useful, it is unclear whether they are the most suitable for recording wetness periods caused by rain. Moreover, there is need for a clear guideline as to the thickness of each coat of paint and the type of paint used as this and possibly other factors are likely to affect the heat capacity of the sensors.

Sentelhas et al. (2005) evaluated the performance of wetness sensors in a cotton crop canopy using unpainted and painted sensors. The results showed that two coats of latex were enough to reduce the coefficient of variation from an average value of 67% to 9% when six sensors were used. A study of LWD above the tomato canopy by Lau et al. (2000) found that sensors with three coats of paint had smaller mean absolute errors compared with unpainted sensors.

Unpainted sensors deployed at 30° and 45° failed to respond to dew onset 15.4% and 30.8% of the time respectively, whereas all painted sensors responded during each dew event regardless of the angle of deployment. Davis and Hughes' (1970) recommendation is to apply three to five coats of paint to circuit-printed sensors (Lau et al., 2000).

On the other hand, Wei et al. (1995), working with a wetness sensor (measuring electrical conductivity of a flexible, copper-coated polyamide film) to detect condensation on tomato plants in a greenhouse, found different results. These authors verified that a coating of acrylic-based latex yielded unreliable results and that vinyl-acetate based latex, in several concentrations, always misrepresented the onset and evaporation of dew, giving poor repeatability and reproducibility for this type of sensor. They therefore suggested the use of unpainted sensors. However, it should be noted that the authors did not use commercially available flat plate sensors but custom-made flexible (bendable), copper-coated polyamide film sensors. Additionally, the study was carried out in a greenhouse where the flat plate sensors have not been examined and as such it is difficult to compare the results of the study conducted by Wei et al. (1995) to the other studies.

A smaller electrode gap may eliminate the need to paint wetness sensors except when the sensor colour must be adjusted to match the wetness duration on plant parts whose drying is strongly influenced by solar radiation (Wei et al., 1995). The better performance of the unpainted flexible sensor may be related to the smaller size of the electrode gap, which was 0.25 mm compared to 1 mm in the commercial one. An unpainted sensor may not detect dew until droplets have grown to a size comparable with the grid spacing (Davis and Hughes, 1970). Although in places where dew deposition is heavy, the size of the water droplets might eventually grow large enough to be detected by an unpainted sensor without any need of the paint, it should be noted that the droplets start small and grow to larger drops, which can cause a slight delay time in wetness detection, resulting in a shorter LWD.

One major flaw of painting the sensors is that, in order for latex to take up water and achieve a resistance change, it has to be hygroscopic in nature. As with most hygroscopic materials, the

latex paint is indifferent to what the state the water is in and will absorb water vapour just as readily as liquid water. To check if the sensor responds to high relative humidity when no physical water is present on the sensor surface, the sensor is enclosed in a plastic bag containing an open beaker of water at room temperature. According to Magarey et al. (2005), if the sensor responds in this environment, then it has to be soaked in deionized water for several hours and then the sensor has to be dried at 100°C. This process should be repeated until high relative humidity response disappears.

1.3.2 Canopy placement

Leaf wetness duration within a canopy is affected by plant structure, architecture and crop canopy height. However, the radiation and turbulence conditions experienced by electronic sensors deployed outside the plant field, say at a standard automatic weather station, and prevent it from mimicking microclimatic crop conditions. On the other hand, measurement of crop LWD directly by installing sensors inside the crop field can introduce other uncertainties depending on the sensor position inside the canopy, angle of deployment and interaction with surrounding leaves (Lau et al., 2000; Dalla Marta et al., 2004). This implies that sensor placement should receive special attention especially if the data are required for use in disease-warning systems.

Some authors have noted that LWD shows different patterns of variation from one crop to another. Wittich (1995) observed that LWD was longer at the top than in the lower part of an apple canopy. Sentelhas et al. (2005) showed that LWD lasted one hour longer at the top of apple and maize canopies than at the bottom; but no difference was found between LWD measured at the different positions of young coffee plants or in grape canopies. In a different study, coffee plants had the longest LWD in the lower portions of the canopy; for banana crop, the upper third of the canopy showed the longest LWD, whereas for the cotton crop no difference was observed between the top and the lower third of the canopy (Santos et al., 2008).

These differences in LWD values have some practical implications in disease warning systems. So such details need to be investigated prior to the application of warning systems. Dalla Marta et al. (2004) observed that disease severity (downy mildew) estimated using LWD data obtained

inside the canopy was lower than the actual severity. On the other hand, the use of LWD data obtained outside the canopy led to a disease severity overestimation. These results seem to indicate that sensor placement is a critical input in disease warning systems. If sensors are incorrectly positioned the implications can have ripple effects on the performance of these systems. The most suitable position to place the sensors is in those portions of a crop canopy that are of greatest importance for the end user of the information. However, it should be noted that deployment of sensors within the canopy may not be considered practical because agricultural deposits from pesticide spraying alter the performance of sensors and must be avoided.

1.3.3 Sensor orientation

Lau et al. (2000) investigated how sensor orientation affected the response of painted and unpainted sensors by making visual observations of free water on tomato leaflets during 13 dew-onset and 11 dew dry-off events. The authors found that all the painted sensors responded during each dew event and that the vertical orientation of the sensors did not significantly influence the accuracy and precision of painted sensors for dew estimation, giving another reason to paint the sensor. Painted sensors, with three and nine coats of painted, deployed at 30° and 45° responded uniformly to dew onset regardless of deployment angle or paint coating. Their recommendation was that if unpainted wetness sensors are used to monitor dew periods, the angle of deployment should be measured and maintained carefully during calibration and field use. Sentelhas et al. (2004a) suggested that flat plate sensors installed at an angle of 30° to 45° to horizontal can provide accurate measurement of LWD when compared with visual observations. They also recommended that this sensor protocol is a good protocol to estimate nearby crop LWD when the longest wetness was observed at the top of the canopies. Based on the evidence provided by those studies, it is suggested that flat plate sensors such as Campbell and Decagon sensors should be oriented at 45° , facing away from the equator and towards the pole. In addition, sensors installed at this angle prevent excessive pooling of water during rain. For most applications, the sensors should be oriented in the compass direction likely to give the longest wetness period. In the southern hemisphere, the preferred orientation for the sensors is south, in order to minimize their exposure to solar radiation in the morning and maximize morning dew exposure.

1.3.4 Number of sensors

There is no consensus as to the exact number of *in situ* sensors to be deployed in a canopy; as multiple sensors could be useful to account for variability in leaf wetness within the crop canopy. Magarey et al. (2005) suggest that, if using a single sensor to estimate LWD in a crop canopy, the optimal position would be just below the top of the canopy, but fully exposed to the night sky. The rationale for this recommendation is that this position can be expected to provide the maximum LWD readings (Jacobs et al., 1990; Potratz et al., 1994), since dew duration is usually greatest at the top of the canopy and placement just below the top of the canopy would slow the morning drying by providing some protection from wind and sunlight. However, for some crops such as coffee plants where the longest LWD was found in the lower portions of the canopy, the above justification may not be valid or needs to be checked under the actual conditions. If a single LWD is utilized to provide wetness measurement, then it is logical to determine the most representative sensor placement in the canopy that would provide accurate disease development estimations.

Penrose and Nicol (1996) found that three sensors have a 92% chance of detecting a wetting event, whereas two sensors would have a 60% chance. A study of LWD in a soybean canopy by Schmitz and Grant (2009) found that measurements of LWD are best performed with multiple sensors at as many locations as cost and time allow. To account for variability in wetness measurement and occurrence, multiple sensors can be installed at a single site (Francl and Panigrahi, 1997), but monitoring and data handling costs rise proportionally as the number of sensors increases. In practice, the number of sensors deployed is restricted by cost and one LWD sensor per crop canopy is often the norm (Gleason et al., 2008; Schmitz and Grant, 2009; Kim et al., 2010). The other problem is the interpretation of LWD obtained from multiple sensors. As when multiple sensors are deployed, it can be difficult to interpret the outputs and indicate the threshold value for the canopy to be wet.

1.4 Modelling leaf wetness

Measurement of LWD is often a challenge due to a number of reasons. Wetness sensors provide indirect measurement of surface wetness duration, have different physical properties from leaves and also require calibration to represent a specific crop (Getz, 1992; Giesler et al., 1996). The precision and accuracy of the sensors is markedly affected by sensor size and shape, orientation, presence and colour of paint coating and even variability among apparently similar sensors (Lau et al., 2000). Sensors also require seasonal calibration, regular maintenance, error checking and occasional replacement. The collection and transfer of data from field to program can be time-consuming and subject to errors. Data-loggers may deplete their batteries at critical times and lightning strikes can cause station meltdowns. When installed in the field, the sensors are also subject to situations where data could be compromised. For example, sensors may be impacted by farm equipment, or debris and bird excreta can accumulate on the surface of the sensors which could lead to the need for a new wetness threshold to be established. Consequently, citrus growers may find the use of sensors unattractive.

To circumvent the problems associated with the operational measurement of surface wetness, attempts have been made to estimate it using simulation models. At least 16 models capable of simulating surface wetness have been developed (Huber and Gillespie, 1992; Magarey et al., 2006b). However, relatively few of these models have been widely used operationally because they are often highly complex and use meteorological measurements not readily available from local meteorological stations (Madeira et al., 2002; Papastamati et al., 2004). Despite the complexity of most simulation models and the lack of standards for defining and measuring surface wetness, it is anticipated that the next 10-20 years will see a shift in the estimation of surface wetness from systems based on *in situ* sensors to those based on simulation models and remote sensing (Rizzo et al., 2006).

The simulation approach has a number of merits. Simulation models can be used to estimate site-specific surface wetness data from climate data to overcome the lack of available surface wetness measurements. The use of a leaf wetness duration model allows for determining the variable wherever the required data are available (Dalla Marta et al., 2005). Unlike the recording of a

sensor which is a representative point measurement, simulation models can produce leaf wetness data of high spatial and temporal resolution if fed with specialized meteorological data. One important application of site-specific leaf wetness could be regional mapping, which can be a powerful tool for decision-making. Advances in computer technology, especially numerical modelling and simulation, have further enhanced the accuracy of weather forecasts: hence by using a surface wetness model it is possible to estimate wetness duration in forecast mode (Magarey et al., 2001). This will allow for the production of warnings and advice based on the forecasted situation, which is critical for the planning of farm operations as it can give enough lead time for scheduling fungicide application and preparing equipment. Lead time is even more important when protective fungicides are available, since they need to be applied before infection takes place.

Just like wetness sensors, models should be calibrated. Simulation models can be calibrated to a given crop by comparison of the model output to visual observations or measurements made by sensors. Although many models accurately describe latent heat flux, few models have been calibrated to simulate observations of leaf wetness duration (Magarey et al., 2006a). Any leaf wetness duration model must be properly calibrated and validated because it cannot be used as a “black box”. It is therefore imperative to calibrate any model under controlled and varied atmospheric, plant and wetness conditions over a broad range of test conditions. Validation remains a key problem too, especially given the variation in leaf wetness duration throughout a canopy and the high uncertainty of current measurement techniques (Magarey, 1999). Most simulation models are virtually untested and hence their usefulness is unproven, confirming the notion that it is easier to formulate models than to validate them. This is underlined by the fact that although there are many reports about leaf wetness model development, there are few papers illustrating the comparison of the models under conditions exploring different sites, years and crops (Wichink Kruit et al., 2004; Sentelhas et al., 2008; Wichink Kruit et al., 2008). It would be highly desirable to find an alternative to visual observation for validation of leaf wetness duration models and sensors.

1.4.1 Physical model

Physically-based simulation models estimate leaf wetness duration based on the energy balance principles that govern the heat exchange processes between the plant surface and the atmosphere. Dew forms when the leaf temperature declines to a temperature below the dew point of the surrounding air. It was recognized that sufficient moisture in air and intensive radiative cooling of the surface are two basic requirements for dew formation. The physical base for dew formation can be described by the Penman-Monteith combination equation. In the equation the latent heat flux can represent dew formation. It is a component of the surface energy balance, together with net radiation, sensible heat flux and soil heat flux. This equation has been used to study dew formation before. Monteith (1957) analyzed the change of the components of the surface energy balance as dew condensed. Monteith (1957, 1963) and Long (1958) pointed out that dewfall represents a flux towards the surface, which makes it the opposite of evaporation, and discussed the weather conditions favourable for dew formation.

Among the advantages of the physical models, is that they can be highly accurate (Pedro and Gillespie, 1982a,b) and have the potential to be readily portable among climates and regions as they are derived from first principles of physical process in the atmosphere. As physical principles used in the models do not change from region to region, the model usually should not require as many adjustments before use as empirical models. However, a serious limitation for practical application is that physical models require certain input parameters, such as net radiation, cloud cover or infrared radiation, parameters which are seldom measured at most standard weather stations. With energy balance or physical models in which all inputs are considered simultaneously, inaccuracy in a single input parameter may greatly influence model performance because errors in input values can be preserved or even amplified (Kincaid and Cheney, 1996).

One important physical model is the Atmosphere Land Exchange model (ALEX). This model describes the transport of heat, water vapour, carbon and momentum within the soil-plant atmosphere. This model is unique because it was developed for practical application in agriculture and weather forecasting (Anderson et al., 2000). The model requires meteorological

inputs of wind speed, temperature, vapour pressure, incoming solar radiation, incoming longwave radiation and precipitation. The soil component of the model requires a description of soil properties by depth including hydraulic conductivity, air entry potential, and bulk density. Total latent heat estimates are calculated by solving for the latent heat contribution from the canopy and the latent heat contribution from the soil surface. The latent heat from the canopy is further divided into components representing the evaporation of free water from the leaf surfaces and the transpiration. ALEX has been used in prior dew studies, such as Kabela et al. (2009) and Hornbuckle et al. (2007).

Physical models can be classified into categories: single layer model, which treat the canopy or plant organ as one layer and multilayer models, which simulate dew formation at different levels inside homogeneous canopies. Representative single layer models include the model proposed by Pedro and Gillespie (1982a,b) and the Surface Wetness Energy Balance (SWEB). Pedro and Gillespie's model estimates dew duration on a single leaf by using micrometeorological data as well as standard weather station data. The SWEB model, has been developed as a potential theoretical standard for surface wetness measurements (Magarey, 1999; Magarey et al., 2006a). The model was designed for a use in a vineyard and assumes that the canopy is a big leaf and simulates surface wetness based on a surface energy balance and water budget. The MICROWEATHER model which computes the dew amount and duration at different layers of crop canopy represents a multilayer model (Luo and Goudriaan, 2000). The model was validated for a rice canopy and maize canopy. An extended review of dew formation simulation models can be found in Huber and Gillespie (1992).

The use of physical models could have some limitations. One of the problems of utilizing physical models require high intense input datasets. The input data from the automatic weather station may not have the same sampling time as that required by the physical model. Physical models may require initial parameters which may not be available immediately or would require accurate determination. The input data required for the model may come from an automatic weather station and not within a crop canopy.

1.4.2 Empirical models

Empirical modeling uses statistical best-fit algorithms to help choose parameters and functions that yield the most accurate estimates of LWD. These models require relatively few input parameters and could therefore be more easily applied in more locations than physical models. However, although empirical models can be highly accurate for sites and regions where they were developed, application of these may not be successful if used in regions where some of the conditions for dew development such as soil moisture, soil texture, or plant canopies differ. If one decides to use an empirical model due to limited availability of data, then the model must be carefully validated for the specific conditions and region as the empirical coefficients and thresholds may require adjustment. Empirical models can depend on approaches based on a threshold (Sentelhas et al., 2008), a decision tree (Gleason et al., 1994), a fuzzy logic system (Kim et al., 2004) or artificial neural networks (Francl and Panigrahi, 1997). Among these, the relative humidity threshold model, the decision tree model and the fuzzy logic system model all require a small number of input variables, which would facilitate wide use of such models.

The period of duration with relative humidity $\geq 90\%$ has been used for a long time to estimate LWD (Crowe et al., 1978; Sutton et al., 1984). This simple model was designated the RH threshold model. The RH model was examined by Winchink Kruit et al. (2004) and modified to form the extended relative humidity model to take into account the high variability of relative humidity. This extended model states that wetness occurs at relative humidity values greater than 87% and that there are additional criteria in the range of 70-87%, depending on the rate of change in relative humidity. For periods with relative humidity between 70% and 87%, the leaves are considered to be wet if the relative humidity increases more than 3% in a 30 minute time period and a decrease of 2% within a period of 30 minute would predict that the leaves are dry. If the average relative humidity is below 70%, the leaf is always taken as being dry. According to Winchink Kruit et al. (2008), the relative humidity threshold value of 87% was derived from surface wetness measurements in the pine forest (Netherlands) and later just applied for all vegetation. It appears then that it might be essential to adopt the relative humidity threshold to local conditions.

Another empirical model is the dew point depression model (DPD), which examines the difference between the measured air temperature and the dew point temperature. Wetness duration is estimated as the length of time that DPD remains between the two dew point depression values. Rao et al. (1998) found that on maize ears, dew point depression values of 1.8 °C or less and 2.2 °C or greater indicated onset and end of wetness respectively. Since these values can vary from one crop/plant to another, the use of this method would require accurate determination of the two reference depression values in order for the model to accurately predict dew duration for a specific crop at a specific locality.

Gleason et al. (1994) suggested a model that combined classification and regression tree analysis with stepwise linear discriminant analysis, which utilizes inputs such as dew point depression, relative humidity and wind speed. That model identifies thresholds for each of these variables above which dew is likely to occur. The model assigns climatic data to one of the four categories according to threshold values of 3.7 °C for DPD, 2.5 ms⁻¹ for wind speed (estimated at 10 m height) and 87.8% for relative humidity. According to this model, no dew occurs: (i) above a DPD threshold of 3.7 °C; (ii) if the wind speed is equal to or greater than 2.5 ms⁻¹ and (iii) if relative humidity is less than 87.8%. If wind speed is less than 2.5 ms⁻¹ or relative humidity is greater than 87.8%, an empirical equation is applied to determine if dew occurs or not.

According to Gleason et al. (2008) the distinction made between empirical and physical models is an oversimplification as most models are hybrids of the two approaches. For example, the Penman-Monteith energy balance model incorporates parameters whose values are determined empirically. Hybrid models tend to overcome the limitations of both approaches and can therefore potentially possess both portability and practical applicability. Although physical models are based on physical principles that govern the presence or absence of water on plant surfaces, these physical principles apply under some assumptions which may deviate from reality. For example, the net loss by radiation within a canopy is accompanied by sensible and latent heat transfer not only between the cooler crop surface and the warmer air above but also between the crop surface and the warmer soil beneath the canopy. So a combination of both models (hybrid) has a potential to produce highly accurate estimations in LWD at any location.

1.4.3 Validation of LWD models using field measurements

Several studies have been conducted that compare LWD measured by a sensor to model estimates. Sentelhas et al. (2008) conducted an experiment that examined leaf wetness duration measured over turfgrass compared to the empirical LWD models using $RH \geq 90\%$, the DPD and the extended RH threshold model. The comparison between the models and the sensors were conducted in Ames, Iowa (USA), Elora, Ontario (Canada), Florence, Tuscany (Italy) and Piracicaba, Sao Paulo (Brazil). It was found that at the Florence and Piracicaba sites, the $RH \geq 90\%$ performed best with mean absolute errors of less than two hours. The extended RH model performed poorest at all locations with mean absolute error ranging between 2.89 h (at Piracicaba) and 4.44 h (at Florence). At the Ames site, the DPD model had the lowest mean absolute error of 2.43 h. This model was also the most successful for the Elora site, where that model had initially been developed, which seem to confirm that empirical models tend to be accurate if locally calibrated. Kabela et al. (2009) compared the ALEX (Anderson et al., 2000) to measurements of duration in both maize and soybean canopies. The authors indicated that there was a good comparison between the physical model and the measurements of leaf wetness sensors, especially under heavy dew conditions, where the model indicated a dew onset a half hour earlier than the first sensor, but indicated drying at the same time as the sensor.

1.5 Conclusion

There is no single “best” method to acquire leaf wetness data since the use of either sensors or models both have their merits and drawbacks. The choice between measurement or modelling leaf wetness should be determined by the purpose for which the data will be used. If estimates of leaf wetness of a large area are required, then it may be reasonable to use a model, provided the model input data is representative of the region and sufficient spatial coverage can be made. Inaccurate input data, gaps in data, or data from a station lacking good maintenance, will not provide accurate estimates of leaf wetness. Using predicted parameter from a weather forecast as an input to LWD model, can introduce error to the LWD predictions. Multiple sensors can also be installed over a large region but such an arrangement would require regular visual observation to check if the sensors have not fallen off or drifted from their initial deployed positions and also to remove contaminants.

The use of a model can eliminate the concern over where to place a sensor in a canopy and when to remove it for regular cleaning, calibration and maintenance. Unlike with sensors, a potential advantage of the models is that they may be used to estimate LWD from a range of available data -on-site weather measurements, off-site or remotely sensed data, or both. If the source of data for the model is an automatic weather station or other modern devices, the use of a data-logger would be recommended. Data-logger can be programmed to record, store and process data at any required time interval and the computed LWD can be immediately relayed to the end users. However, such hardware may be expensive and unattractive to some citrus growers. On the other hand, manual computations of LWD though relatively cheaper, can be cumbersome, time-consuming and subject to errors.

To measure leaf wetness in a relatively small region, it may be appropriate to use an *in situ* sensor. However, like models, sensors are estimators of actual real occurrence of leaf wetness. Sensors are beneficial because they provide information on leaf wetness duration for both dew, rainfall and irrigation events. Once they have been calibrated, they do not require additional weather parameter measurements needed as inputs for the models. As a research community that uses leaf wetness sensors, it is important that we establish a standard methodology for their use. Such a protocol would allow easy comparison and exchange of wetness data between studies.

Historically, sensors have been placed in a field at varying orientation angles, which prevents comparison between studies. The Campbell Sensor (Model 237) is modified by painting and then heated to remove some of the hygroscopic elements of the paint, followed by sensor calibration prior to deployment in field. However, sensors need to be calibrated for specific applications to determine threshold levels for wetness determination. Unlike the Campbell Sensors, the Decagon sensor does not require painting and eliminates the potential discrepancy in results resulting from differing sensor treatment, but likewise requires *in situ* calibration.

1.6 Justification for current study

The above literature review shows that most studies have focused on leaf wetness measurements in perennial plant canopies of grapevine (Dalla Marta et al., 2005; Dalla Marta et al., 2008), apples, coffee, maize, muskmelon (Sentelhas et al., 2005), bananas, cotton (Santos et al., 2008). There have been no studies on the process of dew formation and dissipation in a citrus canopy such as Satsuma Mandarin. This study investigates the performance of two commercially available sensors (Campbell and Decagon) as well as modelling in the determination of leaf wetness within a citrus canopy. In this study, if one sensor is wet, then the whole canopy position was considered to be wet. Citrus is susceptible to diseases and leaf wetness variability may be expected. A profound understanding of the spatial variability of LWD within the citrus canopy is essential to implement or improve the performance of disease warning systems.

1.7 Design limitations

Literature suggests that there is a need to have multiple sensors at each canopy height especially when the sensors are not painted. Due to the high measurement uncertainty, replicated sensors should be used. The use of multiple sensors also increases the probability of detecting a wetness event. According to Penrose and Nicol (1996) two sensors have a 0.6 probability of detecting a wetness event, whereas three sensors would have a 0.92 chance of detecting the wetness event. According to the authors, deploying more sensors results in smaller errors in LWD measurements. Moreover, the deployment of more sensors is one way to reduce the spatial heterogeneity of in-canopy leaf wetness duration measurements (Gleason et al., 2008).

In this study, four sensors, two of each type, were placed in the upper canopy. However, only 2 sensors were used to estimate wetness duration in the lower part of the canopy, one placed on each side of the lower canopy. Ideally, three observers were needed in order to obtain visual observations of wetness measurements simultaneously on all the canopy positions, but this was not possible. So despite these limitations, a field study was carried out to test the practical use of the leaf wetness sensor against a visual score.

1.8 Objectives of the study

The overall purpose of the study, primarily in a citrus orchard in Stellenbosch, is to be able to accurately and reliably measure leaf wetness. The specific objectives of the study were to:

- a) Characterize the process of dew formation and dew dissipation on the upper citrus canopy
- b) Test the performance of existing leaf wetness instruments namely the grid-based resistance sensor (Campbell Scientific, Model 237), the dielectric leaf sensor (Decagon Devices, Model LWS-1)
- c) Assess the theoretical background of the energy balance at a leaf surface and derive an equation for leaf temperature compared to the dew point temperature and
- d) Evaluate the performance of the two models in estimating leaf wetness duration in a Satsuma Mandarin citrus orchard by comparing each model's simulated leaf wetness duration with visually observed leaf wetness duration and leaf wetness sensors values.

1.9 Dissertation composition

This dissertation consists of six chapters. Chapter 2 discusses the operation and performance of two wetness sensors (Campbell and Decagon sensors) in a citrus canopy. Chapter 3 examines the process of dew formation and dissipation at the upper canopy level by considering a few typical days. An analysis was performed to investigate if weather parameters could be used to characterize the process of dew deposition and dew dissipation. Chapter 4 investigates the energy budget of a leaf. An expression of the leaf temperature was deduced from the leaf energy budget. An evaluation of the Newton-Raphson iterative method as an alternative approach in the indirect determination of leaf temperature from meteorological data was investigated. Leaf temperatures predicted from the iteration method were compared with field measurements of leaf temperatures from leaves of three different plants. Chapter 5 focuses on modelling leaf wetness. A physical model, (SWEB) and an empirical relative humidity model (RH) were used to determine leaf wetness duration and the results compared with visual observation of wetness. A summary, conclusions and recommendations of the studies are provided in chapter 6.

Chapter 2

Operation of leaf wetness sensors in a Satsuma Mandarin *Citrus unshiu*

Marchovitch orchard canopy

2.1 Introduction

Leaf wetness duration (LWD) is an important parameter to monitor plant disease epidemiology. Many phytopathological models use leaf wetness duration in combination with other factors in order to assess the infection and pest severity and to manage disease control activities in an efficient way. According to Timmer and Zitko (1996) model-based decisions on fungicide applications in citrus resulted in reduced disease, large increases in fruit production and elimination of unnecessary sprays. Leaf wetness duration is a difficult variable to measure and estimate because it is driven by both atmospheric conditions and their interaction with the structure and composition as well as physiology of the crop canopy. Leaves at different positions within a canopy become wet and dry at different times, which results in spatial variability of LWD. This spatial variability is an important aspect to be considered when measuring LWD (Santos et al., 2008), since a thorough understanding of the LWD heterogeneity within a crop canopy is critical for implementing a disease-warning system that relies on LWD data as inputs.

Literature search and review shows that the Campbell Scientific (Model 237) sensor has been used extensively to estimate LWD in different crop/plant canopies. This model, which operates on the principle of electrical resistance, has been used in several studies that have investigated the spatial variability of leaf wetness duration in different crop canopies such as apples, coffee, grape, maize, cotton and bananas (Henshall et al., 2005; Sentelhas et al., 2005; Dalla Marta et al., 2008; Santos et al., 2008). However, the sensors may require field calibration. The most recent innovation in sensor design is the Decagon Devices wetness sensor, which detects wetness based on electrical capacitance (Gleason et al., 2008). According to Decagon Devices (2007), this sensor has high resolution and can detect very small amounts of water on the sensor's surface. Unlike the Campbell sensors, this type of sensor requires no painting but may require individual field calibration. Savage (2012) recently used this type of sensor to estimate leaf wetness duration for a short grass surface.

This study aimed to:

- i) characterize the spatial variation of leaf wetness duration within a citrus canopy and
- ii) evaluate the performance of the unpainted Campbell Scientific electronic grid sensors sensor (Model 237) and the Decagon dielectric leaf wetness sensors against visual observations and meteorological data.

2.2 Materials and Methods

2.2.1 Field site description

The study was conducted on a citrus orchard at the Welgenvallen Experimental Farm of the University of Stellenbosch (latitude 33°56' S, longitude 18°52' E, altitude 157 m above sea-level) in Western Cape, South Africa. The region is characterized by a Mediterranean climate with cool wet winters and warm, dry, summers. The mean annual precipitation is 673 mm and about 70% of this falls during winter. Mean midday maximum temperatures range from 16 °C in July to 24 °C in December (ARC-ISCW). On average, the temperature drops to 6.6 °C at night in July. The predominantly westerly and northwesterly winds (regimes) generally bring in a lot of moisture mostly in winter. The 2012 winter season exhibited a distinct pattern as it was wetter and colder. Total rainfall recorded in June, July and August, 2012 was 140 mm more than the 48-year long-term mean of 98 ± 18 mm. Favourable weather conditions for dew formation such as clear skies, wide daily fluctuations of temperature and additional moisture from winter rains frequently prevail in the winter season and occasionally occur during other seasons.

2.2.2 Wetness sensors

Flat, printed-circuit wetness sensors, Campbell Scientific sensors (Model 237) (<http://www.campbellsci.co.za/237-1>) were used to measure LWD in the citrus canopy. This type of wetness sensor, is hard epoxy-fibreglass with interlaced gold-plated copper fingers, measuring 7.5×6.0 cm, with a smaller active surface area of about 30 cm². Condensation on the upper surface of the sensor lowers the impedance between the fingers, when the free water bridges the 1 mm spacing between the grid fingers and is measured by a datalogger. A dry sensor has infinite impedance, recorded as 6999 Ω by a CR10X datalogger. Prior to the deployment, the sensors

were also field tested in a growth chamber to determine the agreement between the sensors threshold. The sensors did not undergo treatment such as painting and heating.

Decagon dielectric leaf wetness sensors (<http://www.decagon.com/products/canopy-atmosphere/water/lws-leaf-wetness-sensor/>) were also deployed in the citrus canopy to estimate leaf wetness duration of citrus leaves nearby since it was assumed that the sensor emulated a leaf. This sensor estimates leaf surface wetness by measuring the ability of the material near (1 cm) or on the sensor's upper surface to store charge, if the sensor is placed close or within a crop canopy. The sensor output is voltage (mV signal) which is proportional to the dielectric of the measurement zone and therefore proportional to the amount of water on the sensor's surface. It requires an excitation voltage of 2500 mV and according to the manufacturer recommendation, a datalogger reading of less than 274 mV corresponds to a dry sensor.

2.2.3 Sensor placement in the citrus tree canopy

A total of six leaf wetness sensors, consisting of three Campbell (Model 237) and another 3 Decagon wetness sensors were installed at two different canopy heights in a citrus tree canopy. The tree, was about 2.14 m high and had similar canopy structure and development stage to other citrus trees in the orchard. The citrus orchard was planted in 1994 and consists of mature, fruit bearing *Citrus unshiu* Marchovitch citrus trees. The orchard was not irrigated during the period of this field trial experiment.

A total of four wetness sensors, two of each type, (2 Campbell and 2 Decagon) were all deployed at the same height, in the top two-thirds of the citrus canopy, which was about 1.63 m above the ground. At this height the four sensors were placed at four horizontal positions approximately 30 cm apart along an east-west transect. The order of arrangement of the sensors was as follows: the first sensor, a Campbell wetness sensor (R_1), was located on the extreme eastern side of the upper canopy, followed by a Decagon sensor (D_1), then another Campbell sensor (R_2) and lastly the Decagon sensor (D_2) in that order. Another set of sensors, one of each type of sensor, were also deployed in the lower one-third of the canopy, at a height of 64 cm from the soil surface. Fig. 2.1 shows the photograph of the sensors placed in the upper canopy level of citrus

tree canopy. The Decagon sensor (D_3) was placed on the eastern side of the canopy, at a horizontal distance of 70 cm from the Campbell sensor (R_3) which was on the opposite side of the canopy. All the sensors were mounted on the end of a PVC pipe, oriented at 45° to the horizontal, facing south. The sensors were checked routinely to avoid leaves touching their surfaces.



Fig 2.1 A photo showing wetness sensors located in the upper positions of the citrus canopy at Welgenvallen Experimental Farm of the University of Stellenbosch from 27th July until 30th November, 2012 (Photo courtesy Prof S. Walker)

Meteorological variables which included relative humidity, air temperature, net radiation and wind speed above the canopy. Air temperature and relative humidity above the canopy, were measured by Model CS500 sensor (Campbell Scientific, Logan, UT) at a height of 1.8 m from the ground. A wind sentry (Model 03001) was used to measure the wind speed at a height of 2 m. A Kipp and Zonen net radiometer (NR LITE, Netherlands), mounted at 1.8 m from the ground, measured the net radiation just above the citrus canopy. Leaf temperature was also measured. One thermocouple thermometer was attached onto one of the tagged leaves in the upper canopy whilst the second thermocouple measured the leaf temperature of a leaf in the lower eastern canopy. Both thermocouples were attached to the leaves epidermis by means of plastic clips. All the meteorological and wetness sensors were connected to a CR10X datalogger which was programmed to scan data from each sensor every 5 seconds and averaged it over a 15 minute time period. Rainfall data measurement was obtained from a standard weather station located at a site near the orchard.

2.2.4 Visual observations of dew

The existence of wetness on the leaves during the night and day was assessed by the visual observation method, which involved carrying out visual inspections of wetness on the surface of selected leaves. Initially, a total of 20 leaves from the citrus canopy, with no visible damage to their surfaces, were monitored visually for leaf wetness. The randomly selected leaves from the upper and lower eastern canopy position (10 leaves from each canopy position) were each tagged and numbered for its unique identification. The selected leaves were close to the wetness sensors and no leaf was more than 30 cm from the closest wetness sensor. Later, in the study, visual observation of wetness was extended to the western lower canopy where another 10 leaves were randomly chosen/selected and visual observation of wetness was performed.

Human visual inspections of dew onset were based on the first appearance of small water droplets on any one of the tagged leaves. A leaf wetness index was developed, based on a scoring technique. The score was based on the presence of water that was visible to the human eye. Leaves were scored for visible wetness on a 10 scale wetness ranking. A leaf was considered to be “wet” and assigned a score of 1 (one) when one-tenth (10%) of its upper surface

area was visually observed to be wet. Leaves with no evidence of wetness were considered “dry” and flagged “0”. When the leaf’s upper surface area was completely wet, it was assigned a value of 10 that designated 100 % leaf wetness. During the visual observations care was taken to avoid touching any of the tagged leaves. The visual observations of wetness were carried out every 15 minutes starting from 18h00 until complete surface wetness was obtained during the night and from sunrise until complete dew dissipation in the morning. Light from powerful torches were used to aid the observations of percentage of wet leaf area at night. No inspections were made in the middle of the canopy because it was difficult to effect such measurements at night. Visual observations of leaf wetness in three canopy positions (upper and lower eastern as well as the lower western canopy) were recorded separately. Visual observations of wetness were performed for some selected days from 27th July until 30th November 2012 that amounted to 62 days. However, visual observations of leaf wetness on the lower western side of the canopy began from 7th September 2012 till 30th November, on the same days as the rest of the canopy positions.

2.2.5 Data Analysis

An analysis was performed to investigate the variation of meteorological variations as well as the wetness sensors’ response on a typical dew day. For this analysis, one typical dew days was selected from a total of 24 days, when dew was observed in the upper canopy level. In order to include the entire process of dew formation and dew dissipation, the analysis started from 12h15 until 12h00 the following days. The purpose of this investigation was to get an insight into the spatial and temporal variation of leaf wetness. The response the wetness sensor to leaf wetness was determined by comparing the wetting and drying cycle of each of the wetness sensors (R_1, R_2, D_1 and D_2) with visual observation of wetness in the upper canopy.

The observed daily LWD data were then created by considering 24 hour periods that began at 12h15 and ended at 12h00, by summing all the 15 minute time intervals when the wetness was visually observed. The observed daily LWD was then split into dew days and rainy days. A rain day was defined as a day with measured rainfall ≥ 0.25 mm. The hypothesis was that all the canopy positions had an equivalent LWD. A t-test at 5% probably was performed to determine if

mean LWD were statistically significant from each other during days when wetness resulted from dew, rain or both events. A stepwise regression analysis was performed using SPSS to determine the percentage of LWD variability that could be explained by weather parameters.

To evaluate the performance of the leaf wetness sensors in estimating daily leaf wetness duration, the observed and sensor estimated LWD were compared by regression analysis, R^2 , which expresses the precision of estimates. The estimation errors, mean error and mean absolute errors (MAE) were also determined. The mean error was calculated by averaging the difference between the observed and sensor estimated LWD for 24 hours. The mean error provided a measure of the tendency to over or underestimate LWD whereas mean absolute error assessed the overall accuracy and was the average sum of the absolute difference between the visually observed and sensor measured LWD computed as follows:

$$MAE = \frac{\sum_{i=1}^n |x_i - x_o|}{n}$$

where x_i is sensor measured daily LWD, x_o is the visually observed daily LWD and n is the number of days.

Mean and absolute errors were computed for LWD measured by all the sensors and observed, in both the upper and lower canopy positions. The errors were computed for dew days, rain days and for rain and dew days combined. Daily errors, were also calculated as the difference between daily measured and measured LWD considering each of the sensors in the upper canopy level, for each of the days when dew was observed from 27th July to 30th November, 2012.

2.3 Temporal and spatial variation of leaf wetness in a citrus canopy

2.3.1 Variation of weather data on a dew day considering the upper canopy

An analysis of dew days, indicated that dew was mostly deposited on the leaf whenever the dew point temperature was equal to or fell below the measured leaf temperature (Fig. 2.2). To illustrate the variation of meteorological parameters a typical dew day was analyzed. The variation of meteorological variables as well as wetness sensors' response was examined from

12h15 on 17th August until 12h00 the next day. Dew was observed to form on the night of 17th August 2012 at 18h30. On this night, both the air and leaf temperature began to fall sharply after sunset. The decrease in air temperature was accompanied by an increase in relative humidity (Fig. 2.2). Other parameters that also followed the same decrease pattern include the vapour pressure deficit as well as the dew point depression. Dew deposition started at about 18h30 when the leaf temperature fell below the dew point temperature (Fig. 2.3), which was also confirmed by the visual observations (Fig. 2.3). The leaves remained wet until the next morning (18th August 2012) when dew dissipation occurred. As the sun rose in the morning, turbulence increased causing the leaf to dry quickly.

This onset of dew deposition was also recorded by the wetness sensors in the upper canopy level. In the case of the Campbell sensors, the sensor readings fell from 6999 Ω to below 1000 Ω , whilst for the Decagon sensors, voltage increased from a baseline voltage of about 270 mV as an indication of the leaf wetting process (Fig. 2.4). The kinks on graph of the Decagon sensor (D_1) could have been caused by water droplets dropping off the sensors, followed by more wetting given the further decrease in temperature (Fig. 2.4). The complete dissipation of dew from the upper canopy level also coincided with the drying of the wetness sensors at the same time. All the wetness sensors retained their initial dry state.

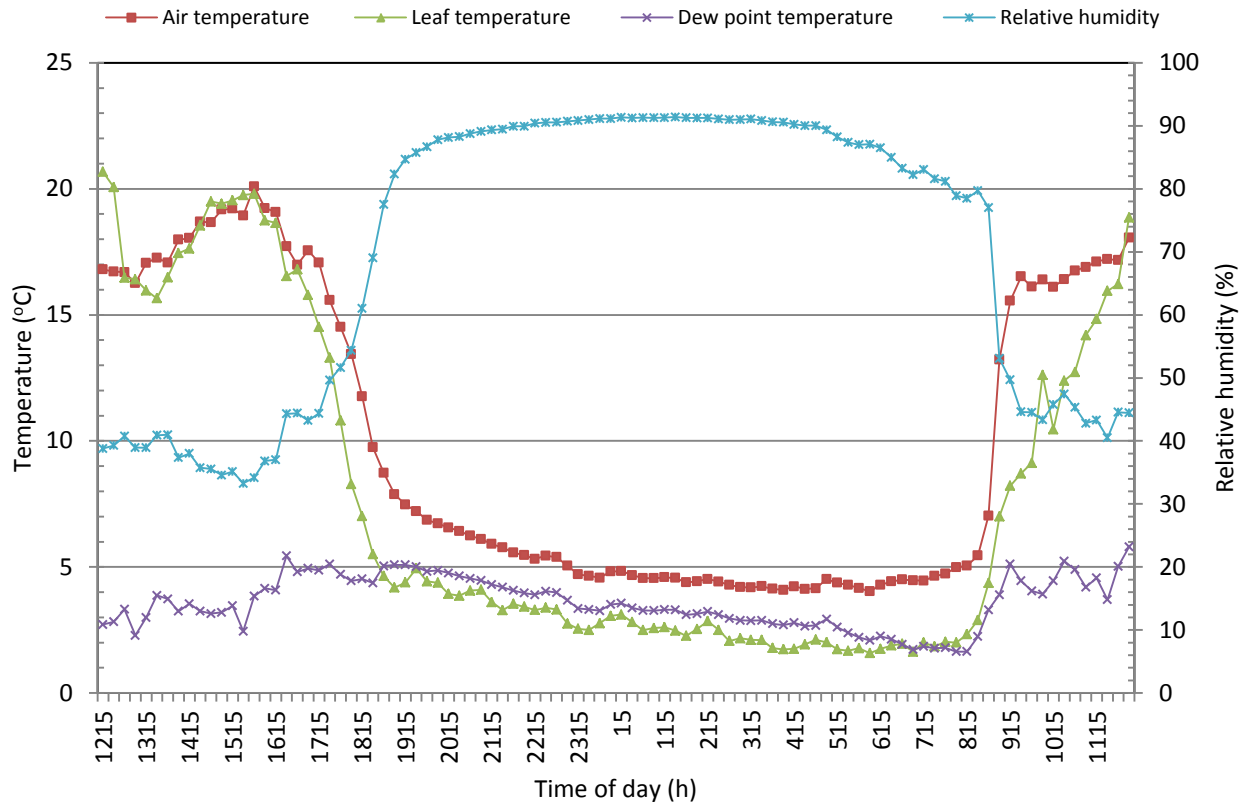


Fig 2.2 Variation of air temperature, leaf temperature, dew point temperature (DPT) and relative humidity (RH) at Welgenvallen Experimental Farm of the University of Stellenbosch from 17th August, 2012 until the next day

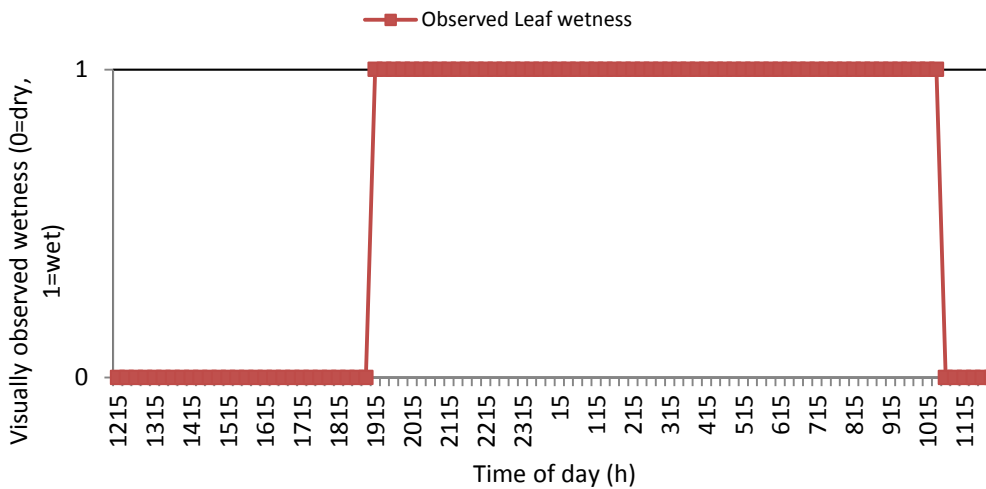


Fig 2.3 Visually observed upper canopy wetness within a citrus canopy at Welgenvallen Experimental Farm of the University of Stellenbosch from 17th August, 2012 until the next day

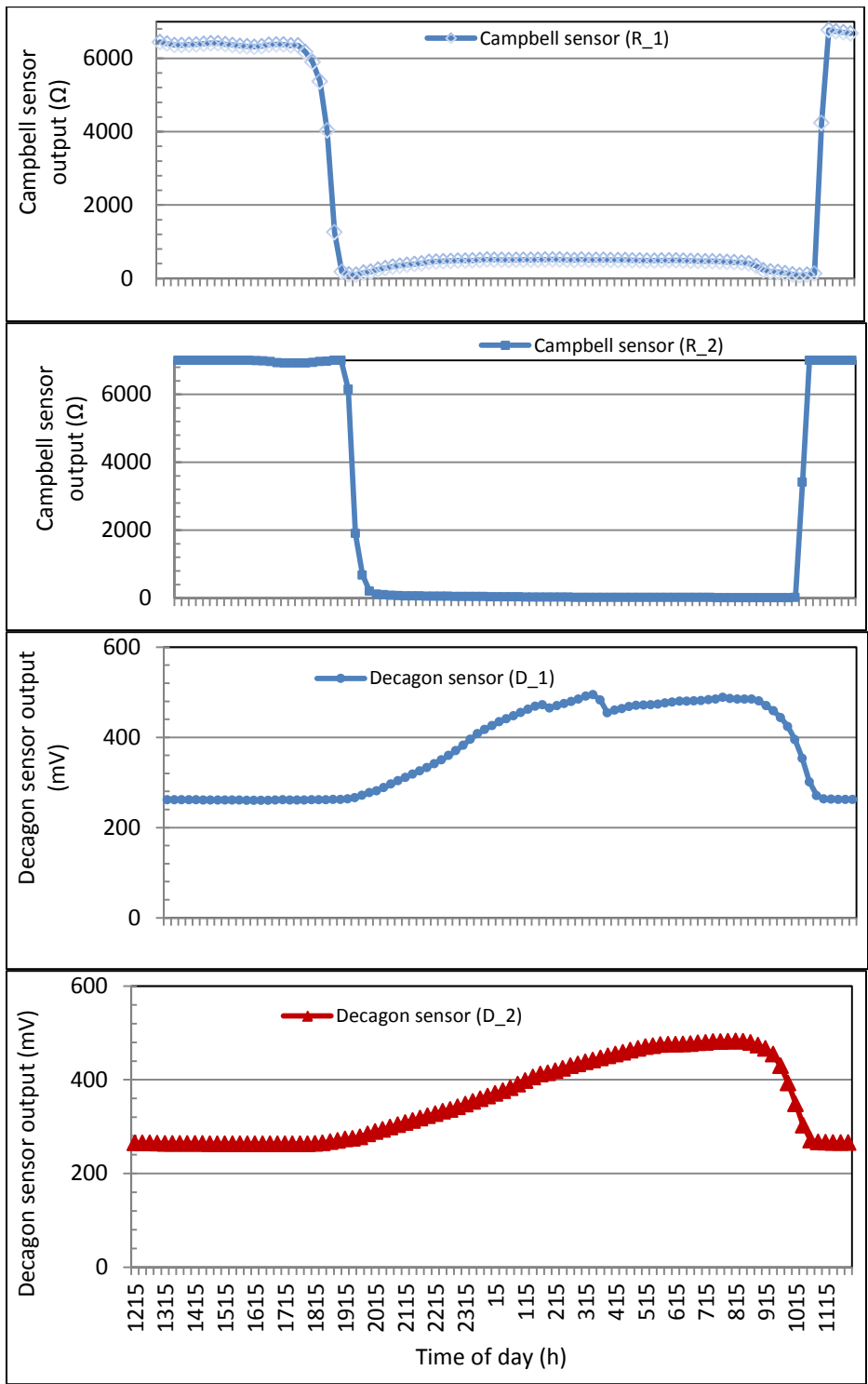


Fig 2.4 Wetness sensors' response (upper canopy level) to dew formation at Welgenvallen Experimental Farm of the University of Stellenbosch from 17th August, 2012 until the next day

In the graphs of sensors' response versus weather parameters as well as the leaf temperature, 4 sections were identified on each graph. Dry1=state of each sensor before dew deposition, the wetting period=dew deposition as well as moisture retention (wetting), followed by the process of dew evaporation=evaporating. Dry2=state of the sensors after dew dissipation. All these states were compared with visual observations of canopy wetness. The sensors' wetness response seemed to mimic the visual observations of canopy wetness. An analysis of the response of the sensors, showed that the wetting of the sensors began when the vapour pressure deficit fell below 0.2 kPa, which coincided with the visual onset of dew deposition in the upper canopy level. Evaporation of moisture from the canopy occurred between 0.2 kPa and about 1.05 kPa, followed by complete dew dissipation (Dry2). All the sensors exhibited a similar pattern to visual observation of the wetting and drying cycle that occurred in the upper canopy level as characterized by the hysteresis shape of the graphs (Fig. 2.6 - Fig. 2.9).

Visual observations of wetness indicated that canopy was wet when relative humidity was mainly 82% and above; and 45% when dry which agreed with sensors' response (Fig. 2.7). Canopy wetness was also observed to be associated with leaf temperature was less than 8 °C (Fig. 2.8), a trend that could also be picked from the sensors' outputs. Probably, these results seem to suggest that the sensors are good at simulating the wetting process. An analysis of visual observations of dew from the 17th August until the next day showed that the process of evaporation was correlated with wider change in each of the weather parameters. For example, during evaporation temperature increased from about 5.0-17.5 °C, relative humidity fell from 79% to about 45%. Vapour pressure deficit increased from about 0.2 to 1.05 kPa. This change occurred early in the morning after sunrise due to increased exposure to solar radiation.

Although the exposure of the sensors in the upper canopy level was almost the same, the degree of wetting varied among the sensors. However, the Decagon sensors had a better agreement than the Campbell sensors, which seems to indicate that there was less variation among the Decagon sensors than the Campbell sensors. It has been suggested that the difference in the degrees among the Campbell sensors can be attributed to aging of the sensors.

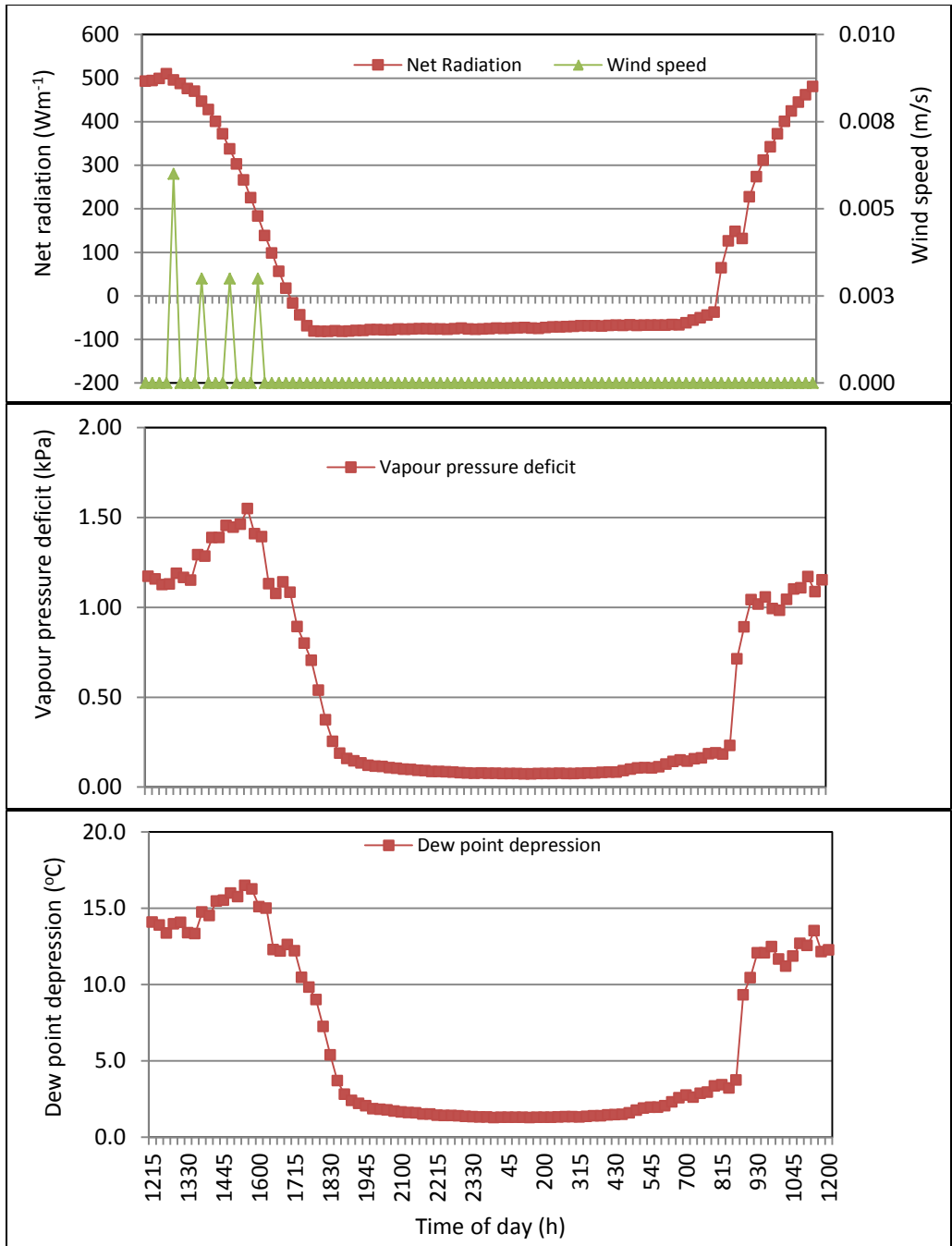


Fig 2.5 Variation of weather parameters at Welgenvallen Experimental Farm of the University of Stellenbosch from 17th August, 2012 until the next day

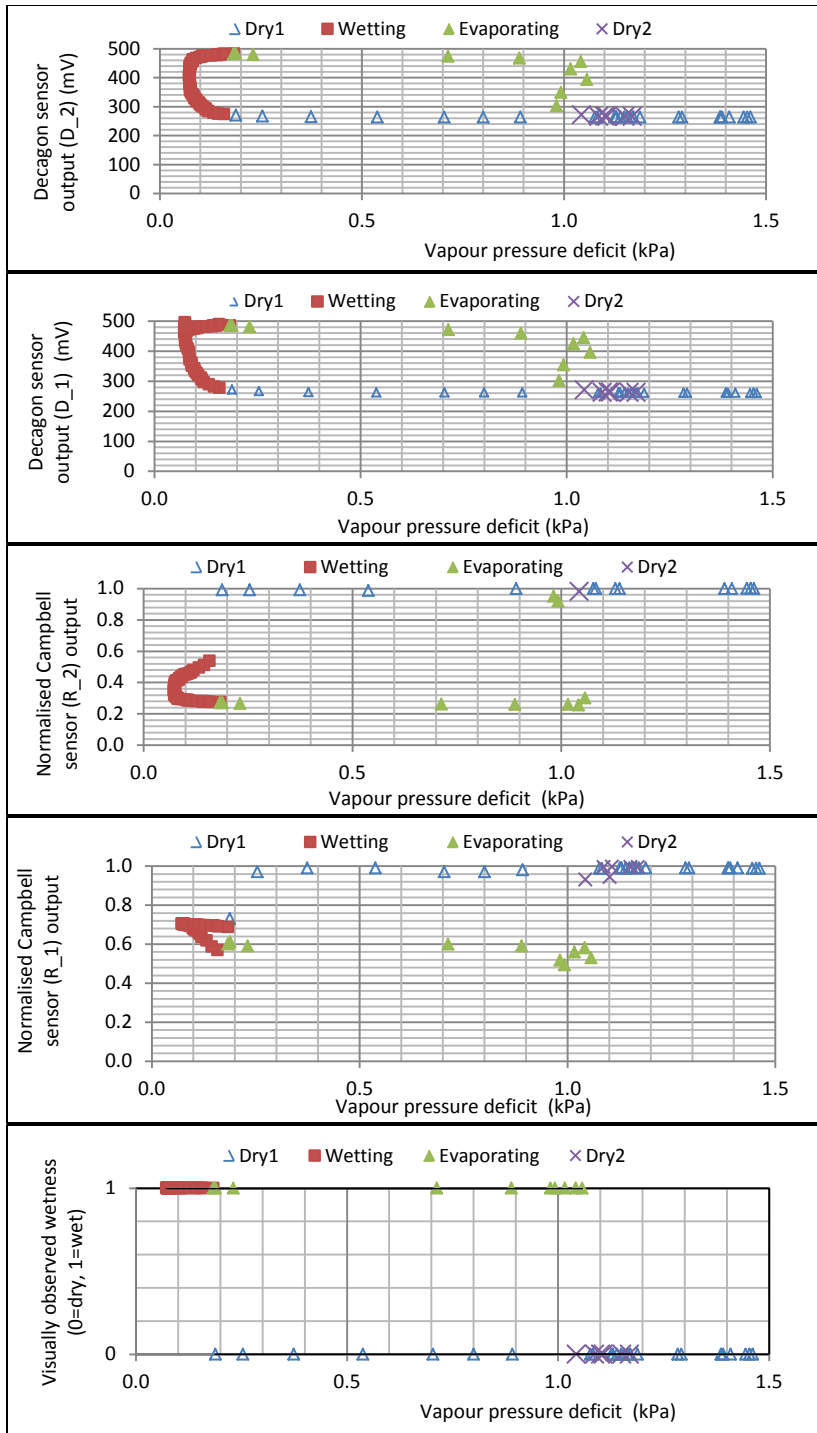


Fig 2.6 Sensors' response to vapour pressure deficit at Welgenvallen Experimental Farm of the University of Stellenbosch from from 17th August, 2012 until the next day

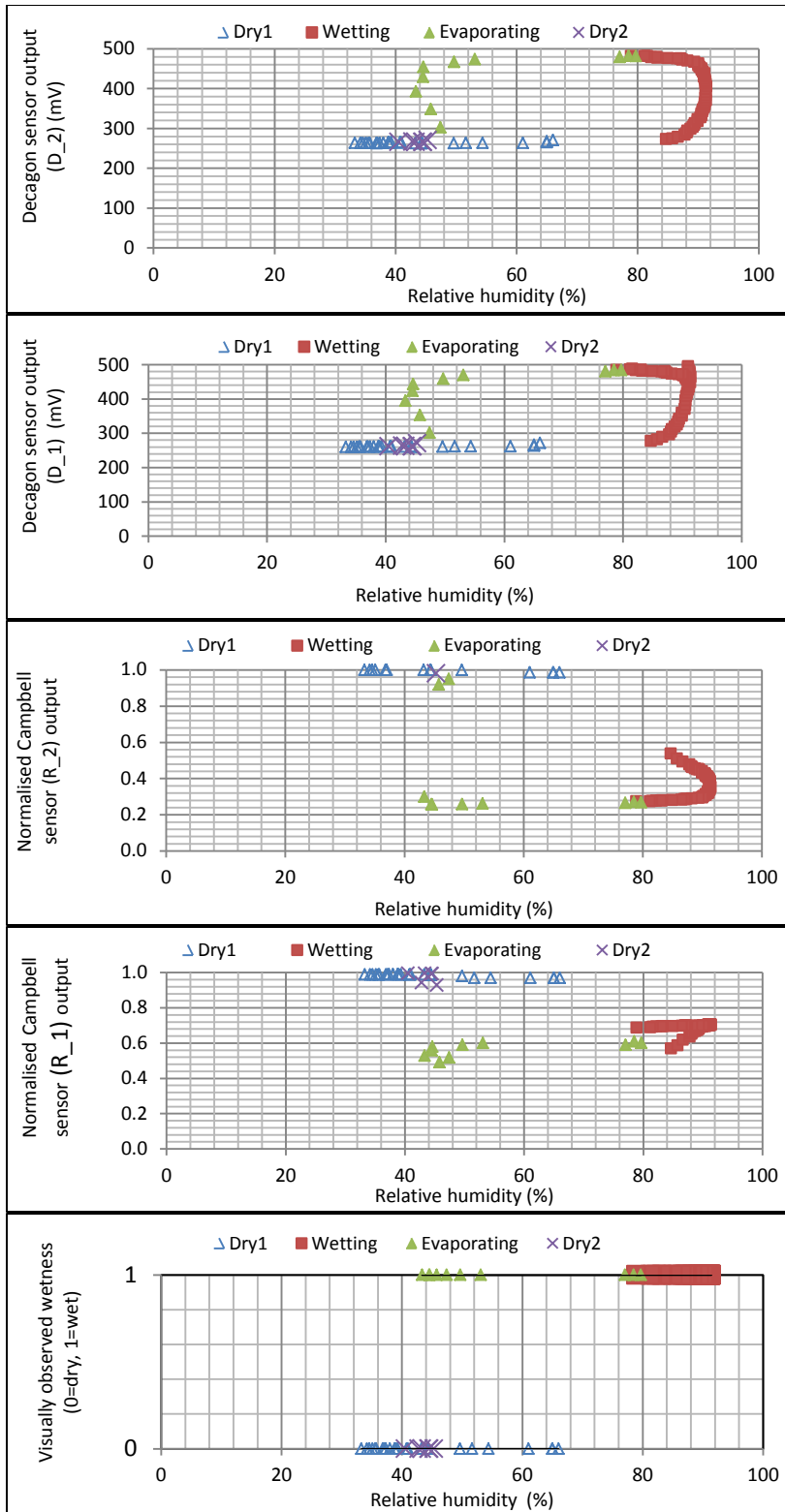


Fig 2.7 Sensors' response to relative humidity at Welgenvallen Experimental Farm of the University of Stellenbosch from 17th August 2012 till the next day

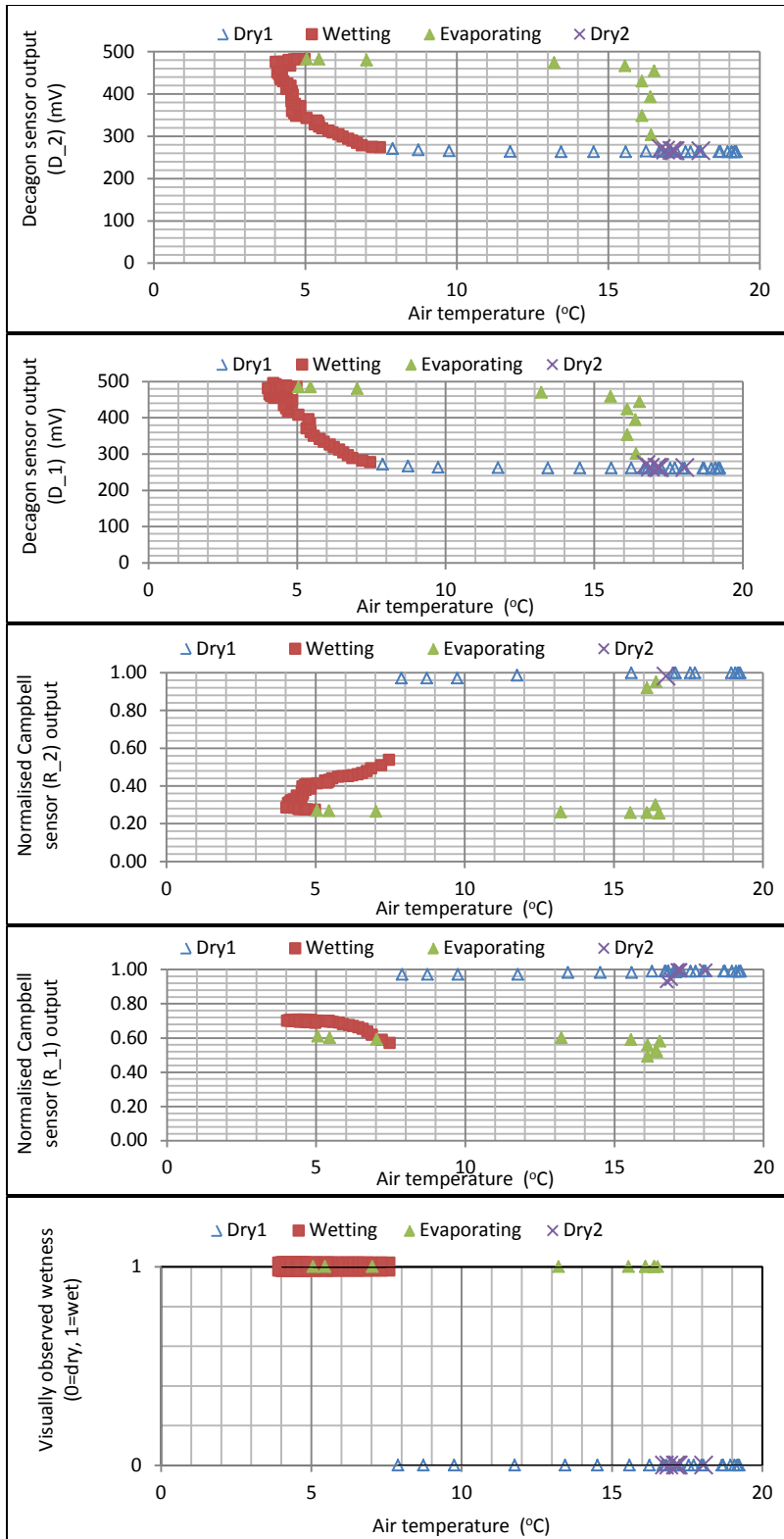


Fig 2.8 Sensors' response to air temperature at Welgenvallen Experimental Farm of the University of Stellenbosch from 17th August 2012 till the next day

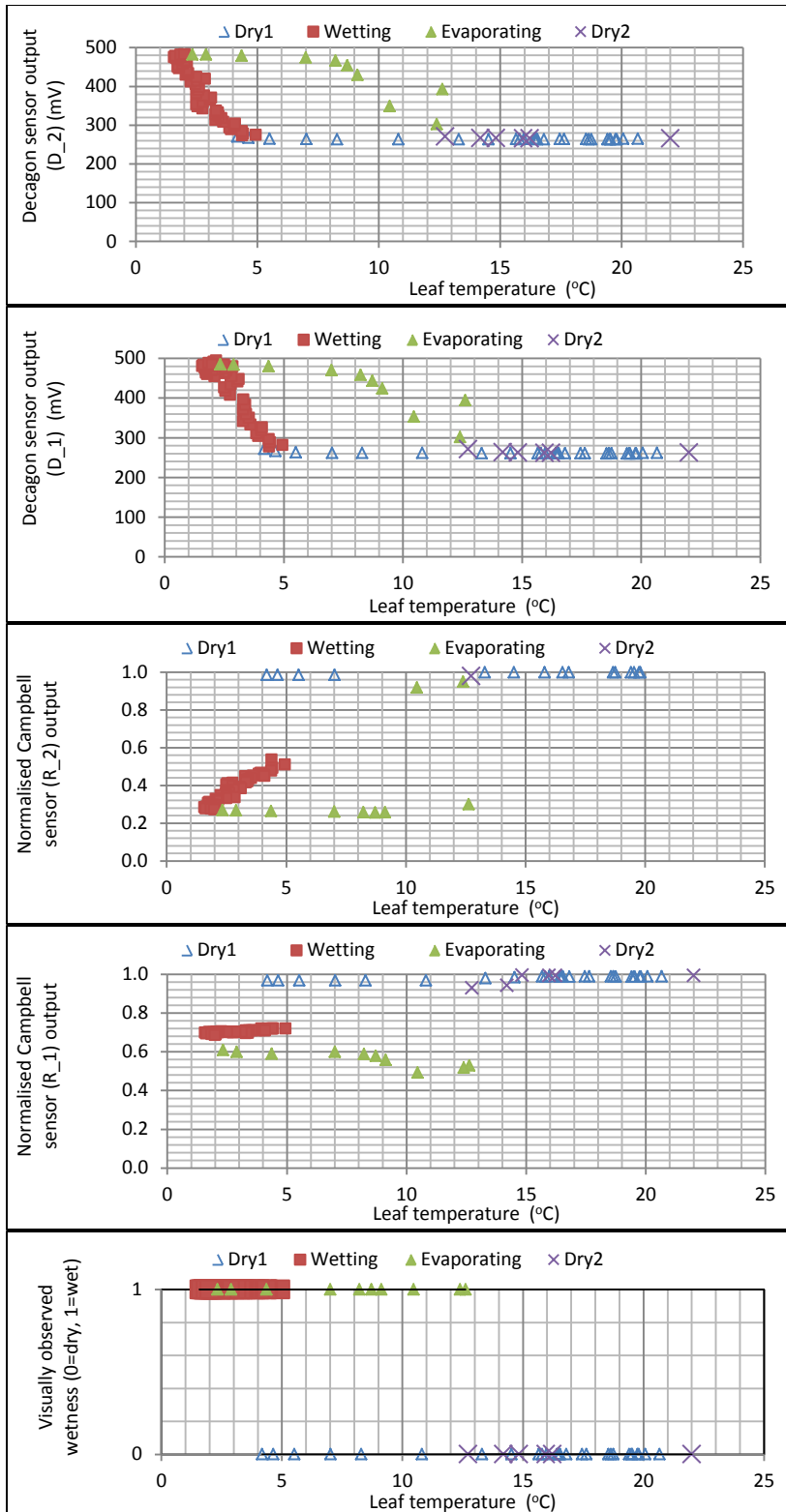


Fig 2.9 Variation of sensors' output as a function of leaf temperature at Welgenvallen Experimental Farm of the University of Stellenbosch from 17th August 2012 till the next day

2.3.2 Determination of wet/dry canopy index

It was observed that when dew was seen at night in both canopy positions, the leaves in each canopy position did not all wet at once. The number of leaves that became wet increased gradually until all (or most) of the leaves became wet. The process of moisture deposition on each leaf initiated with small water droplets (dew) covering less than 10% of the upper leaf surface of the leaf but would eventually grow with time as dew deposition proceeded. The time interval between the first occurrence of leaf wetness and time when at least 50% of the sample leaves became wet was about 30 minutes. The shortest time interval was about 15 minutes whilst the greatest time lapse was about 1 hour. It was also noticed that by the time that at least 50% of the leaves were wet, then at least 50% of the upper surface area of the first wetted leaf was covered with dew. On average, the complete canopy wetting process took about 1 h from first sign of droplets although at times not all the leaves wetted; the longest time interval was 2 h. To avoid underestimating LWD, a conservative threshold of at least one leaf (10% of the sample), being 10% wet, was considered to be a suitable index for a wet/dry canopy.

2.3.3 Visual observations of occurrence of leaf wetness

Although the field trials ran from 27th July 2012 to 30th November 2012, only a total of 62 days were visually observed for leaf wetness. Dew alone formed on the upper canopy more frequently than on the lower canopy position and contributed 47% of all the wetness that occurred during the period of study whilst rainfall accounted for 17 days of the wetness trial affecting the upper canopy. It was also common to observe that on some days, dew initially formed at night and was followed by rains later during the night or the next day. The remainder of the days, a total of 10, were dry (no dew having been visually observed). Dew occurred in the lower eastern canopy on a total of 15 days, which was 9 days less than its occurrence of dew in the upper canopy. The number of dry days in the bottom canopy (eastern) was about twice as much as those in the upper canopy (21 days).

A comparison of the onset time of LWD observed in the both canopy levels indicated different wetness profiles within the citrus canopy. On 9 nights dew formed in the upper canopy level and yet the lower canopy was completely dry. Leaf wetness consistently manifested earlier in the

upper canopy layer, hence the leaves in the upper canopy level were usually wetted before dew started to be deposited on the leaves in the lower canopy. On average dew onset in the upper surface occurred 2 h before its dew onset in the lower eastern canopy. Dew deposition in the lower western canopy occurred 25 minutes earlier than the lower eastern canopy. Initial dew onset on the upper canopy was usually detected between 19h15 and 22h00, but only once was the first dew occurrence as late as 1h15 in the early hours of the next day. Dew was observed to occur occasionally as late as the midnight in the lower canopy.

In the upper, there was a gradual increase of wet leaf area observed as well as the presence of wetness in almost all the leaves. However, in the lower canopy level, the pattern of wetness was that it mainly took place on the outside leaves, followed by some of the leaves in the interior. Wetness was observed in 60% to 100% of the leaves in the upper canopy level, while only a few leaves in the lower canopy wetted (10% to 60%) with the exception of two nights when a high incidence was observed in both canopy levels. The two nights were characterized by high relative humidity and low temperature which could have resulted in high dew deposition, or which could have resulted from rains that fell. There was never a single dew day that all the leaves in the lower canopy position became wet (Table 2.1). Rain, especially when intense, caused the leaves in all both canopy positions to wet almost simultaneously, which minimized the differences in LWD between the canopy positions.

Table 2.1 Incidence of wetness in the upper during dew days only as well as occurrence of wetness in the lower eastern canopy

Night (date)	Incidence of LWD	
	upper canopy	lower eastern canopy
17 August, 2012	90	40
18 August, 2012	100	70
7 September, 2012	100	40
10 September, 2012	100	80
11 September, 2012	100	60
30 September, 2012	90	30
5 October, 2012	70	20
12 October, 2012	100	20
13 October, 2012	100	60
21 October, 2012	60	40
2 November, 2012	100	30
3 November, 2012	70	20
9 November, 2012	60	10
15 November, 2012	90	20
17 November, 2012	90	20

Incidence represents ratio of wet leaves to total number of leaves expressed as a percentage.

2.3.4 Comparison of visually observed LWD at different canopy positions

The statistical analysis of the data revealed that LWD was not homogeneous throughout the canopy and varied according to canopy position (height) and type of wetness (Table 2.2). The vertical distribution of wetness duration in the canopy depended on whether rain or dew was the source of wetness. The differences between mean LWD in the lower eastern and lower western horizontal positions were not as pronounced (not significantly different) as the difference between the upper canopy and any one of the lower canopy positions (significantly different). The greatest differences in mean daily LWD among the canopy positions were observed during days when wetness resulted from dew. These differences in mean LWD between the upper and the two lower canopy positions during dew days were 1.9 h and 1.7 h corresponding to the eastern and western lower canopy positions respectively yet the lower canopy positions differed by less than 30 minutes regardless of the source of wetness. Although the mean daily LWD at the upper canopy and the lower canopy positions were significantly different, the lower canopy positions were not significantly different from each other (Table 2.2). The same pattern persisted when both rain and dew days were combined. During rainy days, there was no significant

difference between all the canopy positions and the mean daily LWD in the upper and lower canopy positions differed by about 1 h.

Table 2.2 Mean daily leaf wetness duration (LWD), in hours per day, in the three citrus canopy positions during different wetness events from 27th July to 30th November, 2013

Type of wetness	Top canopy	Bottom canopy	
		Eastern	Western
Dew	12.2 ^a	10.3 ^b	10.7 ^b
Rain	15.5 ^a	14.3 ^a	14.1 ^a
Rainy and dew days combined	14.0 ^a	12.9 ^b	12.6 ^b

Mean in same row followed by same letter are not significantly different by t-test at 5% probability level.

Generally, for most of the wet days, the daily wetness period lasted longer than 10 h in both canopy positions although the upper canopy had more dew and rain days with higher daily wetness duration exceeding the 10 h. Considering the upper canopy, dew days were likely to last more than 10 h at a frequency of 83% of the total dew days whilst only 2 days had the wetness period of less than 5 h (Table 2.3). When rain was the source of wetness, the probability of the wetness period exceeding 10 h was about 78%, with no wetness period of less than 5 h (Table 2.3). In the lower eastern canopy, 67% of the dew days had wetness period greater than 10 h (67%). When rain was the source of wetness, the probability of wetness lasting more than 10 h was lower as compared to the upper with a value of 65%. Two rain days resulted in the lower canopy drying up in less than 5 h (Table 2.4). The lower western canopy exhibited a pattern similar to the lower eastern canopy position. 9 out of 14 dew days (64%), had the wetness period lasting more than 10 h. 63% of the rain days were, the lower western canopy were wet for more than 10 h (Table 2.5).

Table 2.3 Categories of daily observed LWD according to their duration (X) in hours considering a period of 51 days when wetness occurred in the upper canopy level

Wetness condition	$0 < X \leq 5 h$	$5 < X \leq 10 h$	$10 < X$	Number of days for upper canopy
Number of dew days	2	2	20	24
Number of rain days	0	6	21	27
Number both rain and dew days	2	8	41	51

Table 2.4 Categories of daily observed LWD according to their duration (X) in hours considering a period of 41 days when wetness occurred in the lower eastern canopy

Wetness condition	$0 < X \leq 5 h$	$5 < X \leq 10 h$	$10 < X$	Number of events days for lower eastern canopy
Number of dew days	1	4	10	15
Number of rain days	2	7	17	26
Number both rain and dew days	3	11	27	41

Table 2.5 Categories of daily observed LWD according to their duration (X) in hours considering a period of 30 days when wetness occurred in the lower western canopy

Wetness condition	$0 < X \leq 5 h$	$5 < X \leq 10 h$	$10 < X$	Number of events days for lower western canopy
Number of dew days	3	2	9	14
Number of rain days	1	5	10	16
Number both rain and dew days	4	7	19	30

2.3.5 Discussion of spatial variations

The observed total LWD, calculated as the sum of the wet hours during the entire period amounted to 725 h in the upper canopy level compared to 527 h in the lower canopy. This indicates a gap of 198 h between the upper and lower canopy. These differences can be attributed to the night thermal patterns that occur in the citrus canopy. During the night, the mean air temperature profile at the top of the canopy becomes unstable due to loss of long wave radiation and thus the unstable lower vegetation layer is capped and thereby decoupled from the above canopy region (Jacobs and Nieveen, 1995).

Air and leaf temperature data show that the leaf temperature in the upper canopy layer was lower than the average air temperature. The variation of leaf temperature varied in the same manner as LWD, colder at the top than at the bottom. The leaves in the upper canopy were 0.80 °C cooler than those in the lower canopy (Table 2.6). Leaf temperature in the upper canopy level was 0.33 °C lower than air temperature thereby causing dew deposition, whereas in the lower canopy level

air temperature was lower than the leaf temperature by 0.47 °C. Dalla Marta et al. (2008) also found the same pattern in a grapevine. The authors noted that the leaves in the upper canopy of a grapevine were 0.60 °C cooler than those in the bottom layer. The higher difference in leaf temperatures (0.80 °C as compared to 0.60 °C) of the citrus could be attributed to the dense canopy of the citrus canopy. The higher leaf temperature in the lower canopy layer (as compared to leaf temperature in the upper canopy level) seemed to have given rise to lower and delayed condensation in this canopy layer due the cooling process lasting longer.

Table 2.6 Average leaf and air nightly temperature measured from 27th July to 30th November 2012 during dew days (n= 22)

Parameter	Value \pm SD (°C)
Average air temperature	8.65 \pm 2.75
Leaf temperature (upper canopy level)	8.32 \pm 3.17
Leaf temperature (lower canopy level)	9.12 \pm 2.97

The explanation for the early deposition of dew on the top canopy is related to the exposure of the top canopy to the sky. In a mature canopy such as the citrus, the top canopy is directly exposed to the sky, and consequently is generally the first region to exhibit wetness (Lulu et al., 2008; Santillán-Núñez, 2009). The leaves in this layer create a barrier that reduces radiant and convective heat loss from the ground, delaying the cooling of surfaces of the lower canopy, and thereby subsequently delays dew formation (Batzer et al., 2008). The overall result was that, dew deposition occurred earlier in the upper canopy than in the lower canopy position and consequently hence the differences in the dew-onset between the two canopy positions. Shorter dew events in the lower canopy level were a result of late dew onset since all the canopy positions dried almost at the same time.

The number of wet leaves and degree of leaf wetness often differed according on the canopy layer indicating a LWD spatial variability within the same canopy layer. Depending on the position of a leaf within any canopy layer, a leaf can be totally or partially screened by the upper foliage or exposed to the sky and consequently, it may be subjected to very different radiative

balances determining a different condensation phenomenon. This means that the sensor output is closely connected to the sensor arrangement (placement) inside the canopy, an aspect that must be considered when positioning sensors.

The observed LWD data show that the citrus canopy in Stellenbosch displayed spatial heterogeneity in LWD in height and in horizontal position within the citrus canopy. When examining both dew and rainy days, there was a significant effect of canopy position on mean LWD. The differences in LWD variability are associated not only with weather conditions but also the plant structures as well as the planting system, crop age and crop management (Sentelhas et al., 2005). According to Monteith and Unsworth (1990), the LWD inside the crop canopy can be longer or shorter than the top depending on the crop structural characteristics and consequently on its microclimate. For example, in particular the trichomes could act as condensation points preventing dew reaching the leaf surface, which would appear as dry to an observer. Studies conducted by Wittich (1995), Santos et al. (2008), Batzer et al. (2008) and Sentelhas et al. (2005) to evaluate the spatial variability of LWD in different crop canopies found that LWD have shown significant different patterns of variation from one crop canopy to another.

In this study, the LWD also showed spatial variability within a citrus canopy. The daily mean LWD between the upper and lower was about 2 h, which is similar to results by Sentelhas et al. (2005), Bazter et al. (2008) and Wittich (1995) all for apple trees. Generally citrus and apple trees have a similar shape of canopy which is characterized by upper canopy which has unobstructed exposure to the sky and is generally the first to exhibit wetness during both dew and rain events. On the other hand, LWD spatial variability in a citrus canopy contrasts other plants. For example, LWD in coffee plants was 1.5 h longer in the lower canopy portions of the canopy than the top (Sentelhas et al., 2005; Santos et al., 2008). The reason for this is that the conical shape of the coffee plants exposes leaves at all the levels to the sky and promotes the beginning of wetness almost immediately. During the morning, however, the top of coffee is expected to receive more total solar radiation and stronger winds than the other positions, resulting in a more rapid dry-off and hence shorter LWD (Sentelhas et al., 2005).

These findings emphasize it is not only the weather parameters that affect LWD but also plant structure and height which affect the microclimate. It can therefore be concluded that the citrus canopy in Stellenbosch showed spatial variability in LWD and this variable was not only affected by weather conditions but also by canopy characteristics such as plant height and leaf exposition whose interaction determines the microclimate. These findings point to the importance of taking cognizance of the spatial heterogeneity of LWD in citrus, if measurements are required for disease-warning systems. The understanding of LWD variability is crucial as it can help to improve the performance of the disease warning systems. Since factors such as arrangement of plants, crop age and crop management practices can affect the crop-climate microclimate, it is possible the pattern of spatial variability of LWD in citrus can change as citrus trees grow older and bigger and if crop management practices also change. According to Pangga et al. (2011), the changing size of and characteristics of a growing plant canopy modifies the microclimate and influences disease development.

No significant differences between the upper and the lower canopies were noted during rain days, with the longest mean LWD occurring in the upper canopy level. Sentelhas et al. (2005) also found similar results for crop-canopies of maize, grapes and apples on rainy days. The author observed that the mean LWD in the upper and lower canopy positions of apple trees differed by less than 1 h, with longer mean LWD in the upper canopy. This pattern was similar to the findings for the citrus canopy, except that the mean LWD difference was between 1 and 1.5 h. The possible reason for this is that because the rain often wets the entire canopy, especially when intense or occurring for a long time (several hours), which reduced the differences between canopy heights. However, it should be noted that the rainy days included days that rains preceded dew events (about 11 nights), and so the higher mean LWD in the upper could be attributed to the effect of dew. Consequently, when both dew and rain days were combined, the pattern of the spatial variability of LWD in the citrus canopy was similar to that observed during dew days.

The middle canopy (where visual observations were not performed) probably had a lower mean LWD than the upper canopy, but a longer LWD than the lower canopy because the canopy trees

were mature plants with no spaces between the trees. Griffiths (1978) suggested that during the daylight hours, the added vertical currents of the thermals can cause an almost independent cell (between plants if there is space between them) to develop and at ground level the air may flow at 180° to that of the free air above the trees. This wind flow could promote a drying process that starts in the top canopy followed by the bottom and finally the middle layer. As micromet measurements were not performed between the citrus row, this cannot be conclusive and would have to be a recommendation for a future micromet study.

Since the daily LWD was longest in the upper citrus canopy, this canopy level should be considered as a standard for measurements when considering its use in diseases-warning systems for citrus. Moreover, visual observations of wetness in the upper canopy of the citrus during dew days can also be used to infer wetness for the lower canopy. This is because when the incidence of LWD in the upper canopy was less than 60%, no wetting of the leaves in the lower canopy level was noted. However, the converse was true. From a practical view point, visual observations might not be a feasible, as the grower would need manpower to perform such wetness surveys which could mean an extra expense. One way to overcome this could be to utilize LWD measured by wetness sensors located in the upper canopy level. The degree of wetness of the sensors located in the upper canopy level could be then be related with the onset of the wetting process in the lower canopy level.

The longer the LWD duration, the more susceptible the citrus would be to diseases that require a longer wetness period to infect a leaf somewhere in the canopy (Hahn, 2009). The mean LWD was about 10 h, and so the citrus in Stellenbosch could be more susceptible to pathogens that require a minimum of at least 10 h to be infected assuming other weather conditions for their development were favourable (Vincent and Garcia-Jimenez, 2008).

2.4 Performance of leaf wetness sensors

2.4.1 Wetness duration and weather conditions

The daily mean temperature, relative humidity, wind speed and net radiation, computed using 24 h day, during dew days, rainy days and dry days are shown in Table 2.7. Generally, dry days had higher values of mean daily air temperature, wind speed, and net radiation as compared to both dew days and rainy days. Relative humidity was highest on rainy days (77%) and lowest (52%) during dry days. Wind speed was lowest (0.45 ms^{-1}) during dew days and highest during dry days (1.34 ms^{-1}). Higher wind speed at night can disrupt the stable or nearly neutral conditions that favour dew formation.

Table 2.7 Average daily weather conditions (\pm SD) for different wetness categories during the period between 27th July - 30th November 2012 at Stellenbosch in the citrus orchard

	Dew days (n=24)	Rainy days (n=27)	Dry days (n=11)
Air temperature ($^{\circ}\text{C}$)	14.35 ± 0.63	12.82 ± 0.70	18.28 ± 1.33
Relative humidity (%)	69.98 ± 1.06	76.53 ± 1.86	51.77 ± 3.42
Wind speed (ms^{-1})	0.45 ± 0.05	0.75 ± 0.13	1.34 ± 0.39
Net radiation (Wm^{-2})	119.66 ± 11.24	62.61 ± 12.34	135.64 ± 17.67

n: number of days assessed.

A further analysis of the average daily weather variables calculated during the “wet period” showed that the shorter periods of shorter LWD (less than 10 h) were associated with mean temperature of 18°C or above and relatively lower relative humidity (80%). On the other hand, longer periods of wetness ($\text{LWD} > 10 \text{ h}$) were correlated with lower temperature in the range between 5°C and 14°C and relative humidity greater than 80%. The vapour pressure deficit during ranged between 0.125 and 0.268 kPa for LWD periods greater than 10 h. (Fig. 2.10).

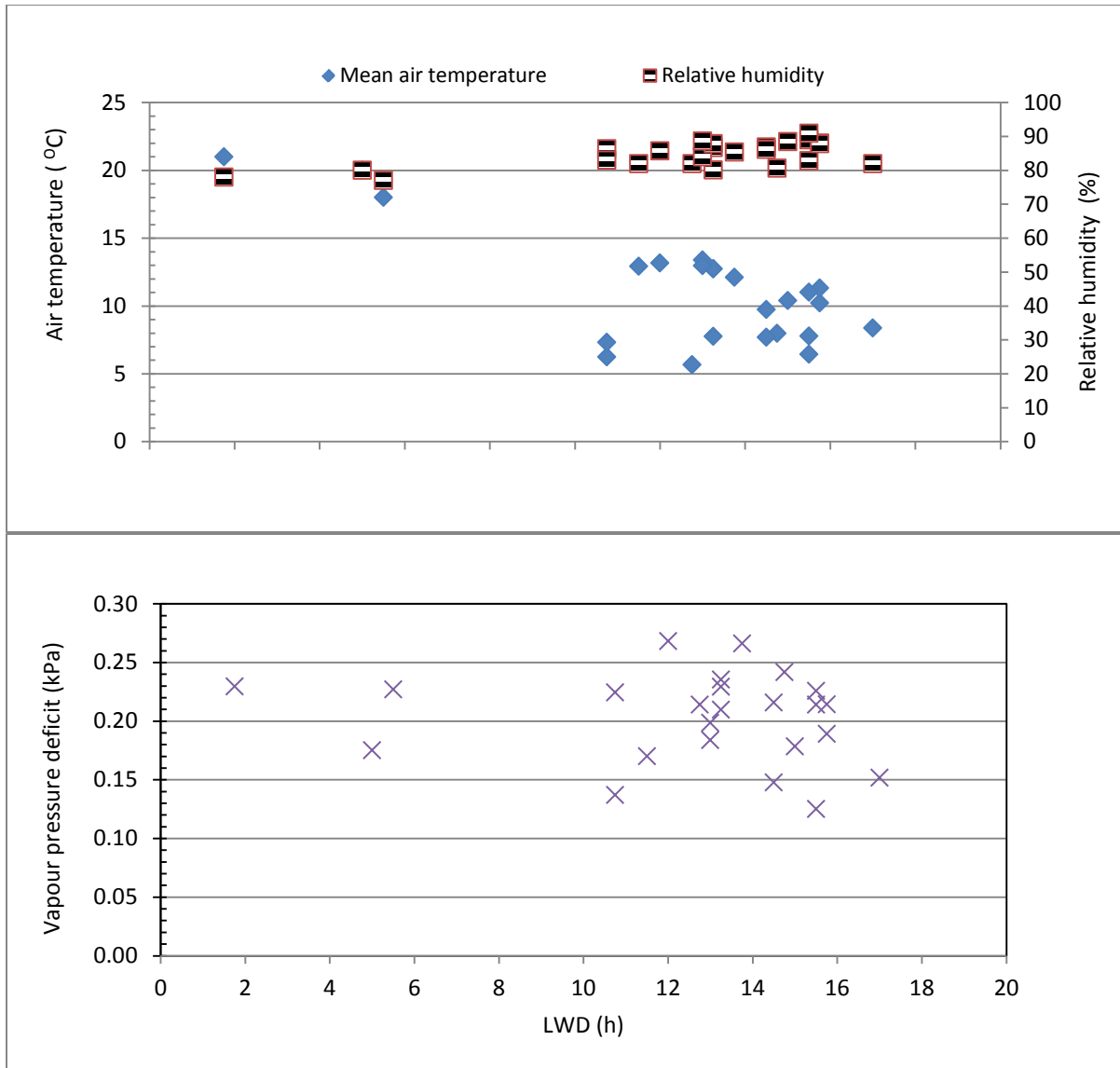


Fig 2.10 Relationship between LWD and weather parameters (temperature, relative humidity, net radiation and vapour pressure deficit) when the canopy was wet during dew days only (n=24)

To quantify the effect of weather parameters to LWD, a stepwise multiple regression approach was applied. The variables initially considered were hourly air temperature, relative humidity, and vapour pressure deficit. Wind speed was not a factor in this study because of the presence of windbreaks. The regression shows that relative humidity is the variable explaining the greatest part of variability ($R^2=62$), however the R^2 increased by almost 9.2% when the temperature was associated with relative humidity, and it further increased by 8.8% when also considering the

vapour pressure deficit. There remained an unexplained variability of 20% (Table 2.6). This means that in determining LWD with a regression model, the standard agrometeorological variables explained only 4/5 of the dew duration and other elements must therefore be found for obtaining a more precise simulation.

Table 2.8 Coefficient of determination (R^2) for the meteorological variables effect on LWD by stepwise multiple regression model

Variable	R^2
Relative humidity	62.0
Air temperature	9.2
Vapour pressure deficit	8.8
Unexplained	20

2.4.2 Sensor testing

Prior to the deployment of the sensors in the field, the sensors were placed in placed in a growth chamber, where they were sprayed with the same amount of water (tap) and allowed to dry. This process was repeated using distilled water and rain water. Results indicated that there was a good correlation between the sensors. The coefficient of determination between the Decagon and Campbell wetness sensors were 0.99 and 0.92 repectively. No significant differences were noted in LWD among all the sensors. It was then concluded that differences among sensor readings in the citrus canopy would be attributed to variations in microenvironment.

2.4.3 Sensor calibration

The sensors were individually calibrated by determining the wet/dry threshold for each of the sensors when at least one of the sampled leaves was wet. All the three the Campbell wetness had different average wet/dry threshold values. The same trend was also noted in Decagon wetness sensors. Table 2.9 shows the calibration values for each of the sensors. The fact that all the sensors had different wet/dry threshold values, emphasizes the importance of individually calibration of wetness sensors.

Table 2.9 Wet/dry threshold values for Campbell wetness sensors (R_1, R_2 and R_3) as well as Decagon wetness sensors (D_1, D_2 and D_3)

Statistics	Sensor					
	R_1 (Ω)	R_2 (Ω)	R_3 (Ω)	D_1 (mV)	D_2 (mV)	D_3 (mV)
	958.4	1100.2	850.9	272.2	273.7	270.3
	985.9	1258.7	868.7	268.5	269.4	268.5
	1012.2	1000.8	980.2	269.1	268.1	272.9
	1012.3	980.4	1105.6	275.8	273	270.1
	900.8	890.6	869.8	270.3	272.9	267.6
Average value	974.9	1046.1	935.0	271.2	271.4	269.9
Standard deviation	41.6	125.4	96.8	2.6	2.2	1.8

There was a good relationship between the observed and measured LWD in the upper canopy level as compared to the lower canopy. Considering all the wet days from 27th July to 30th November 2012, the coefficient of determination (R^2) was significant and ranged between 0.91 to 0.95 (Fig. 2.12). The highest R^2 of 0.94 and 0.95 corresponded to the measurements from the Decagon sensors and visual observation. In the lower canopy level, there was a large dispersion of data between observed and predicted LWD, hence a relatively weaker correlation between LWD measurements ($R^2=0.60$ and 0.64) (Table 2.10). When only dew days were considered, a good agreement was also observed between sensors' and visually observed LWD in the upper canopy, though with the smaller coefficient of determination values and the widest range varying between 0.82 and 0.90. Again the performance of the Decagon sensors was superior to that of the Campbell sensors (Fig. 2.12). As for the lower canopy level, R^2 was lower with values of 0.57 and 0.58 corresponding to the Campbell and Decagon sensors respectively.

The correlation between observed and sensor predicted LWD was best when rain was the source of wetness. Considering the upper canopy level, all the graphs had the highest slopes of regression being close to 1. The R^2 coefficients of linear regression between the LWD estimated from the sensors with data visually observed in the upper canopy, had the highest values (best relationships) as R^2 ranged from 0.93 to 0.96 (Fig. 2.13). In the lower canopy level, when it rained, the observed and measured LWD also exhibited the strongest agreement as compared to wetness that resulted from dew or when both and rains were considered. R^2 computed during

rainy days were 0.64 and 0.61, corresponding to the western and eastern lower canopy positions. However, when dew was the source of wetness, the coefficients of determination were almost the same (0.58 and 0.57) on both sides of the lower canopy. Correlation values (R^2) of 0.64 and 0.61 were obtained when considering both rain and dew days were combined (Table 2.10).

Generally the sensors in the lower canopy were not able to predict LWD well. Each of the sensors in the lower canopy positions consistently performed poorly as compared to the worst sensor in the upper canopy. However, both canopy positions exhibited the same trend in that LWD measurements (observed and sensor estimated) in these canopy positions had the strongest agreement during rainy days and the largest spatial variability when wetness resulted from dew. The fact that sensors at the lower canopy level performed badly is consistent with Sentelhas et al. (2005) findings on other crops. The author noted that the coefficient of determination (R^2) (precision) decreased from top of the canopy when in different crops as such as apples, coffee, and grape vines. This seems to suggest that sensor placement within a canopy has an influence on the precision of sensors. Lulu et al. (2008) and Santos et al. (2008) also confirmed the same findings. Lulu et al. (2008) further noted that the coefficients of determination during rainy days were significantly higher than on dew days for the grapevine.

In the upper canopy, where the sensors in the upper canopy were all exposed directly to the sky as most of the leaves in this canopy level, the use of a single sensor located anywhere in this canopy can still provide a good estimate of LWD. However, this seems to suggest that the horizontal location of the sensors within the lower canopy position is more critical than its location in the upper canopy. Zhang and Gillespie (1990) suggested that if the top canopy is associated with the longest LWD as in the case of the citrus canopy, then a LWD sensor placed at 30 cm over turf grass can provide an accurate estimate of LWD in the upper canopy. The use of a LWD sensor placed at 30 cm can eliminate the problem of placing sensors in the canopy, which can interfere with activities such as spraying and other management activities in citrus canopies.

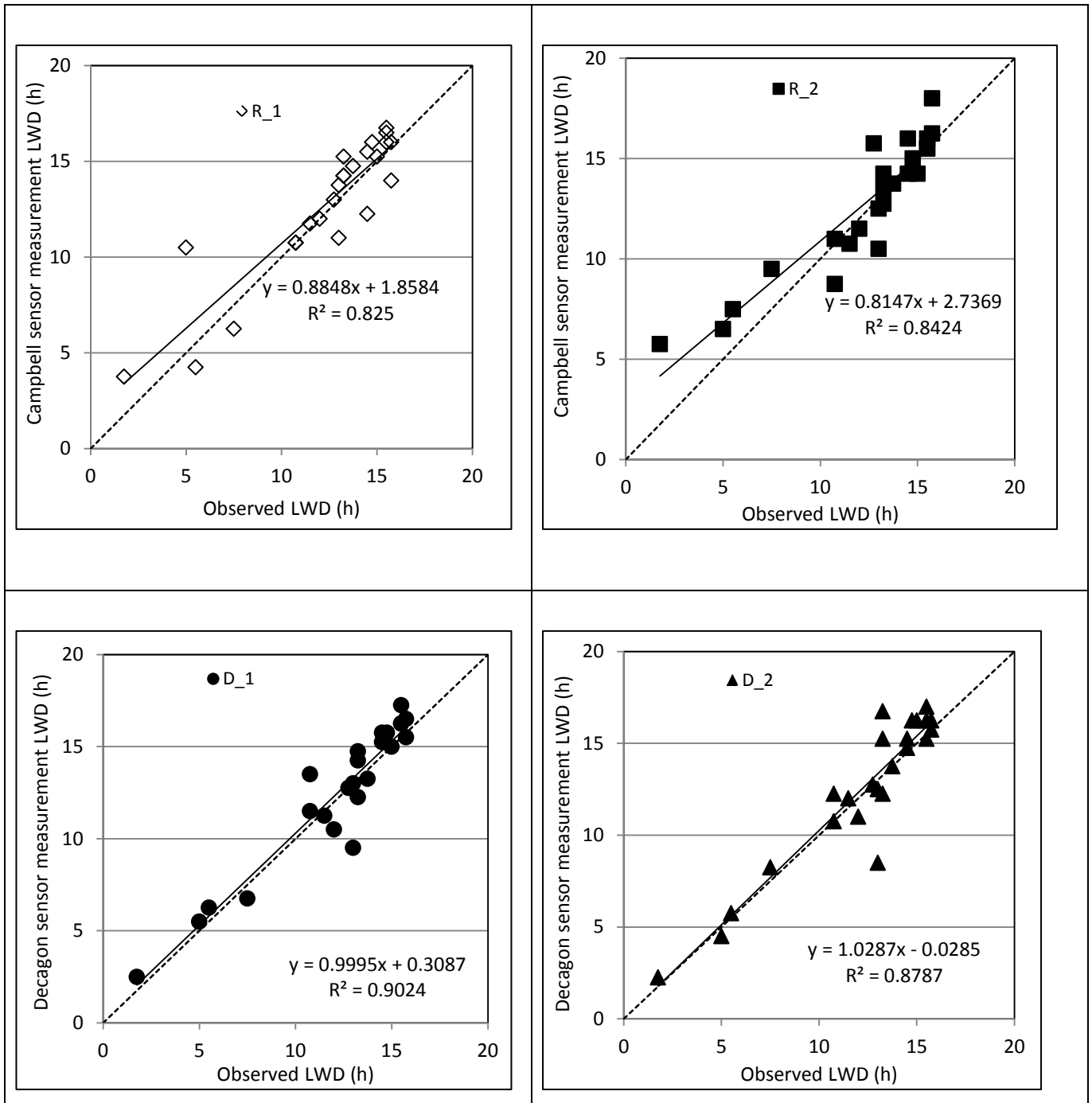


Fig 2.11 Relationship between visually observed and sensor measurement LWD in the upper canopy level considering only dew days (n=24, p<0.05) considering sensors R_1, R_2, D_3 and D_4

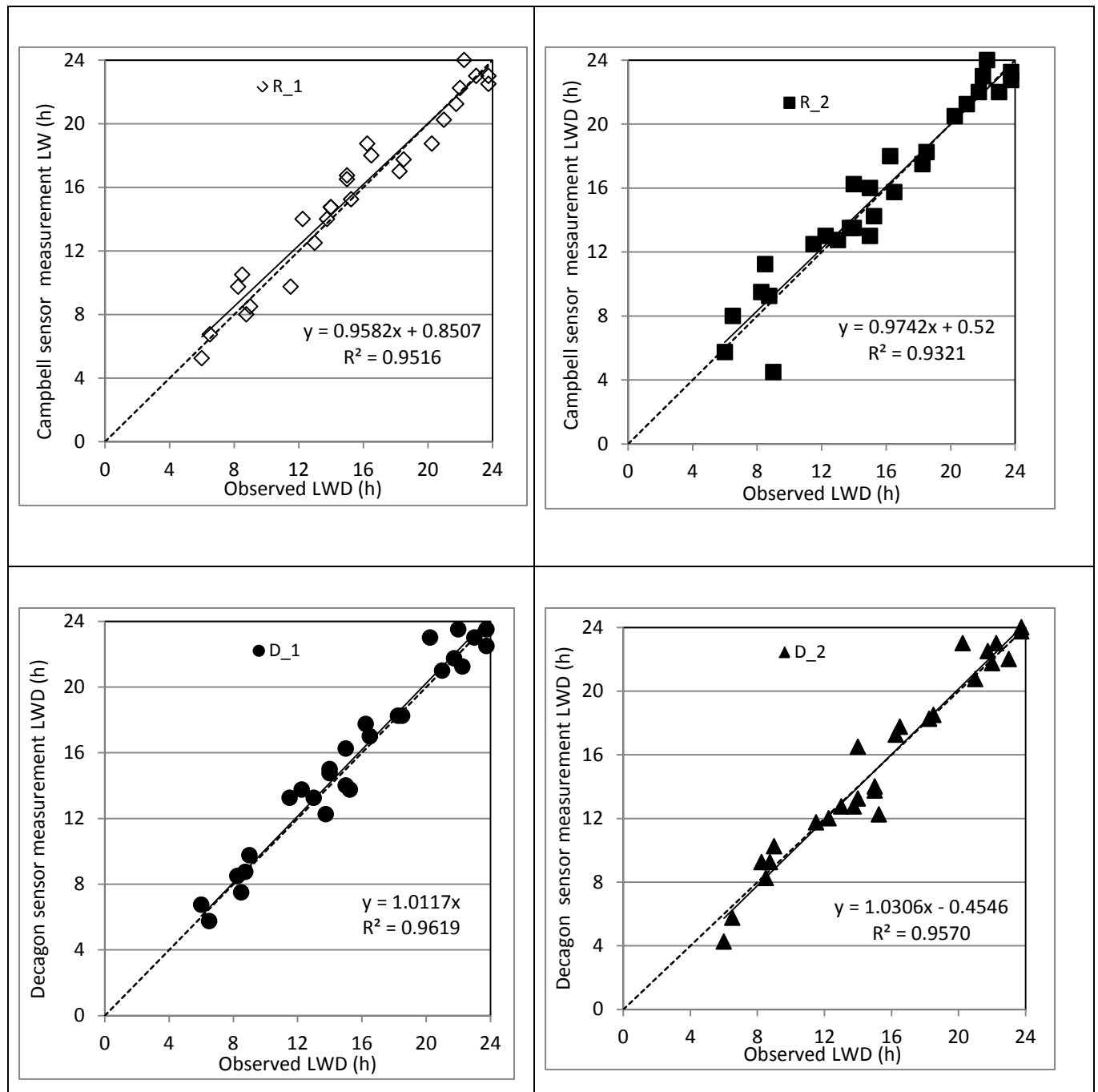


Fig 2.12 Relationship between visually observed and sensor measurement LWD in the upper canopy level during rainy days (n=27, p<0.05) considering sensors R_1, R_2, D_3 and D_4

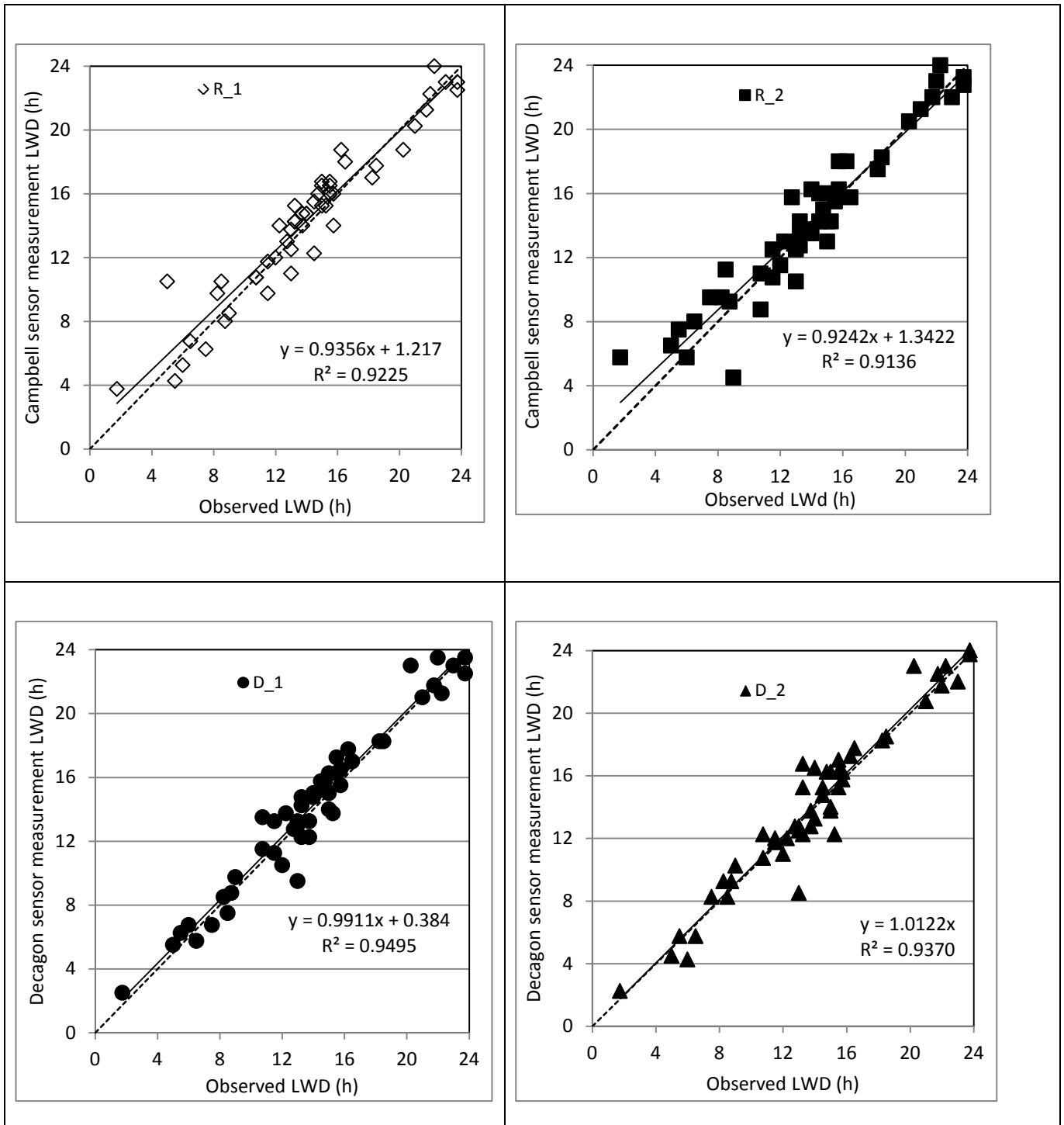


Fig 2.13 Relationship between visually observed and sensor measurement LWD in the upper considering all the wet day (n= 51; p<0.05) considering sensors R_1, R_2, D_3 and D_4

Table 2.10 Coefficient of determinations for the lower citrus canopy considering visually observed and measured LWD for different wetness days

Canopy position	Sensor	All wet days	Dew days	Rain days
Western	R_3	0.6387	0.5689	0.6397
Eastern	D_3	0.5952	0.5751	0.6098

2.4.4 Mean and absolute errors of LWD measured by wetness sensors

The sensors in the upper canopy level exhibited a tendency of overestimating LWD during dew days especially when the wetness period was greater than 10 h (Fig. 2.11). As compared to the Campbell wetness sensors, the Decagon sensors showed very little bias for LWD of less than 10 h. The ME of the Campbell sensors were 0.45 h and 0.47 h as compared to 0.30 h and 0.32 h for the Decagon wetness sensors (Table 2.11). When wetness resulted from rain, two sensors (one of each type) overestimated LWD. However, one of the Decagon sensors, D_2 almost showed no bias during rainy events (Table 2.12). All the sensors in this canopy level had lower ME (lower bias) if compared with dew only days. The Decagon sensor (D_1) had the largest ME of magnitude 0.22 h, followed by Campbell sensors with a ME of 0.20 h. When all the rain and dew days were combined, all the sensors in the upper canopy level showed a bias that was skewed towards overestimation (Fig. 2.13) with a maximum ME still less than 1 h (Table 2.11). Considering the lower canopy position, the Decagon sensor located in the lower eastern canopy, overestimated LWD the most (1.15 h). On the contrary, the Campbell sensor (R_3) positioned on the lower western side underestimated LWD by 0.17 h during dew and displayed a similar pattern during rainy days as well as when both rain and dew days were considered together. On the other hand, the Decagon sensor (D_3) located on the lower eastern canopy overestimated LWD by 0.70 and 0.99 h during rainy days and when all the days were combined respectively (Table 2.11).

The accuracy of the sensors, against visual observations, was higher in the upper than the lower canopy level. Hence, wetness sensors in the upper canopy level estimated LWD with a higher accuracy as compared to those in the lower canopy level (Table 2.11). During dew days, the MAE of all the sensors in the top canopy varied between 57 to 70 minutes, with the Decagon

sensors having MAE of less than 1 h. In contrast, the sensors in the lower canopy level had lower accuracy with larger MAE of 2 h and 2.65 h corresponding to the lower eastern and western parts of the canopy. Considering rain days, all the sensors measured LWD with higher accuracy during rainy days. The MAE for all the sensors in the upper canopy level on rainy days were 1.02, 1.08, 0.85 and 0.89 h corresponding to the sensors R_1, R_2, D_1 and D_2 respectively. The sensors in the lower canopy had MAE of 2.83 and 2.40 h. When both rain and dew days were considered, the sensors in the upper canopy position had MAE in the range between 0.90 h to 1.10 h (Table 2.11).

Table 2.11 Mean errors between LWD measured by wetness sensors and observed at different canopy heights and sides of the bottom canopy

Canopy position	Sensor	Dew days		Rain days		Day with rain and dew	
		ME (h)	MAE (h)	ME (h)	MAE (h)	ME (h)	MAE (h)
Upper canopy	R_1	0.45	1.16	0.20	1.02	0.32	1.08
	R_2	0.47	1.11	0.12	1.08	0.28	1.10
	D_1	0.30	0.95	0.22	0.85	0.26	0.90
	D_2	0.32	0.97	0.02	0.89	0.16	0.93
Lower canopy	R_3	-0.17	2.65	-0.80	2.83	-0.05	2.85
	D_3	1.15	2.00	0.70	2.40	0.99	2.20

Considering the upper canopy level, an analysis of the daily error, calculated as the difference between measured and observed daily LWD, by each wetness sensor during dew only day is shown in Fig. 2.14 and Fig. 2.15. Most the overestimation errors were less than 2 h. The Campbell sensors, R_1 and R_2 overestimated LWD in 16 and 13 days respectively. Occasionally the Decagon sensors, overestimated LWD by more than 2 h or underestimated LWD (DOY: 279, 286 , 308). It was also noted that on some days when one of the sensors would overestimate LWD whilst the other would underestimate it (DOY, 246).

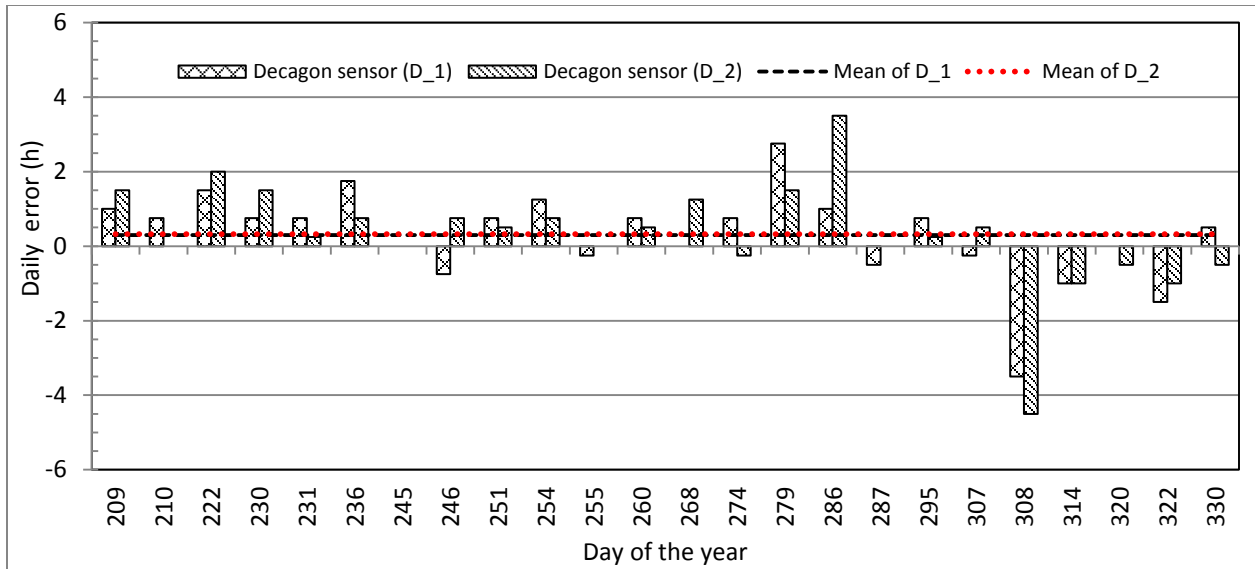


Fig 2.14 Difference between daily measured and observed LWD considering the Decagon sensors for the upper canopy level sensors for the upper canopy level for dew days (n=24) when dew was visually observed from 27th July to 30th November, 2012

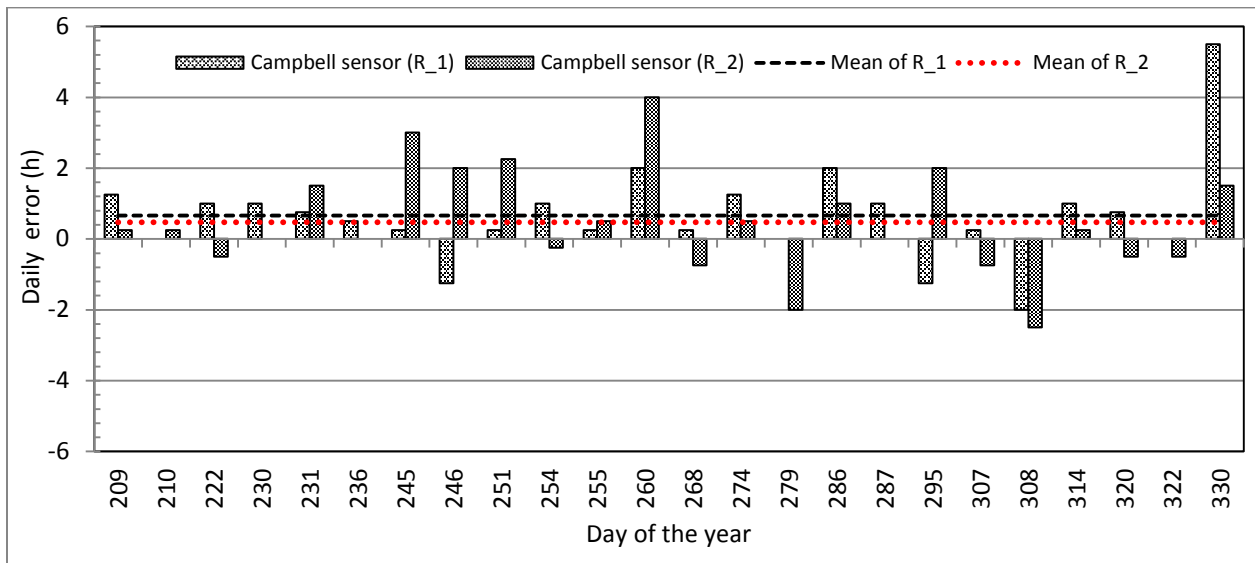


Fig 2.15 Difference between daily measured and observed LWD (daily error) considering the Campbell sensors for the upper canopy level for dew days (n=24) when dew was visually observed from 27th July to 30th November, 2012

There was a notable difference between the total number of leaf wetness duration in the top canopy and the bottom canopy for the whole period of study. Visual observations of the total leaf wetness duration in the top canopy was 131.55 h higher than in the lower canopy (Table 2.12). A

similar pattern was also displayed by the total number of LWD in the upper canopy as compared to lower canopy position. The visual observations of LWD at both canopy levels were lower than the measured values. On average, the measured LWD in the upper canopy was 100.75 h longer than in the lower western canopy level.

Table 2.12 Total leaf wetness duration (h) observed and measured during considering dew and dry days (n=34)

Canopy position	Measurement	Total LWD (h)
Upper	Visual observation	293.75
	Sensor R_1	304.50
	Sensor R_2	305.00
	Sensor D_1	301.00
	Sensor D_2	301.50
Lower (western)	Visual observation	162.20
	Sensor D_3	202.25

Considering the upper canopy, the total overestimation in the upper canopy was mainly caused by the the fact that on three nights, the observer did not record any dew while the sensors recorded an average of 10 h over the three days. On the lower canopy level, a similar situation was recorded in which in five nights dew was not visible but was detected by the sensors. These differences could have been determined by different factors. Firstly, during the experiment dew formed in small quantities and the physical difference between the artificial surface and the citrus leaf were probably critical. In particular the trichomes could act as condensation points preventing dew reaching the leaf surface, which appeared dry to the observer (Dalla Marta et al., 2007). Leaf wetness sensors are always placed fixed in one place, compared to leaves that can be shaken and even turned upside down due to wind action. Wind can cause the thin layer of water on leaves to dry faster than that of fixed wetness sensors.

To understand the origin of the errors made by the sensors, all the LWD values were compared with the visual observations for the phases of wetting and drying using average values from all

the sensors in the upper canopy The results indicated a good agreement between sensors and observations for the time of drying and a relatively poor agreement during the time of wetting (Fig 2.6- 2.9). The average relative error between the observations and the measurements for the wetting time was 30 minutes whilst the average for drying phase was about 10 minutes. To explain this difference, it is possible to hypothesize that sensors cool and get wet sooner than the leaves due to their physical structure (limited active area, colour) and the total absence of physiological processes (Dalla Marta et al., 2007). On the hand, the drying process is strictly depended on the incoming solar radiation received by the leaves in the early morning that causes a fast, simultaneous and homogenous drying of the leaves and the sensors.

2.5 Conclusion

It can be concluded that LWD in the citrus canopy exhibited spatial variation and varies depending on the canopy position and wetness event. The mean daily LWD in the upper canopy level was 1.5 h and 1.9 h higher than in the lower western and eastern of the canopy respectively. However, during rainy days, the upper canopy displayed the same trend as during dew days, the mean daily LWD in the lower western and eastern canopy positions were 1.4 h and 1.2 h less respectively than the upper canopy position. When both the rainy and dew days were considered, the LWD in the top was statistically different from the lower canopy positions and was about 1 h longer than the lower canopy. However, no statistically significant difference was noted between the two lower canopy positions.

Both the Decagon and unpainted Campbell sensors placed in the upper canopy level proved to be good estimators of LWD. Generally the Decagon sensors had a slightly higher accuracy and precision than the Campbell sensors. However, even the unpainted Campbell (Model 237) deployed in the upper citrus canopy can provide good estimate of LWD. The poor performance of LWD sensors placed in the lower canopy implies these sensors should not be used as input in disease warning systems.

Chapter 3

Process of dew formation and dissipation in upper citrus canopy by considering a few typical days

3.1 Introduction

Dew is a form of condensation, which is of great importance to agriculture because of the different roles it plays. On occasions, it may be beneficial to crops by decreasing the vapour-pressure deficit in the vicinity of the dew drops and thus allowing stomatal opening and photosynthesis (Slatyer, 1967) thus promoting plant growth. Dew condensation on plant leaves is highly important, enabling direct absorption of the water through the cuticle (Boucher et al., 1995; Jacobs et al., 2000; Zhuang and Ratcliffe, 2012). Direct absorption of dew through plant leaves improves flowering and fruit quantity, which is desirable for fruit production. However, on the other hand, the presence of dew on the plant leaves can promote disease development. When water is deposited on leaves for critical periods and temperatures are favourable, fungal spores and other plant pathogens may develop that can be extremely harmful to citrus plants.

In order for dew to form, the temperature of the leaf surface must cool below the dew point temperature of the surrounding air, resulting in the condensation of excess moisture on the surface of the leaf. The condensing water vapour can originate from a wet soil, dewfall (water vapour from atmosphere to a surface), and/or guttation (Garratt and Segal, 1988; Monteith, 1957; Beysens, 1995). Guttation is a release of moisture onto the plant surface by the plant itself through internal mechanisms. Since guttation only accounts for a small proportion of total dew amount, it is usually not considered in studies of dew formation. Dew can occur when soil water evaporates during the night and is intercepted by the canopy. Dewfall is the condensation flux of atmospheric water vapour to the surface of the leaf, essentially occurring first in the area most affected by atmospheric humidity, the top of the canopy.

In the western province, one of the most important citrus areas in SA (Department of Agriculture, Forestry and Fisheries, 2011), favourable conditions for dew formation prevail mostly during winter and occasionally during other times of the year. Such conditions may be conducive for the development of diseases affecting citrus. Although the physics governing the process of dew formation is known, the interactions between dew and the canopy are less well

understood phenomenon. The distribution of dew within a canopy is not homogeneous and changes in time depending on the weather, leaf distribution and architecture of the plant canopy (Jacobs and Nieveen, 1995). The dew formation efficiency depends both on the surface on which it is formed, as well as on the series of meteorological parameters defining the state of the atmosphere. The study of dew has focused primarily on its presence and duration of surface wetness as an indicator for plant pathogen activity (Monteith, 1957; Royle and Butler, 1986). Multiple studies on dew formation have been conducted in many crop canopies as well as high value plants such as grapevines (Haasbroek, 2006), apples (Batzer et al., 2008) and lilies (Jacob et al., 2005). Despite the importance of the citrus, very little is known about the influence of dew formation and dew evaporation on a Satsuma citrus canopy, most likely because no easy measurement technique is available. The purpose of this study is to characterize the process of dew formation and dew dissipation from the upper citrus canopy.

3.2 Materials and Method

3.2.1 Site description

The study was conducted on an orchard at the Welgenvallen Experimental Farm of the University of Stellenbosch (latitude 33°56' S, longitude 18°52' E, altitude 157 m above sea-level) in Western Cape, South Africa. The region is characterized by a Mediterranean climate with cool wet winters and warm, dry, summers. The mean annual precipitation is 673 mm and about 70% of this falls during winter. Mean midday maximum temperatures range from 16 °C in July to 24 °C in December (ARC-ISCW climate database, 2013). On average, the temperature drops to 6.6 °C at night in July. The predominantly westerly and northwesterly winds (regimes) generally bring in a lot of moisture mostly in winter. The 2012 winter season exhibited a distinct pattern; it was wetter and colder. Total rainfall recorded in June, July and August was 140 mm more than the 48-year mean of 98 ± 18 mm. The mean minimum as well as maximum temperatures during the 2012 winter were below the long term average values. Favourable weather conditions for dew formation such as clear sky skies, wide daily fluctuations of temperature and additional moisture from winter rains frequently prevail in the winter season and occasionally during other seasons.

Satsuma mandarin trees are cold-tolerant; they are adapted to regions with winters too cold for other citrus fruits. Moreover, because of its apparent low total heat requirement, the Satsuma (*Citrus Unshiu*) ripens earlier than any of the oranges or other mandarins. The citrus orchard was planted in 1998 with *Miho Wase* Satsuma mandarin (*Citrus Unshiu* Marcovitch) trees that were grafted on Carrizo citrange rootstock (*Citrus sinensis* and *Poncirus trifoliata*). The experimental site was surrounded by other fruit trees. The Satsuma mandarin trees were planted on ridges with a row spacing of 4 m and with trees 1.5 m apart in the row. The rows are oriented north to south to maximize solar radiation absorption during the winter season. During the experimental period, the average height of the citrus trees was about 2.14 m, with a LAI of 3.67. The soil type was a shallow clayey loam of the Kroonstad soil form (Ochric Planosol) with a high clay content (Soil Classification Working Group, 1991).

3.2.2 Data and Measurements

To study dew formation and dissipation in the upper part of the citrus canopy, a total of 24 dew days were selected from the period 27th July 2012 to 30th November 2012. Table 3.1 shows all the days when visual observations of wetness were performed. A total of 24 days, when wetness resulted from dew, were selected from a total amount of the days with visual observations of 62 days. Days when wetness resulted from rain as well as dry days were excluded from the detailed analysis. Moreover, from a disease-infection point of view, a user will automatically assume that the leaves were wet it had rained. Despite the visual observations of dew being done at both canopy levels, calculations and analysis of dew formation and dissipation were only confined to the upper canopy due to the limited number of days that dew occurred in the lower canopy. The measured meteorological data for these 24 days (described in chapter 2) of air temperature, relative humidity, wind speed and net radiation as well as leaf temperature, at 15 minute time interval were utilized to study the process of dew formation and dew evaporation. Other parameters were also computed from the measured weather parameters included dew point temperature (calculated from relative humidity and air temperature), vapour pressure deficit and dew point depression as the difference between air temperature and dew point temperature.

Table 3.1 Days when wetness with all the visual observations were performed (Dew refers to wetness on the upper canopy level)

DOY	Date (2012)	Type of wetness	Comment
209	27 July	Dew	Night clear, calm and cold
210	28 July	Dew	Night partly cloud
211	29 July	Dry	Completely overcast
216	03 August	Rain	Night overcast, very light showers
217	04 August	Rain	Few scattered clouds, rained early morning
218	05 August	Rain	Rained during day, night and early morning
222	09 August	Dew	Clear, calm night
223	10 August	Rain	Overcast and rained heavily
224	11 August	Rain	Overcast and rains
229	16 August	Rain	Rained most of the day
230	17 August	Dew	Very clear, calm night
231	18 August	Dew	Clear, calm night
232	19 August	Rain	Cloudy and rains
236	23 August	Dew	Clear, calm night
237	24 August	Rain	Night overcast, early morning rains
238	25 August	Rain	Scattered clouds, cloudy and rains
243	30 August	Rain	Rained afternoon, partly cloudy at night, early morning showers
244	31 August	Rain	Rains throughout the day
245	01 September	Dew	85% clear, calm night
246	02 September	Dew	Partly cloudy night
251	07 September	Dew	Clear, calm night
252	08 September	Rain	Initially clear sky, then cloudy sky, drizzling
253	09 September	Rain	Overcast and rains throughout the day
254	10 September	Dew	Clear, calm night
255	11 September	Dew	Clear, calm night
256	12 September	Rain	Rains from late afternoon, till next day
257	13 September	Rain	Rains afternoon, partly cloudy at night
258	14 September	Dry	Cloudy, slightly wind night, warm
259	15 September	Dry	Clear sky, warm
260	16 September	Dew	Mostly overcast
265	21 September	Rain	Rains
266	22 September	Rain	Rains afternoon and partly cloudy conditions at night
267	23 September	Rain	Rains throughout the day
268	24 September	Dew	Clear sky
271	27 September	Rain	Rainy day
272	28 September	Dry	Mainly overcast
273	29 September	Dry	Completely overcast

Table continued

274	30 September	Dew	Clear, calm night
334	29 November	Dry	Mostly cloudy
279	05 October	Dew	Mostly clear sky
280	06 October	Rain	95% cloudy, rained early morning
281	07 October	Dry	Night completely overcast
286	12 October	Dew	Clear, calm night, warm
287	13 October	Dew	Clear and calm night
288	14 October	Dry	Rather cloudy and warm
293	19 October	Rain	Rained heavily from afternoon into night
294	20 October	Rain	Showers throughout the day
295	21 October	Dew	Started partly cloudy but became mostly clear
306	01 November	Dry	Partly cloudy night
307	02 November	Dew	Mostly clear night (80%) with isolated clouds
308	03 November	Dew	Partly cloudy night
314	09 November	Dew	Mostly clear and calm night
315	10 November	Rain	Partly cloudy, followed by rains
316	11 November	Rain	Initially partly cloudy, followed by rains
320	15 November	Dew	Mostly clear night
321	16 November	Rain	Rain throughout the day
322	17 November	Dew	Clear and sky
328	23 November	Rain	Rains from late afternoon and night
329	24 November	Rain	Rained afternoon, clear night
330	25 November	Dew	Rather windy, Fair weather
333	28 November	Dry	Mostly cloud night
334	29 November	Dry	Mostly cloudy
335	30 November	Dry	Mostly cloudy
335	30 November	Dry	Mostly cloudy

The occurrence, frequency and duration of dew episodes were also calculated from the measurements by a set of four leaf wetness sensors, two of each type (two Campbell Scientific (Model 237) and two Decagon Dielectric leaf wetness sensors) installed in the top one third of the canopy, 30 cm from the top of the canopy. All the wetness sensor measurements were classified as 1 or 0 zero to indicate whether the sensor was wet or dry respectively based on the individual sensor field calibration performed. The canopy was considered to be wet when at least 10% of 1 leaf was visually observed to be wet.

3.2.3 Data analysis

The initial analysis was to characterize the process of dew formation and dissipation by examining the changes in the meteorological parameters as well as the leaf temperature during the occurrence of these two processes. Theoretically, dew is deposited on a surface when the temperature of the surface becomes equal or less than the dew point temperature of the air in contact with the surface. So this theoretical onset of the first occurrence of dew each day was computed from the dew point temperature calculated from the measured air temperature and the measured relative humidity and compared with time of the visual observation of dew on the canopy. A similar analysis was performed to compare the calculated dew point with the time when the wetness sensors' detected onsets of dew. An analysis of least significant difference was also performed to test if the visually observed and sensor measured dew dry-off times were significantly different.

In order to identify the combination of weather conditions that prevailed during dew condensation, a frequency analysis was done. Initially it was assumed that dew deposition occurred whenever, the leaf temperature fell below the dew point temperature. All the data sets which included the first onset of dew which was visually observed and any other data set when the leaf temperature fell below the dew point temperature were considered. The data from each weather parameter was then sorted into ascending order and classified into 4 categories each of the same range. All possible combinations of relative and temperature categories that prevailed during the dew formation events were identified and expressed as a fraction of all the dew formation events. Wind was not considered a factor because it was always low due to the presence of a wind break. The only two factors that were used in this analysis were relative humidity and air temperature

3.3 Frequency of occurrence of dew formation and dissipation

The monthly distribution of the 24 days that dew was visually observed was 2 days in July, 4 days in August, 8 and 4 days in September and October. In November, the frequency of occurrence of dew was 6 days. However, only a total of 22 days were considered for the analysis of dew formation and dew formation, as on one of the days, 21st October 2012, the thermocouple

that was attached to the leaf fell off. The first occurrence of dew formation mostly occurred between 19h45 and 22h30 and occasionally after 24h00 (Fig. 3.1). Only twice did the process of dew formation start after 24h00. The most frequent times of the first occurrence were 20h30 and 2045h. The process of dew formation was followed by a wet period and then by the process of dew dissipation which ended the following day. Dew dissipation usually ended between 8h45 and 10h30 (Fig. 3.2). However, it was also observed to consistently occur between 6h15 and 8h00, less frequently on a total of 7 days.

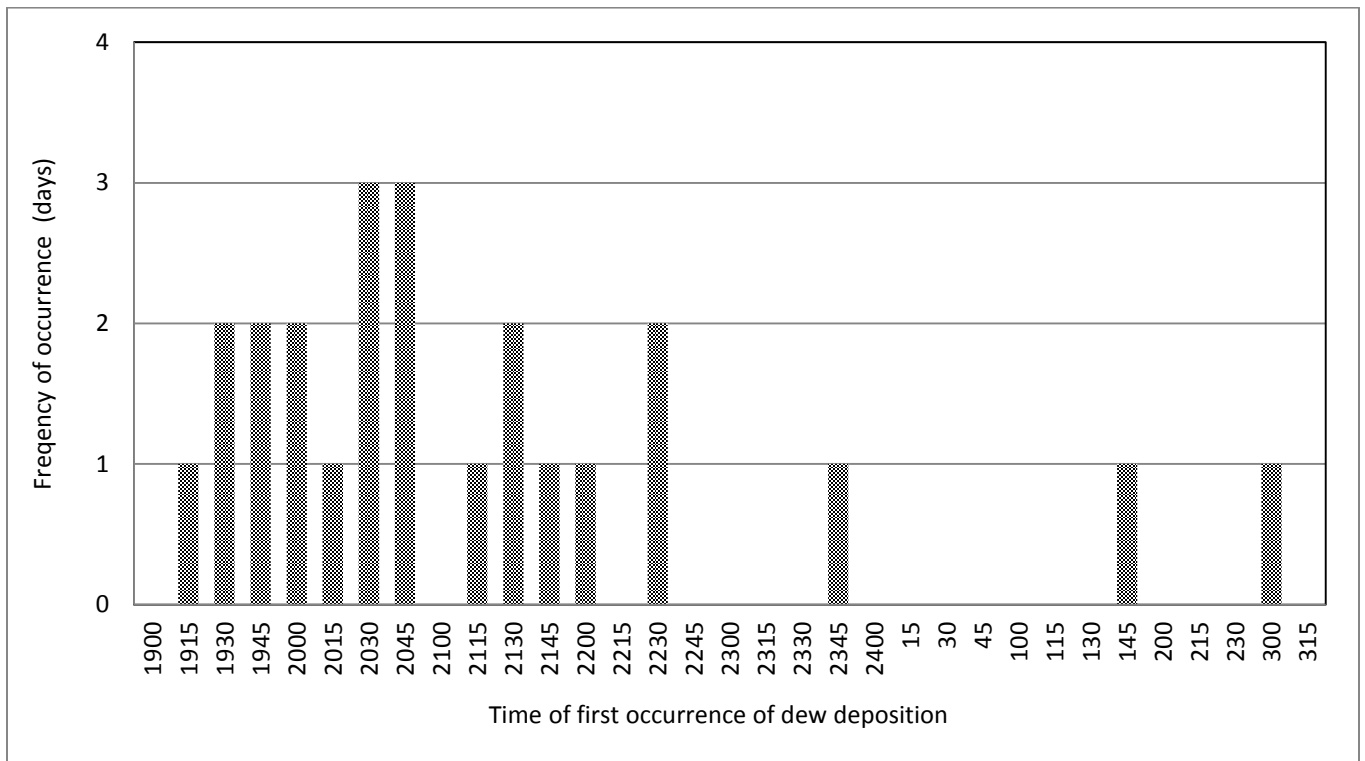


Fig 3.1 Frequency of first occurrence of visual observations of dew formation from a citrus canopy during field experiment for the period 27th July to 30th November, 2012

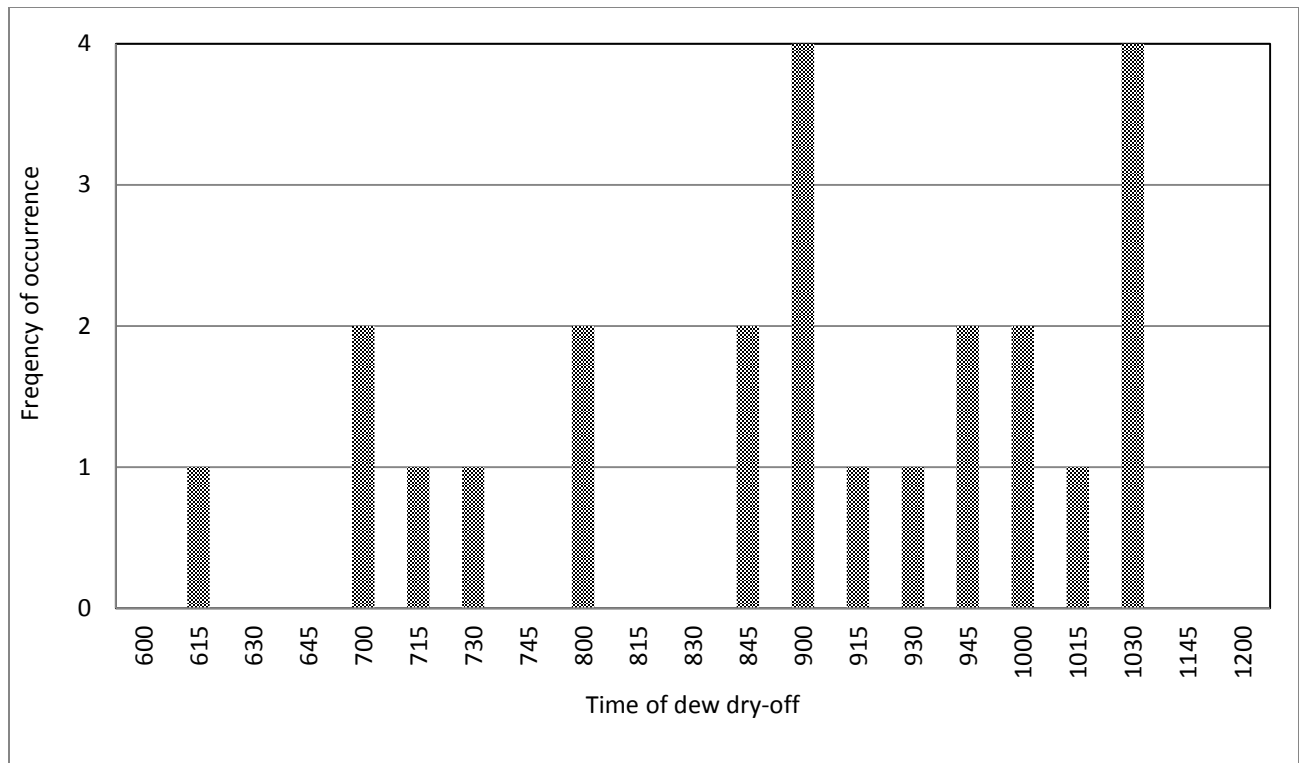


Fig 3.2 Frequency of visual observations of dew dry-off from citrus orchard leaves for the period of 27th July to 30th November 2012

It was also observed that on all the dew days, the process of dew formation began in the top of the canopy which seemed to confirm that the type of condensation was dewfall from moisture in the atmosphere not from a wet soil. According Jacobs et al. (2005), when dew deposition starts on the upper layer of the canopy, then the process of dewfall dominates. Dew started accumulating at night, when the nights were characterized by mostly clear skies (Table 3.1) and calm as the wind speed did not exceed 1 ms^{-1} (Table 3.1). Nocturnal net radiative loss plays an important role in the dew formation process. Luo and Goudriaan (2000) indicated that dew formation normally occurs at night as a result of radiative cooling of the leaf surface which is followed by condensation of water vapour.

The low wind speed was attributed to the presence of wind breaks. The effect of wind on dew formation is complex. On one hand, wind brings moisture that enhances dew formation. On the other hand, it can also increase the heat exchange with air by convection and turbulence, but then prevents or hinders dew from forming.

The results in this study indicated that dew forms under conditions with low wind speed (less than 1 ms^{-1}) which is consistent with Beysens et al. (2005)'s findings but contradict other studies. Jackson and Moy (1999) indicated that low wind speeds (less than 0.5 ms^{-1}), do not stir up the air sufficiently and lead to a local deficit of water vapour due to poor circulation and that under their conditions a favourable wind speed is $1\text{-}2 \text{ ms}^{-1}$. Previous studies have shown that a wind speed of $3.0\text{-}3.6 \text{ ms}^{-1}$ is favourable for dew formation, while a speed of 4.57 ms^{-1} adversely affects dew formation (Monteith, 1957). Muselli et al. (2002) found that a wind speed of 4.5 ms^{-1} is a threshold for dew formation as above it no dew was recorded. This shows that correlation analyses between dew formation and climate data are highly empirical but can help little in understanding the underlying physical phenomena (Scherm and Van Bruggen, 1993).

On three days (DOY 245, 274 and 287), it was observed that there was a delay to the start of evaporation after sunrise and at most it lasted 30 minutes (274). These results are consistent with the findings of Schneebeli et al. (2011) who studied dew formation on a tropical forest. The author noted that this prolonged dew continued 2 h after sunrise. According to the author this time delay between sunrise and the beginning of evaporation most probably depends on the location as well as the structure and type of canopy and is therefore only qualitatively comparable to the findings of this study. The delay in evaporation after sunrise can be explained with Priestley & Taylor equilibrium equation (Priestley and Taylor, 1972), which is used to estimate actual evaporation. In this equation, evaporation is proportional (linear) to the difference between net radiation and the soil heat flux. Measurements made by Clothier et al. (1986) on alfalfa show that this difference is small after sunrise and starts to increase significantly 1 hour after sunrise.

Table 3.2 Time that dew deposition ended as well as the duration of the delay in evaporation after sunrise

DOY	Time that dew deposition ended	Delay in evaporation after sunrise (min)
209	6h30	*
210	6h00	*
230	6h30	*
231	3h45	*
236	6h45	*
245	7h30	15
246	2h45	*
251	6h45	*
254	6h50	*
255	5h30	*
260	5h30	*
268	6h00	*
274	7h00	30
279	5h30	*
286	6h45	*
287	7h30	15
307	3h30	*
308	24h00	*
314	6h15	*
320	6h15	*
322	6h15	*
330	6h00	*

* means condensation ended before sunrise.

3.4 Comparison of dew onset and dry-off as measured by three different methods

The process of dew formation started when the leaf temperature fell below the ambient dew point except one night when condensation occurred when the canopy temperature was still 1.4 °C above the dew point temperature. Theoretically, for dew to form on a leaf, the leaf surface temperature must decrease below the dew point of the ambient air (Beysens, 1995). Dew forms as a result of radiative cooling of a surface and not because of a decrease in air temperature (Klemm et al., 2002), so one needs to take care which temperature are used in these types of comparisons.

Both the theoretical method (dew point temperature method) as well as the sensors' measurements detected first occurrence of dew formation earlier than the visual observation method (Table 3.3). The theoretical method, based on the dew point temperature, predicted that dew deposition earlier as compared to its detection by the sensors as well as the visual observations. The theoretical method detected the first occurrence of dew onset first, followed by the sensors and lastly the visual observations (Fig. 3.3). Visual observations of canopy dew onset occurred on average 46.30 ± 30.94 minutes after the theoretical method had occurred. The greatest difference was 1.75 h which occurred twice during the study. The mean difference in the time of the first occurrence of dew onset between the theoretical and wetness sensors amounted to an average of 15.65 minutes and discrepancy was never greater than 0.4 h on any day (Table 3.3). Sensors detected the first onset of dew occurrence on average 30.65 ± 21.88 minutes before the visual observation, with a maximum difference of 1.25 h. The observed time of dew onset agreed well with the onset derived from the theoretical method ($R^2=0.93$) as well as with the sensor estimated time of dew onset ($R^2=0.97$) (Fig. 3.4). The good agreement between observed time of dew onset and sensor estimated time of dew onset confirm that wetness sensors can estimate dew onset in a citrus with high accuracy.

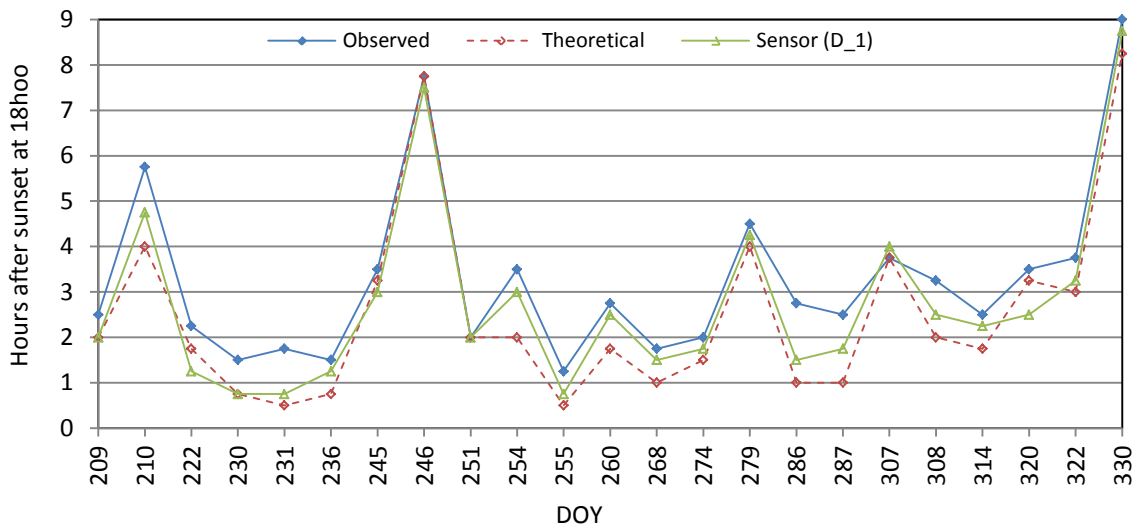


Fig 3.3 Time of the first occurrence of dew deposition based on visual observations (observed); sensors (one of the sensors) (D_1) and dew point temperature (theoretical method) for all the dew days during July to November 2012

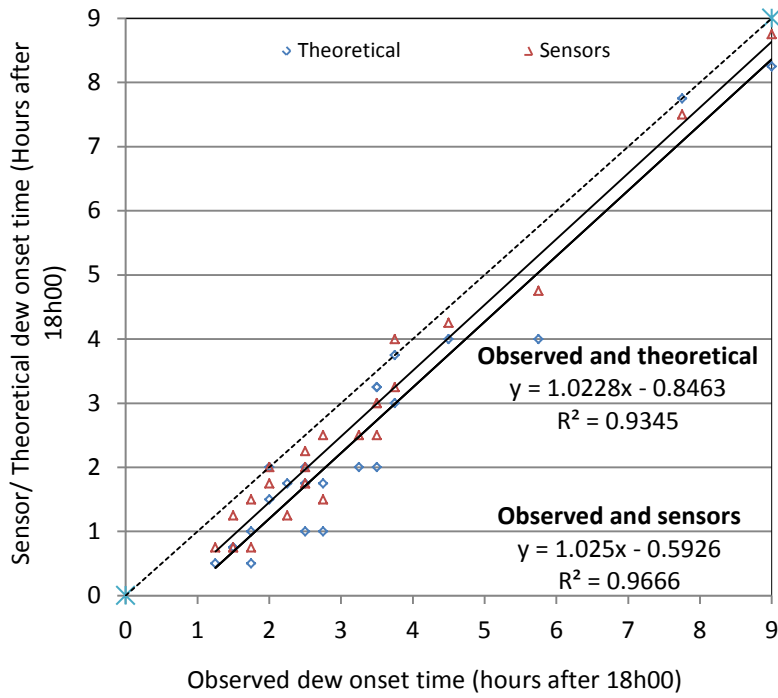


Fig 3.4 Comparison of time of the first occurrence of dew deposition between visual observations, sensors and theoretical method considering all the dew days (n=23)

Table 3.3 Time of first occurrence of dew onset according to visual, theoretical as well as according to sensor measurement in citrus canopy during 2012

DOY	Dew onset				Wetness ending	
	Time of dew onset (visual observation)	Difference (h)			Time of visual dry-off	Difference (h)
		a	b	c		
209	20h30	0.50	0.50	0.00	10h15	-0.50
210	23h45	1.75	1.00	-0.75	8h00	-0.25
222	20h15	0.50	1.00	0.50	8h00	0.50
230	19h30	0.75	0.75	0.00	10h30	-0.25
231	19h45	1.25	1.00	-0.25	9h00	-0.50
236	19h30	0.75	0.25	-0.50	10h30	-0.25
245	21h30	0.25	0.50	0.25	9h00	-0.50
246	1h45	0.00	0.25	0.25	7h30	0.25
251	20h00	0.00	0.00	0.00	10h30	0.00
254	21h30	1.50	0.50	-1.00	10h00	-0.50
255	19h15	0.75	0.50	-0.25	9h45	-0.25
260	20h45	1.00	0.25	-0.75	7h00	-0.25
268	19h45	0.75	0.25	-0.5	10h00	0.00
274	20h00	0.50	0.25	-0.25	10h30	0.25
279	22h30	0.50	0.25	-0.25	8h45	0.00
286	20h45	1.75	1.25	-0.50	8h45	0.20
287	2030	1.50	0.75	-0.75	9h30	0.25
295	*	*	*	*	1h15	-0.25
307	22h30	0.00	-0.25	-0.25	9h15	0.50
308	21h15	1.25	0.75	-0.50	7h15	-0.25
314	20h30	0.75	0.25	-0.50	9h00	0.00
320	20h45	0.25	1.00	0.75	9h00	0.25
322	21h45	0.75	0.50	-0.25	7h00	0.00
330	3h00	0.75	0.25	-0.50	6h15	-0.75
Average		0.77	0.51	-0.26		-0.10
Standard deviation		0.52	0.36	0.41		0.33
Maximum		1.75	1.25	0.75		0.50

where: a = observed – theoretical time onset; b = observed – sensor time onset; c = theoretical – sensor onset times and d= observed – sensor measured dew dry-off times.

* Day 295 not considered because the thermocouple that was attached to the leaf fell off.

An analysis of least significant difference shows that there no significant difference in the times of dew dry-off between the measured (sensor) and the visual observation. At most the difference between dew dry-off times between the sensor and visual observation was 30 min (Fig. 3.5). In 5 out of all the dew days, both the visual observations and the sensor estimated dew dry-off at the same time (Table 3.3). However, the sensors predicted dry-off time agreed to within 6% with the visually observed dew dry-off time. A comparison between the methods exhibited a very good correlation, ($R^2=0.93$) with most points scattered around the 1:1 relationship (Fig. 3.6). The slope of the graph was close to 1 and the linear regression line is $y=0.9799x+0.2689$ with a standard deviation of estimate of 0.34. The unexplained variance was only 7% (Fig. 3.6). The results indicate that on average, the sensors detected that the canopy was dry 6 minutes after the canopy was observed to be dry.

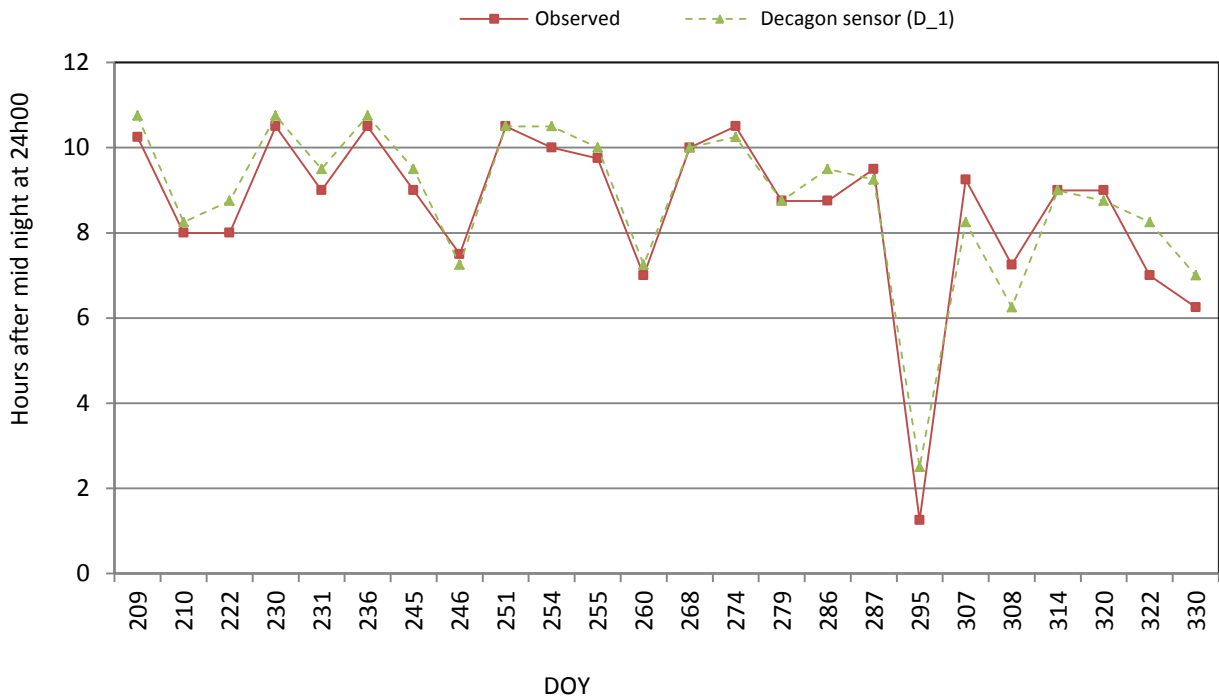


Fig 3.5 Dew dry-off time based on visual observations as well as one of the wetness sensors (D_1) for all the dew days during July to August 2012 in citrus orchard in Stellenbosch

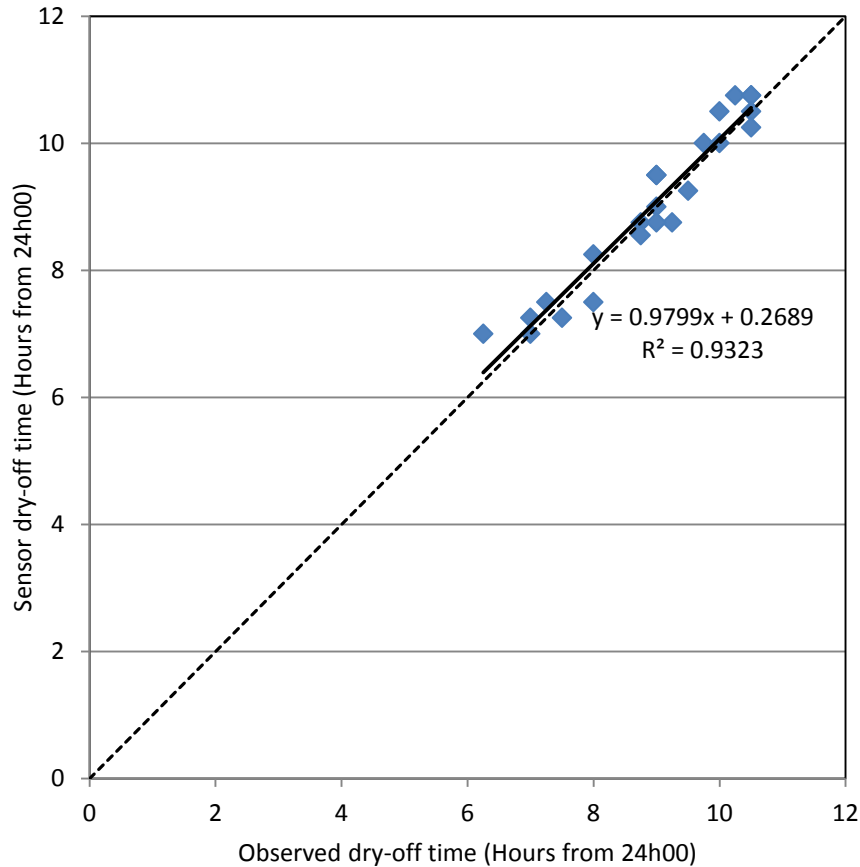


Fig 3.6 Comparison of observed and sensor dry-off for the days that dew occurred (n=22) from 27th July to 30th November, 2012

To analyze the trends in weather parameters, all the times for 22 dew days (DOY 222 and 295 not considered) were synchronized so that it started 2 h before the onset of first occurrence of dew onset on each day. This was done because dew deposition did not take place at the same time every day. An analysis of the air and leaf temperature, relative humidity, vapour pressure deficit, wind speed and net radiation from 2 h before the onset of dew condensation until the canopy was completely dry is shown in Fig. 3.7. Leaf temperature dropped to the lowest temperature between 8-12 hours. As the air temperature decreased, relative humidity showed an upward trend. The air temperature declined more slowly once dew begins to form because heat is released during this process.

When the amount of condensation over a given period exceeds the evaporation of condensate over that same period, condensation is observed to have occurred. Condensation water will accumulate if this condition prevails, otherwise it will evaporate. The assumption is that at the surface there is a boundary layer of air that is saturated and has the same temperature as the surface. This boundary layer interacts with the surrounding air causing condensation or evaporation of condensate in a dynamic relationship that is driven in large part by the vapour gradient. The moisture flux across this gradient is controlled by the rate of air movement and the roughness of the surface. During dew deposition, condensation is the dominant process whilst evaporation is the major process during dew dissipation. However, when the rate of evaporation is equal to the rate of condensation, then equilibrium is reached and the leaf temperature remains stable. During this period, the same moisture is retained on the leaves.

Table 3.4 Mean values of weather parameters during the onset and end of condensation as well as when the leaf was completely dry. (\pm SD) calculated for each of the 22 days

DOY	Start of condensation (n=1260)	During time between start and end of condensation (n=1260)	End of condensation (n=1260)	Leaf completely dry (n=1260)
Leaf temperature ($^{\circ}$ C)	8.40 \pm 3.28	6.78 \pm 2.34	8.87 \pm 3.01	19.85 \pm 5.66
Air temperature ($^{\circ}$ C)	11.75 \pm 3.29	9.30 \pm 2.92	9.56 \pm 3.06	17.35 \pm 4.48
Dew point temperature ($^{\circ}$ C)	9.01 \pm 3.23	7.42 \pm 2.81	7.57 \pm 3.07	8.40 \pm 3.32
Saturation vapour pressure (kPa)	1.44 \pm 0.31	1.19 \pm 0.24	1.54 \pm 0.25	2.05 \pm 0.55
Actual vapour pressure (kPa)	1.17 \pm 0.25	1.06 \pm 0.20	1.09 \pm 0.21	1.12 \pm 0.23
Vapour pressure deficit (kPa)	0.27 \pm 0.11	0.13 \pm 0.09	0.37 \pm 0.13	0.93 \pm 0.43
Relative humidity (%)	81.82 \pm 5.82	87.48 \pm 4.45	89.23 \pm 5.61	48.21 \pm 11.40
Net radiation	-74.40 \pm 6.57	-68.29 \pm 5.82	-34.83 \pm 7.25	291.91 \pm 9.71
Wind speed (ms^{-1})	0.07 \pm 0.21	0.03 \pm 0.10	0.05 \pm 0.15	0.39 \pm 0.28

An analysis of the mean weather parameters and leaf temperature at the start, during time between start and end of condensation, end of condensation and when the leaf was completely dry indicated some variations. Air temperature, dew point temperature, saturation vapour pressure, vapour pressure deficit and wind speed had lowest during the time between the start and

end of condensation. Leaf temperature also exhibited the same trend. A comparison of air temperature and vapour pressure deficit showed that at the end of condensation air temperature and vapour pressure deficit were 0.47 °C and 0.10 kPa higher respectively (Table 3.4). The same trend was exhibited by wind speed. Generally all the weather parameters except relative humidity had the highest values when the leaf was completely dry.

The process of dew dissipation was of shorter duration compared to dew condensation. Generally dew dissipation was characterized by an upward trend in the meteorological parameters except for relative humidity, which exhibited a sharp decrease (Fig. 3.7). The high temperature after sunrise led to higher saturated vapour pressure and thus a larger saturation vapour pressure deficit which explains why dew dissipation was the more dominant process than dew condensation. Higher air temperature would result in an increase in evaporative demand of the air.

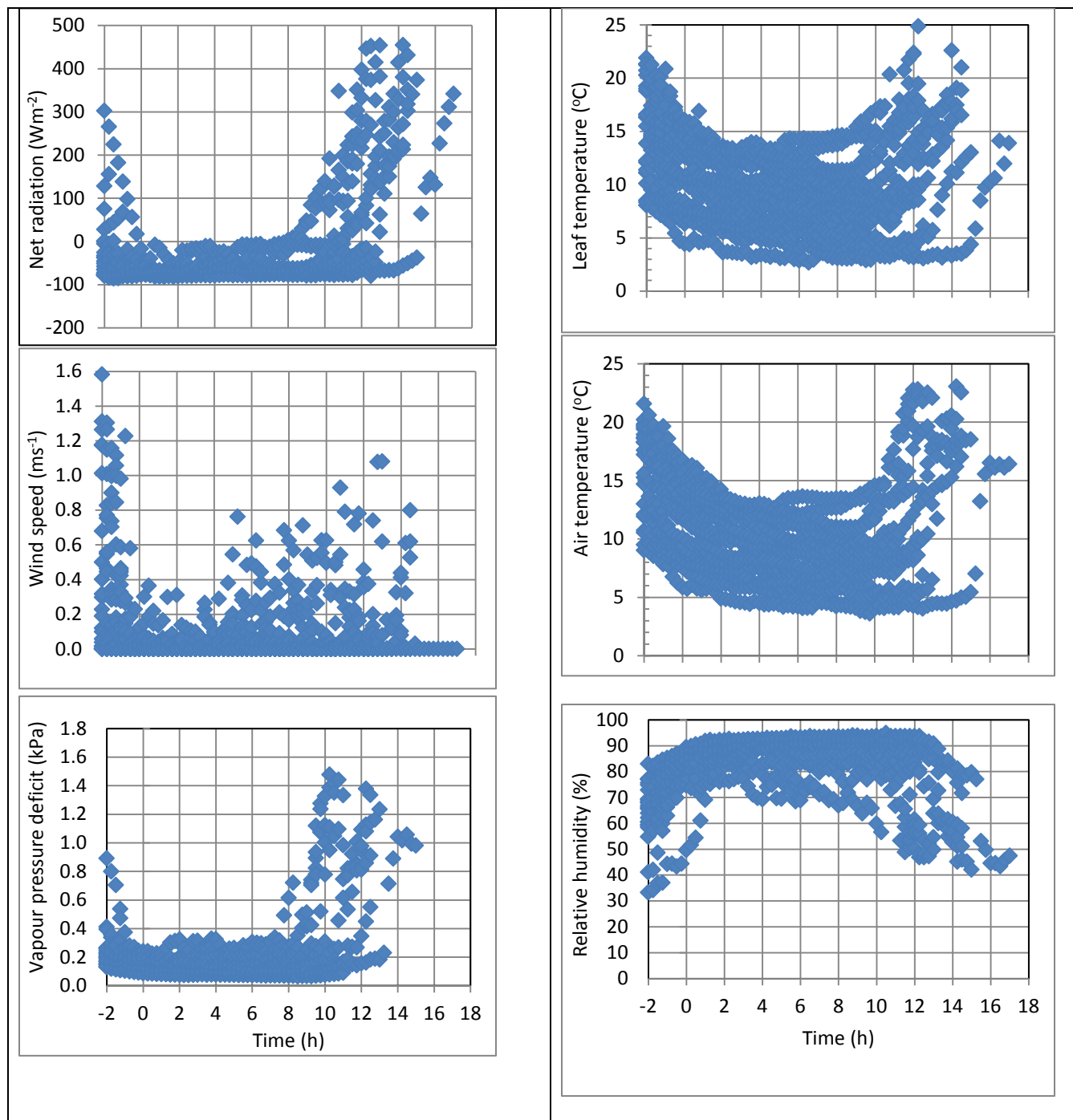


Fig 3.7 Variation of meteorological parameters as well as the leaf temperature from 2 hours before dew deposition began until the canopy was dry, at 15 minute intervals showing all data for the 22 dew days at 15 time interval in a citrus canopy at Stellenbosch for the period from 27th July to 30th November 2012

An analysis of variance showed that there was no significant difference between the meteorological parameters at the start and end of condensation ($p < 0.05$). The mean time of dew formation and the time that the canopy was fully wet period (before evaporation) was 12.00 ± 3.58 h, with a maximum period of 16.25 h. However, the process of evaporation that occurred after a “fully wet period” was shorter, only lasting 3.02 ± 1.95 h. These results seem to indicate that generally, on a daily time scale the time of dew formation combined with the fully wet period had a greater contribution to LWD. Consequently, the longer this time is, the longer the wetness period (LWD). This is probably rather important to those who want to know about the relationship between the LWD and the occurrence of disease infestation. Dew formation in the canopy is one of the critical environmental factors affecting the development of plant pathogens and diseases. Plant diseases increase in severity in direct relationship to the length of time the leaves are wet (Sirjusingh and Sutton, 1996).

3.5 Conditions necessary for dew formation

Relative humidity and air temperature were classified into four categories (Table 3.5). It was assumed that wind was not an important factor because of the presence of the windbreak.

Table 3.5 Classification of weather variables during dew formation

	Weather parameter	
	Air temperature (°C)	Relative humidity (%)
Mean (\pm SD)	10.75 ± 3.41	84.67 ± 6.32
Range	3.00 – 19.00	67 - 95
Intervals	4	7
Category 1	3.01 - 7.00	67.01 - 74.00
Category 2	7.01 – 11.00	74.01 – 81.00
Category 3	11.01 – 15.00	81.01 – 88.00
Category 4	15.01– 19.00	88.01 – 95.00

The process of dew deposition was a complex process that did not result from a single combination of weather parameters but was rather a consequence of a matrix of mainly two meteorological variables (Table 3.6). Various combinations of relative humidity and air temperature gave rise to the process of dew condensation. Higher relative humidity had a good positive correlation with dew formation. Dew accumulation at in the upper citrus canopy occurred more frequently when the relative humidity was above 88% and when the temperature was in the range between 3-11 °C. When relative humidity was greater than 88% and air temperature between 7-11 °C, dew formed 43.6% of the time. However, for the same relative humidity and air temperature less than 7 °C, the probability of occurrence was 20.6%. When the air temperature was higher for example, between 11 and 15 °C, the percentage of occurrence was only 16.1%. Occasionally, dew formation was possible with RH between 81 and 88% ($81\% < RH < 88\%$) and $T < 11^{\circ}C$, and this represented 14.4% of total occurrences.

Table 3.6 Occurrence of wetness at 15 minute interval based on air temperature and relative humidity variables categories

RH category	Temperature category	Number of occurrences
1 (67-74%)	1	2
	2	5
	3	*
	4	*
2 (74-81%)	1	2
	2	3
	3	4
	4	3
3 (81-88%)	1	41
	2	45
	3	9
	4	3
4 (>88%)	1	123
	2	260
	3	96
	4	*

*where a blank cell represents a zero (0).

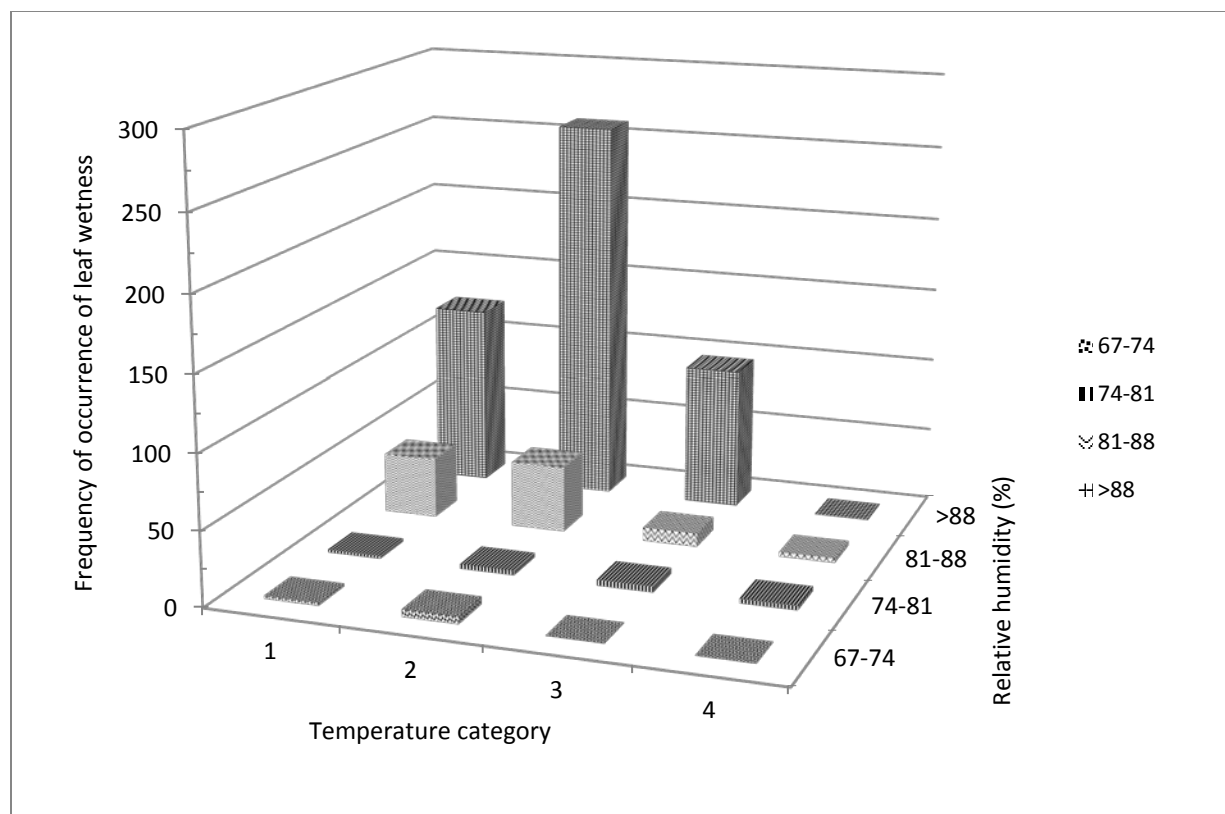


Fig 3.8 Occurrence of leaf wetness in a citrus orchard at Stellenbosch from 27th July to 30th November 2012 (n=596)

However, occurrence of dew was clearly associated with meteorological conditions such as high relative humidity, absence of cloud cover and low wind speed. According to Garratt and Segal (1988) dew is most common on nights with clear skies and light winds, and when the lower atmosphere is moist. High relative humidity contributes to dew formation by providing a continuous supply of water vapour for condensation and reducing the rate of evaporation. Although relative humidity is a key parameter, it is one of the most difficult parameters to assess as it is also a function of air temperature. However, various studies have reported good correlation between dew formation and high relative humidity. Jackson and Moy (1999) as well as Smith (1958) reported that a relative humidity greater than 90% was the threshold for dew occurrence under certain conditions. In contrast, Shaw (1973) found a good correlation between dew formation and periods of relative humidity above 85%. In this study, an average value of $84.67 \pm 6.23\%$ and above was commonly associated with dew which agrees with Shaw's findings. On each day, the highest value of relative humidity was reached was during the night when the

air temperature was lowest. This result seems to indicate that relative humidity of 100% is not necessary for dew formation and that dew is deposited on the canopy whenever the leaf temperature is equal to or less than the ambient air dew point temperature. Cloud cover is another key meteorological factor for dew formation. On all the days that dew was observed on the citrus plants, the skies were clear. Without clouds to reflect the heat radiated from the earth's surface, the surface is able to cool rapidly (Wallin, 1963). Dew condenses on the coolest body; the plant must cool faster than its surroundings (Monteith and Unsworth, 1990).

3.6 Conclusion

It can then be concluded that if the weather forecast indicates that the temperature is likely to be less than 11°C and relative humidity is likely to be greater than 85% during the winter season, at Welgenvallen Experimental Farm of the University of the Stellenbosch, in Stellenbosch, there is a 64.2% chance of dew formation during the night. If the relative humidity is between 81-85%, then the chance of dew formation is lower. Although such information is important to citrus growers, it would be even more helpful to have a model that computes LWD in the event of a high likelihood of dew formation. This computed LWD will then be of more use to the citrus growers since the incidence of disease is correlated with period of wetness. The computed LWD can then be used as an input into disease warning systems and utilized for planning preventative spraying activities.

Chapter 4

Leaf energy balance

4.1 Introduction

The leaf is the site of many of the physiological processes in plants and ultimately it is the leaf temperature which determines the rate of these processes for many species. Optimal photosynthetic rates occur at leaf surface temperatures of approximately 25°C while temperatures in excess of 35°C can severely reduce the photosynthetic rate due to reduced enzyme activity (Oberhuber and Edwards, 1993). Leaf temperature directly affects both and disease metabolic activities and ultimately influences the amount and application or need for management and pest/disease control (Yang et al., 1990). When a plant is under stress due to lack of water, it tends to close the stomata to decrease transpiration leading to an increase in leaf temperature. Hence Bailley (1985) and Challa et al. (1988) observed that leaf temperature is one of the most important and controlled parameters in modern greenhouses.

The measurement of the temperature of leaves or the canopy as an indicator of both abiotic and biotic stresses has gained the attention of scientists for many years (Jones, 1992). Since leaf temperature has been shown to vary when plants are subjected to water stress condition, it has become an important tool or index for plant water status and drought risk assessment. Consequently, canopy temperature was used to develop the crop water stress index (CWSI), which is key to develop irrigation strategies for better water use efficiency and reduce effect on quality or quantity of yield. According to Mannini and Anconelli (2007), leaf temperature is a parameter used to estimate of amount stress in strawberry. Studies by Masakata et al. (2006) found that leaf temperature was a useful indicator to estimate the drought tolerance for line selection in upland rice breeding. Recent studies have also shown that canopy temperature measurements in citrus can be used to detect moderate to severe plant water stress (Ballester et al., 2013; García-Tejero et al., 2011; Zarco-Tejada et al., 2012).

Leaf temperature can be measured directly, before the development of the infra-red thermometer, leaf temperature had only been measured directly, mostly by means of thermocouple thermometers. The use of a thermocouple is still an effective method for measuring leaf

temperature because its performance compares well with those measurements made with an infra-red thermometer (Acock, 2002). However, in cases where direct measurement of leaf temperature may not be feasible, the determination of leaf temperature by Newton-Raphson iterative approximation offers an alternative method (Pedro and Gillespie, 1982a,b). Such an approach has a distinct advantage that most of the input weather parameters are measured at regular automatic weather stations. Pedro and Gillespie (1982a,b) applied an iteration procedure to estimate leaf temperature and the difference between leaf and air temperature. The results were then utilized in estimating leaf wetness duration.

The purpose of the study was to:

- i) deduce of the leaf temperature expression from the leaf energy equation, and
- ii) assess the performance Newton-Raphson iteration method in the determination of leaf temperature by comparing the calculated and measured leaf temperature values from field experimental data.

4.2 Theory

Leaves exchange radiation with the sky and the ground and also exchange sensible and latent heat with the surrounding air. By applying the principle of conservation of energy (First Law of Thermodynamics) to a leaf or canopy, the difference between all the energy fluxes into and out of the leaf must equal the rate of storage, thus

$$R_n + LE + H + G = M + \Delta S$$

where R_n is net radiation, LE is latent heat flux, H is sensible heat flux, G is conduction of flux via the soil surface, M is the metabolic heat flux and ΔS is net physical storage of energy. G is considered to be negligible for a thin leaf surface. The minor terms involving the production of metabolic energy and energy storage are assumed to be insignificant as suggested by Gates et al. (1965) and can therefore be neglected and omitted, resulting in the form of energy balanced to be used in this application, namely:

$$R_n + H + LE = 0 \tag{4.1}$$

Equation 4.1 can be expanded (Pedro and Gillespie, 1982a) and expressed in terms of weather parameters as follows:

$$\left[aR_d + \alpha aR_d + \varepsilon L_d - \varepsilon \sigma (T_a + 273)^4 \right] - \left[2h_c (T_l - T_a) + \left[\frac{0.622}{P} 2h_w (e_s - e_a) \right] \right] = 0 \quad (4.2)$$

where a is leaf shortwave absorptivity, R_d is incoming shortwave radiation, α represents the albedo of the surface below the leaf, ε is leaf emissivity, L_d is incoming longwave radiation, σ is Stefan-Boltzmann constant, T_l is the leaf temperature, T_a is air temperature, h_c is convective heat transfer coefficient for one side of the leaf, h_w is water vapour transfer coefficient for one side of the leaf, e_s saturation vapour pressure at T_l , e_a is ambient vapour pressure and P is atmospheric pressure.

According to Ede (1967), the heat transfer coefficient h_c , in equation 4.2, is dependent on wind speed and effective leaf length and is computed as:

$$h_c = 40 \left[\frac{u}{w} \right]^{0.5}$$

where u is wind speed and w is effective leaf length in the direction of the wind. Three different values of w were used for the three plant species.

The vapour transfer coefficient, h_w , was calculated by Ede (1967) by:

$$\frac{h_w}{h_c} = 1.07 \left(\frac{\lambda}{C_p} \right)$$

where λ and C_p are latent heat of vaporization of water and specific heat of the air respectively.

It is assumed that the lower side of the leaf and the surface below the leaf have sufficiently similar temperatures that no significant net longwave exchange occurs between them. Therefore, Equation 4.2 can be solved for ΔT ($T_l - T_a$) by eliminating T_l (Miller, 1971; Kreith and Sellers, 1975; Norman, 1979).

Hence,

$$\Delta T = \frac{[aR_d + \alpha aR_d + \varepsilon L_d - \varepsilon \sigma (T_a + 273)^4] + \left[\frac{0.622}{P} 2h_w (e_s - e_a) \right]}{\left[4\varepsilon \sigma (T_m + 273)^3 + 2h_c + \frac{0.622}{P} 2h_w S \right]} \quad (4.3)$$

where T_m is average temperature between T_l and T_a and S is slope of the saturation vapour pressure curve at T_m .

Substituting $\Delta T (T_l - T_a)$ and net radiation $[aR \downarrow + \alpha aR \downarrow + \varepsilon R \uparrow - \varepsilon \sigma (T_a + 273)^4]$ in equation 4.3 results in equation 4.4:

$$T_l = T_a + \frac{[R_n] - \left[\frac{0.622}{P} 2h_w (e_s - e_a) \right]}{\left[4\varepsilon \sigma (T_m + 273)^3 + 2h_c + \frac{0.622}{P} 2h_w S \right]} \quad (4.4)$$

Usually, to solve a complicated expression such as equation 4.4 involves the application of the numerical approximation method. Among the approximation methods, Newton-Raphson iterative technique is a good one because it can rapidly reach the solution with the required accuracy (Qin et al., 2002).

Rewriting equation 4.4 according to Newton-Raphson format yields a function $F(T_l)$ which is dependent of the leaf temperature.

$$F(T_l) = T_l - T_a + \frac{[R_n] - \left[\frac{0.622}{P} 2h_w (e_s - e_a) \right]}{\left[4\varepsilon \sigma (T_m + 273)^3 + 2h_c + \frac{0.622}{P} 2h_w S \right]} \quad (4.5)$$

However, T_m is initially unknown. It is also assumed that the vapour pressure at the leaf surface is equal to the saturation vapour pressure at T_l . A new value for T_l is computed from the equation given by:

$$T_s^{n+1} = T_s^n - \frac{F(T_s^n)}{F'(T_s^n)} \quad n = 0,1,2,3,\dots \quad (4.6)$$

where $F(T_s^n)$ and $F'(T_s^n)$ are the values of the function $F(T_s)$ and its derivative at (T_s^n) . Geometrically, the Newton-Raphson method means that the tangent at the point $(T_s^n, F(T_s^n))$ of the curve $y = F(T_s)$ is extended to the intersection with T_s axis at T_s^{n+1} , which is used as the new approximation to the solution T_s . If T_s^n is a good approximation, it can be expected that T_s^{n+1} approximates T_s^n still better. Iteration is stopped when $T_s^{n+1} = T_s^n$, and this will be the required leaf temperature. To apply Newton-Raphson iteration, it is initially assumed that $T_l = T_a$ and equation 4.4 was solved for T_l . The first estimated value for T_l , and T_m then become available and are used in further iteration calculations until a satisfactory T_s is found as a solution.

4.3 Materials and Methods

4.3.1 Field site description

The research was conducted at the Cape Peninsula University of Technology (CPUT) Bellville Campus (latitude 33°56' S, longitude 18°38' E) near Cape Town, from 15th May to 17th June 2010. Three field experiments were performed at two different locations under different climatic conditions with different plant species. Two of the experiments were conducted at the first site whilst the last was set up at a different location about 5 km from the initial site. The site of the first experiment consisted of six trees (all of the same type), in a row, separated by a distance of about 3 m from each other. The *Ficus microcarpa* were almost of the same height, about 4 m and most of their mature leaves had an upper surface area of between about 8 to 12 cm². Two undamaged dark green leaves of approximately the same size and orientation were chosen on the tree and approximately at the same height from the ground. Leaves on these trees were used for experiment 1. The first experiment was conducted using *F. microcarpa* trees with sensors at different heights and then with a range of distances of weather station from the tree. Experiment 2 was performed using *Strelitzia nicolai* whilst in the last experiment flowering plant, *Agapanthus praecox* was used. Both experiments had no treatments.

All the meteorological sensors were initially installed at a height of 2 m above the ground whilst the distance from the experimental tree was initially 1 m. All the data collected on a CR10X datalogger (Campbell Scientific) where the sensors were scanned at 10 seconds intervals and averages calculated and stored every 10 minutes and hourly. Net radiation was measured using a net radiometer (Kipp and Zonen) which was installed above the leaves. A cup anemometer (Wind Sentry 03101-5, R.M. Young) was used to measure wind speed. Air temperature and relative humidity were measured with a CS500 sensor (Campbell Scientific). The leaf temperature was measured with a copper-constantan thermocouple which was attached to the underside of the leaf by a small metal clip.

4.3.2 Experimental procedure

In the first experiment with *F. microcarpa*, the temperature sensor height remained unchanged for this first part of the experiment. The experiment ran from 15th May 2010 for a period of 3 days. The distance between the automatic weather station and the *F. microcarpa* was then increased to 2 m, then 3 m and lastly 7 m while maintaining automatic weather station at a height of 2 m. For each distance, the measurements were recorded over a period of 3 days (18th May to 20th May 2010, 21st May to 23rd May 2010 and from 24th to 26th May 2010). A further experiment with a fixed distance of 2 m between the automatic weather station and the *F. microcarpa*, the height of the leaf temperature sensor was then changed to 1.5 and 3 m maintaining a similar position at a distance of 2 m from the tree. For each distance, the measurements were recorded over period of three days, from 27th to the 30th May 2010.

The second field experiment was set up at the same site with the following changes. An indigenous flowering plant, called *S. nicolai*, was used in place of the tree and its distance from the automatic weather station automatic weather station was 2 m. *S. nicolai* is characterized by relatively large leaves with an area of approximately 1680 cm². The leaves of the *S. nicolai* plant where the thermocouples were attached were about 1 m from the ground. All the other sensors were installed and remained fixed at 2 m above the ground. This experiment was conducted from 31st May 2010 to 11th June, 2010 for a period of 12 days.

The third and final experiment in this series was carried out at the Nursery Complex within CPUT grounds, about 5 km from the first site. The procedure was the same as in the second experiment except that another indigenous flowering plant, *A. praecox*, growing in a pot was used for the investigation which was conducted over a period of 6 days from 11th June to 17 June 2010. The *A. praecox* plant was watered daily so that there was enough water in the root zone, hence the plant was never under water stress. The automatic weather station was a distance of 2 m from the plant.

4.3.3 Data Analysis

The Newton Raphson iteration method was used to calculate leaf temperature using the hourly weather data from each of the three field experiments as an input. The leaf temperature that was determined by iteration was then correlated with the hourly measured leaf temperature. In each case, the measured leaf temperature was computed as the average leaf temperature value of the two leaves. The procedure was repeated, after replacing all the zero values of wind speed by a value of 0.0005 as this is the degree of accuracy of the wind sensor and one cannot do the iteration calculation with a wind speed value of zero. Net radiation data was sorted into positive and negative values, generally representing day and night. Since net radiation is the driving force for leaf temperature, the radiation data was segregated into low and high values. Low values of net radiation represented night whilst high values represented the day. To better characterize the data set, temperature, relative humidity and wind speed values were then also sorted in ascending order from which two grouped data sets were classified by high and low values. The classification of air temperature was based on its average the period of study. When the temperature was above this average value, it was considered to be high. The average relative humidity at night was about 60% and so the classification of relative humidity was based on this threshold value. Table 4.1 below shows the classification of the weather parameters.

Table 4.1 Classification of weather parameters from automatic weather station at CPUT during May and June, 2010

Weather parameter	High value	Low value
Relative humidity	$\geq 60\%$	$< 60\%$
Air temperature	$\geq 15\text{ }^\circ\text{C}$	$< 15\text{ }^\circ\text{C}$
Net radiation	day	Night
Wind speed	$\geq 1\text{ ms}^{-1}$	0.0005

This was performed in order to establish if one could improve the coefficient of determination and use different criteria at different times of the day. Mean leaf temperature was then calculated for each group of data and this was done to assess whether high or low values of weather variables improved the correlation between the computed and measured leaf temperature values. A sensitivity analysis was also performed to determine the effect of pressure on the Newton Raphson iteration method. The sensitivity analysis was computed using the highest and lowest values of pressure measured at the study site.

In each of the cases, the calculated and measured leaf temperature values were compared by regression analysis using the coefficient of determination (R^2), Willmott agreement index (D) (Willmott et al., 1985). The precision of the estimates is given by the R^2 value, which indicates the degree of dispersion in relation to the average (the random error). The accuracy is given by D, which ranges from zero for no agreement, to 1 for perfect agreement. The product of these two indexes, a new index was proposed by Camargo and Sentelhas (1997), called confidence index C, which combines both the precision and accuracy of estimates into one index. This index is computed as the product of the square root of R^2 , which expresses the precision of the estimates and the index D which expresses the accuracy. The difference between the measured and calculated leaf temperature were then used to calculate the mean error (ME), which describes the direction of the error bias and the mean absolute error (MAE), which indicates the magnitude of the average error for each of the field experiment that was performed.

4.4 Results and Discussion

4.4.1 Leaf temperature deduction

The energy balance expresses the exchange of energy by a plant with the environment hence the absorbed net radiation should balance the outgoing fluxes of sensible heat, latent heat, heat storage and soil heat as shown in equation. For a thin leaf, the change in energy storage and soil heat fluxes are ignored because they are negligible compared to the other components fluxes (Richards, 2009). The author noted that the other assumptions include:

- (i) The leaf is assumed to be horizontal and elevated, so their upper surfaces receive no reflected shortwave radiation, and receive longwave radiation solely from the sky hemisphere;
- (ii) The lower surface of the leaf is assumed to only receive shortwave radiation reflected from the underlying canopy;
- (iii) It is assumed that the leaf and underlying canopy have sufficiently similar emissivity and temperature values that longwave radiation exchanges between them cancel, and
- (iv) It is useful to also assume the leaf surface neither absorbs nor releases liquid water, and no runoff occurs.

Net radiation is the sum of incoming and outgoing radiation. For a thin leaf the energy and radiation balance can be expressed as:

$$R_n = R_d - R_u + L_d - L_u = H + LE \quad (4.7)$$

where R_n is net radiation, R_d incoming shortwave radiation, R_u outgoing shortwave radiation, L_u incoming longwave radiation, L_u outgoing longwave radiation, H sensible heat flux and LE latent heat flux. The net short wave radiation can be expressed in terms of the solar global radiation as follows:

$$R_d - R_u = (1 - \alpha)R_g \quad (4.8)$$

R_g which is the solar global radiation, α is surface albedo.

The upward longwave radiation can also be conveniently written as follows (Jones, 1992) (considering the reflection and emission of long wave radiation at the leaf surface):

$$L_u = \varepsilon\sigma T_l^4 + (1 - \varepsilon)L_d \quad (4.9)$$

where ε is surface emissivity, σ is the Stefan Boltzmann constant and T_l is the leaf temperature.

Replacing the terms in equation (4.7) by equations (4.8) and (4.9) yields:

$R_n = (1 - \alpha)R_g + L_d - [\sigma\varepsilon T_l^4 + (1 - \varepsilon)L_u]$, which can then be simplified to

$$R_n = (1 - \alpha)R_g + \varepsilon L_d - \sigma\varepsilon T_l^4 \quad (4.10)$$

The sky is the main source of the downward long wave radiation, hence,

$\varepsilon L_d = \varepsilon L_{sky}$ and so equation (4.10) can also be written as:

$$R_n = (1 - \alpha)R_g + \varepsilon L_{sky} - \sigma\varepsilon T_l^4 \quad (4.11)$$

Equation (4.11) has a non-linear 4th order term, T_l^4 which can be linearized with 1st order Taylor's expansion series. According to Taylor (1975) expansion:

$$f(x) \approx f(x_0) + (x - x_0) \frac{df}{dx} \quad (4.12)$$

Applying equation (4.12) to the term $\varepsilon\sigma T_l^4$ yields, taking note that x_0 , represents the air temperature, then

$$\varepsilon\sigma T_l^4 = \varepsilon\sigma T_a^4 + 4\varepsilon\sigma T_a^3 (T_l - T_a) \quad (4.13)$$

Replacing the term $\varepsilon\sigma T_l^4$ in equation (4.11) by $(\varepsilon\sigma T_a^4 + 4\varepsilon\sigma T_a^3 (T_l - T_a))$ from equation 4.13, we obtain:

$$R_n = (1 - \alpha)R_g + \varepsilon L_{sky} - \varepsilon\sigma T_a^4 - 4\varepsilon\sigma T_a^3 (T_l - T_a) \quad (4.14)$$

Equation (4.14) now has both leaf and air temperature explicit in it. The objective is to now isolate the same parameters in the other components of the leaf energy budget which are sensible heat flux and latent heat flux.

Sensible heat flux is the transfer of heat away from or to a surface by turbulent transport and diffusion. Its intensity depends on a heat transfer coefficient and the temperature gradient between the surface and the surrounding air and is given by:

$$H = C_p g_H (T_l - T_a) \quad (4.15)$$

where H is the sensible heat flux, C_p is the heat capacity of air, g_H is heat conductance. T_l and T_a are leaf and air temperatures respectively.

According to Davie (2003), the conductance can be computed from the equation:

$$g_H = k^2 u \rho_a \left[\ln \frac{z-d}{z_o} \right]^{-2} \quad (4.16)$$

where k is the Von Karman constant, u is wind speed at height z , ρ_a is molar density of the air, z is the height at which wind speed is measured, d is the zero plane displacement and z_o roughness coefficient.

The other component of the leaf energy budget is the latent heat flux. This is the energy transport into the atmosphere by energy attached to water molecules when changing from liquid to vapour. turbulent flow, driven by vapour-pressure gradient. Latent heat flux can be expressed as:

$$LE = \lambda g_v \frac{(e_s - e_a)}{P} \quad (4.17)$$

where λ is the latent heat of vaporization, g_v is the vapour transfer coefficient, e_s is the saturation vapour pressure at leaf temperature and e_a is the actual ambient vapour pressure and P is the air pressure, boundary layer and stomatal resistances respectively. Following Brutsaert (1982), the heat and vapour transfer coefficients are assumed to equal, that is $g_v = g_H$.

The mathematical operations that follow are meant to isolate the term isolate $(T_l - T_a)$ as in the case with net radiation and sensible heat flux. Applying Taylor's expansion series, up to the 2nd order gives:

$$e_s(T_l) = e_s(T_a) + e_s^1(T_l - T_a) + \frac{e_s^{11}}{2}(T_l - T_a)^2 \quad (4.18)$$

where:

$$e_s(T)^1 = \frac{de_s(T)}{dT} \quad \text{and} \quad e_s(T)^{11} = \frac{d^2e_s(T)}{dT^2} \quad (4.19)$$

The squared term in the Taylor series expansion is negligible, hence

$$e_s(T_l) = e_s(T_a) + e_s^1(T_l - T_a) \quad (4.20)$$

Using equation (4.16) in (4.13) results in:

$$LE = \frac{g_v \lambda [e_s(T_a) + e_s^1(T_l - T_a) - e_a]}{P} \quad (4.21)$$

which is rearranged as :

$$LE = \frac{g_v \lambda [e_s^1(T_l - T_a) + e_s(T_a) - e_a]}{P} \quad (4.22)$$

Denoting the vapour pressure deficit, $e_s(T_a) - e_a$ as D, then equation (4.22) can be written as:

$$LE = \frac{g_v \lambda [e_s^1(T_l - T_a) + D]}{P} \quad (4.23)$$

which if expanded further using equation (4.15) can be expressed as:

$$LE = \frac{g_v \lambda \left[\frac{de_s(T)}{dT} (T_l - T_a) + D \right]}{P} \quad (4.24)$$

But $S = \frac{de_s(T)}{dT}$, which is the slope of saturation vapour pressure function. Therefore, the final expression of the latent heat flux can therefore be written as:

$$LE = \frac{g_v \lambda [S(T_l - T_a) + D]}{P} \quad (4.25)$$

Equation (4.7) can now be rewritten in terms of all the components of the leaf energy balance (with energy storage and soil heat flux fluxes are ignored) using equations (4.14), (4.15) and (4.22) as:

$$(1 - \alpha)R_g + \varepsilon L_{sky} - \varepsilon \sigma T_a^4 - 4\varepsilon \sigma T_a^3 (T_l - T_a) = k^2 u \rho_a \left[\ln \frac{z-d}{z_o} \right]^{-2} C_p (T_l - T_a) + \left[k^2 u \rho_a \left[\ln \frac{z-d}{z_o} \right]^{-2} \lambda \frac{(S(T_l - T_a) + D)}{P} \right] \quad (4.26)$$

From the equation (4.26), leaf temperature T_l can be expressed as follows:

$$T_l = T_a + \frac{(1 - \alpha)R_g + \varepsilon L_{sky} - \varepsilon \sigma T_a^4 - \left[k^2 u \rho_a \lambda \left[\ln \frac{z-d}{z_o} \right]^{-2} \frac{D}{P} \right]}{\left[4\varepsilon \sigma T_a^3 + k^2 u \rho_a C_p \left[\ln \frac{z-d}{z_o} \right]^{-2} + k^2 u \rho_a \lambda \left[\ln \frac{z-d}{z_o} \right]^{-2} \frac{S}{P} \right]} \quad (4.27)$$

The expression for leaf temperature shows that the meteorological parameters that affect leaf temperature include air temperature, net radiation, wind speed, air pressure and vapour pressure deficit. Air temperature provides the reference temperature to which the leaf temperature tends. Increasing the radiative heat load on leaf while maintaining the other factors constant always tends to increase the leaf temperature. When net radiation is negative, commonly as low as -100 Wm^{-2} (Jones, 1992) on a clear night the leaf temperature must be below the air temperature. The net radiation absorbed by a leaf is dependent on the value of the reflection coefficient for solar radiation. When the vapour pressure deficit increases, with the other parameters being constant, it lowers the leaf temperature.

4.4.2 Assessment of the Newton-Raphson method in leaf temperature determination

For all the plants, leaf temperature computed by the iteration method was generally lower than the measured temperature. A comparison of the measured and calculated leaf temperature showed that the *S. nicolai* plant had the highest coefficient of determination ($R^2=0.69$), followed by the potted *A. praecox* ($R^2=0.52$). The *F. microcarpa* had the lowest precision of the estimates ($R^2=0.24$) when considering all the measurements with uncorrected wind speed and unsegregated weather parameters. For the same measurements (data), both the *A. praecox* and the *S. nicolai* had the highest agreement index (0.75) whilst the tree measurements had the lowest values. As for the confidence index (C) the values were 0.28, 0.54 and 0.63 corresponding to the tree (*F. microcarpa*), *A. praecox* and *S. nicolai* leaves respectively. For the *S. nicolai*, the measured leaf temperature was mostly higher than the calculated temperature. When the air temperature was below $15 \text{ }^\circ\text{C}$, the calculated leaf temperature was lower than the measured leaf temperature. Fig. 1 shows the diurnal variation of temperature with time of the day for *S. nicolai* for a period of 12 days. The calculated leaf temperature was always greater than the measured leaf temperature when the air temperature was above $20 \text{ }^\circ\text{C}$.

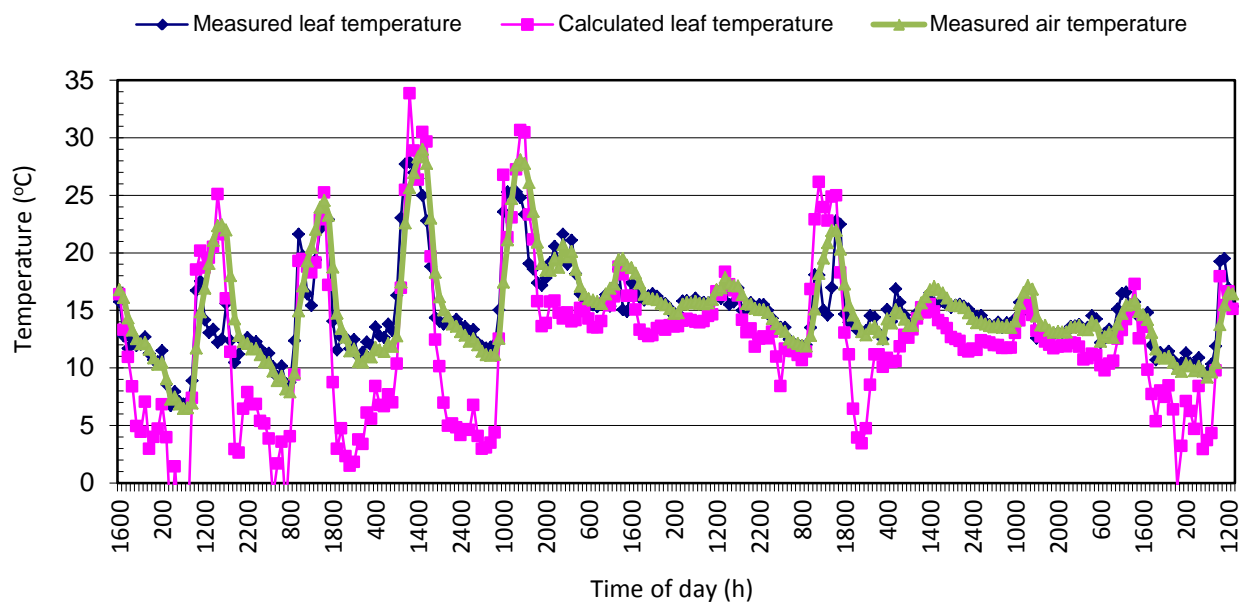


Fig 4.1 Diurnal variation of temperature with time of the day for *S. nicolai* for a period of 12 days as from 31st May to 11th June, 2010 from hourly data

As for the *A. praecox*, the calculated leaf temperature was mostly less than the measured temperature, except for two occasions that the calculated temperature-greater than the measured temperature (Fig. 4.2).

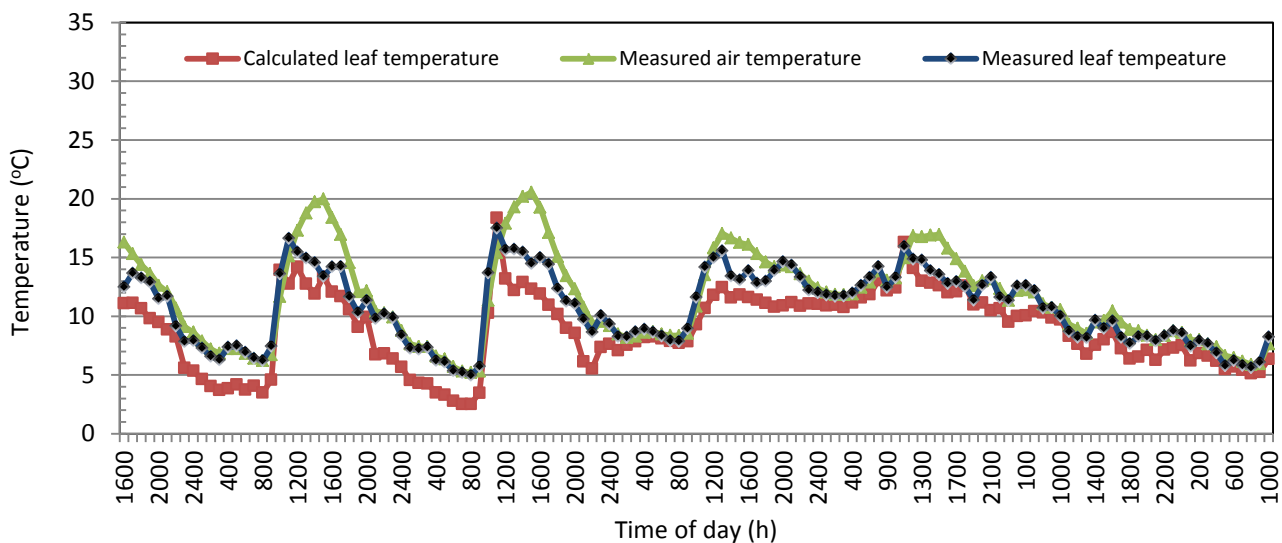


Fig 4.2 Diurnal variation of temperature with time of the day for *A. praecox* from 11th to 16th June 2010 from hourly data

The use of segregated parameters generally increased the relationship between the measured and calculated leaf temperature. In the case of *F. microcarpa*, when the zero wind speed was replaced by stall speed (0.005 ms^{-1}), the coefficient of determination increased from 0.24 to 0.31. The best correlation was produced when the wind speed was low. Fig. 4.3 compares the measured and calculated leaf temperatures. The comparison of the predicted and measured temperature at 2 m height, in the case of the *F. microcarpa*, shows that when the measured temperature was $10 \text{ }^\circ\text{C}$, the calculated leaf temperature was generally less than the measured temperature. From $10 \text{ }^\circ\text{C}$ to $18 \text{ }^\circ\text{C}$, generally the calculated was about $2\text{-}3 \text{ }^\circ\text{C}$ less than the measured value. Above $20 \text{ }^\circ\text{C}$, the calculated value was often $5\text{-}10 \text{ }^\circ\text{C}$ less than the measured (Fig. 4.3).

When the *F. microcarpa* leaf was 2 m at a height of 3 m on tree and the wind speed replaced by stall speed, the coefficient of determination, R^2 , was higher ($R^2=0.38$) than in the previous case. Overall the measured temperature was more often greater than the calculated temperature value. The calculated value was never greater than $15.5 \text{ }^\circ\text{C}$, but the measured value was as high as about $25 \text{ }^\circ\text{C}$. Between $7 \text{ }^\circ\text{C}$ and $15 \text{ }^\circ\text{C}$ there was a good agreement between the measured and the calculated values (Fig. 4.4).

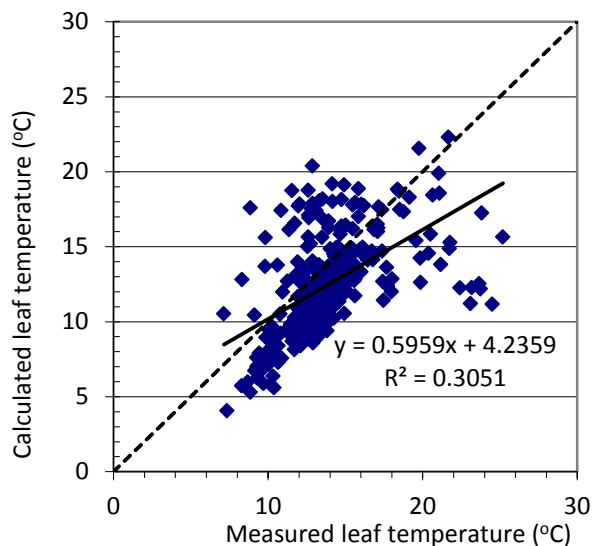


Fig 4.3 Comparison of calculated and measured leaf temperature when *F. microcarpa* leaf was 2 m away from an automatic weather station placed at height of 2 m (with wind speed replaced by 0.005 ms^{-1}) for the period 18th to 20th May 2010 (n=332) based on 10 minute data

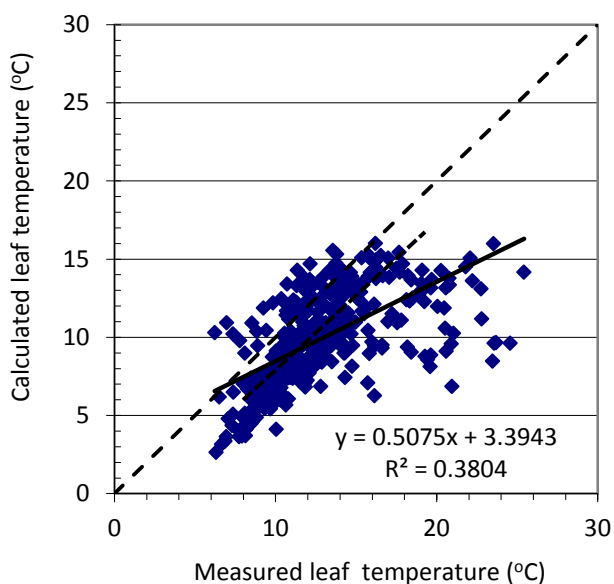


Fig 4.4 Comparison of calculated and measured temperature when the *F. microcarpa* leaf was 2 m away at a height of 3 m on tree (with null wind speed replaced by 0.005 ms^{-1}), for the period 27th to 30th May, 2010 (n=365) based on 10 minute data

For the *S. nicolai*, (Fig. 4.5), when the measured temperature was below $15 \text{ }^\circ\text{C}$, the calculated leaf temperature was always less than then the measured temperature. However, above $20 \text{ }^\circ\text{C}$, the points on the graph are evenly scattered around the 1: 1 line. R^2 had a range of values from 0.42 to 0.88 which was significantly higher than that for *F. microcarpa*. The best correlation between the measured and calculated temperature was produced for the *A. preacox* ($R^2=0.89$) when the wind speed was replaced with stall speed (Fig. 4.6). However, the calculated leaf temperature was always less than the measured temperature except for 2 points (Fig. 4.6).

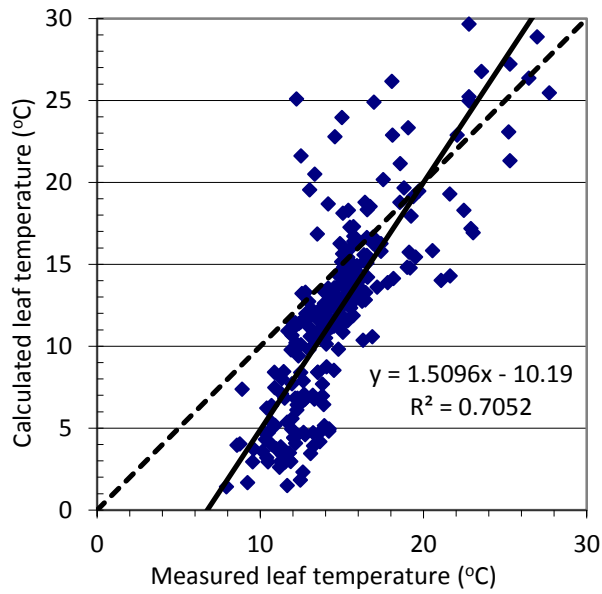


Fig 4.5 Comparison of calculated and measured leaf temperature for *S. nicolai* for the period 31st May to 11th June, 2010 (n= 263)

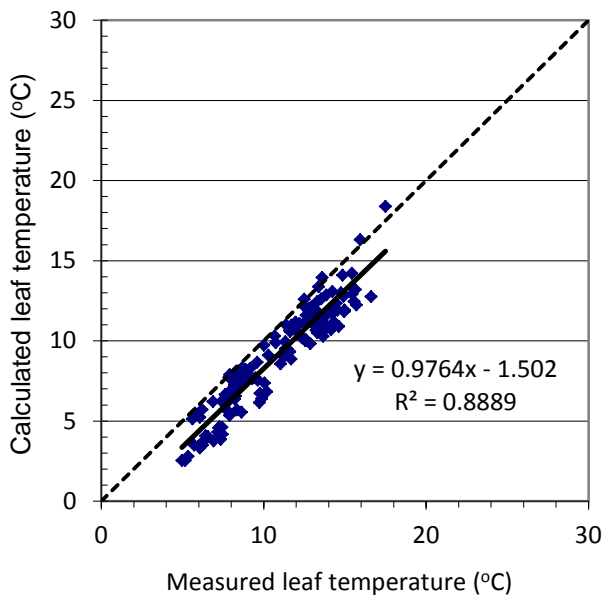


Fig 4.6 Comparison of calculated and measured leaf temperature for *A. praecox* (with wind speed of 0.005 ms^{-1}) (n=135) for the period from 6th June to 11th June 2010

A. praecox showed the strongest relationship between measured and calculated leaf temperatures, followed by the *S. nicolai* and *F. microcarpa* had the poorest results. When all the zero values of wind speed were replaced by the stall speed (0.0005 ms^{-1}), the relationship between the measured and estimated leaf temperature for *A. praecox* improved with the coefficient of determination changing from 0.52 to 0.89 and the accuracy increased because the mean absolute error decreased by more than half (from 4.19 to 1.78 °C). Both the indices of agreement and confidence rose to 0.96 and 0.91 respectively (Table 4.2). The weather conditions that produced the highest agreement index ($D=0.97$) included night time, high relative humidity, low temperature (less than 15 °C) and low wind speed.

Table 4.2 Coefficient of determination (R^2), mean error (ME), mean absolute error (MAE), agreement index (D) and the confidence index (C) for the leaf temperature and weather parameter measurements of the indigenous *A. praecox* from 6th June to 11th June 2010

Weather parameter		R^2	ME (°C)	MAE (°C)	D	C	n
All data with uncorrected wind speed		0.52	-2.94	4.19	0.75	0.54	135
All data with zero wind speed values replaced by 0.0005		0.89	-1.75	1.78	0.96	0.91	135
Segregated net radiation (Wm^{-2})	Positive net radiation (day time)	0.81	-1.69	1.78	0.88	0.79	50
	Negative net radiation (night time)	0.87	-1.77	1.78	0.97	0.90	85
Segregated relative humidity (%)	High relative humidity ($\geq 60\%$)	0.88	-1.69	1.70	0.97	0.91	90
	Low relative humidity ($< 60\%$)	0.59	-2.09	2.17	0.58	0.44	35
Segregated air temperature (°C)	High temperature ($\geq 15^\circ\text{C}$)	0.47	-1.97	2.04	0.49	0.34	85
	Low temperature ($< 15^\circ\text{C}$)	0.86	-1.70	1.71	0.97	0.90	50
Segregated wind speed (ms^{-1})	High wind speed ($\geq 1 \text{ ms}^{-1}$)	0.77	-1.55	1.55	0.90	0.79	10
	Medium wind speed (< 1 and $> 0.0005 \text{ ms}^{-1}$)	0.89	-1.57	1.57	0.95	0.90	22
	Low wind speed (0.0005 ms^{-1})	0.96	-2.50	2.61	0.97	0.95	103

n is the number of samples in each category

For *S. nicolai*, it is evident that sorting the weather data into high and low categories also brought a few changes to R^2 values (Table 4.3). This value only increased to 0.88 (from 0.71) and 0.70 (from 0.69) in the case of low wind speed and high relative humidity respectively. The agreement index D, was 0.91 for positive net radiation. However, the exhibited a pattern opposite *A. praecox* at high temperature and low relative humidity. Generally, the *S. nicolai* had higher MAE values than the *A. praecox* (Table 4.3) and this probably also affected the indices that were computed. The mean absolute error (MAE) was highest at low wind speed (8.55 °C), which was more than double the error produced when wind speed was low.

Table 4.3 Coefficient of determination, mean error, mean absolute error, agreement index and the confidence index coefficient of indices for the leaf temperature measurements of the *S. nicolai* plant from 31st May to 11th June 2010

Weather parameter		R^2	ME (°C)	MAE (°C)	D	C	n
All data with uncorrected wind speed		0.69	-2.78	3.98	0.75	0.63	263
All data with zero wind speed values replaced by 0.0005		0.71	-2.66	3.86	0.77	0.64	263
Segregated net radiation (Wm ⁻²)	Positive net radiation (day time)	0.56	0.99	2.66	0.91	0.68	85
	Negative net radiation (night time)	0.68	-4.41	4.43	0.64	0.52	178
Segregated relative humidity (%)	High relative humidity (≥60%)	0.70	-3.45	3.82	0.66	0.55	221
	Low relative humidity (<60%)	0.69	-2.26	3.65	0.79	0.66	42
Segregated air temperature (°C)	High temperature (≥15°C)	0.48	-0.35	2.85	0.88	0.60	119
	Low temperature (<15°C)	0.64	-4.58	4.70	0.66	0.53	144
Segregated wind speed (ms ⁻¹)	High wind speed (≥1 ms ⁻¹)	0.42	-1.08	1.59	0.72	0.47	62
	Medium wind speed (<1 and >0.0005 ms ⁻¹)	0.71	-2.16	3.83	0.82	0.69	40
	Low wind speed (0.0005 ms ⁻¹)	0.88	-8.55	8.55	0.61	0.57	161

n: sample size in each category

Compared with the other plants, the *F. microcarpa* tree showed the worst relationships ($R^2=0.31$), fairly reasonable accuracy ($D=0.68$) and very low confidence index ($C=0.39$) (Table

4.4). Sorting the data in ascending order and then having high and low values of datasets, improved the precision (R^2 increased) in 4 cases out of 9. The mean absolute error (MAE) had minimum and maximum values of 2.19 and 3.73 °C respectively and an average value of 2.64 °C. Although the index of accuracy, D, was fairly high with values fluctuating between 0.51 and 0.83, the confidence index, C values were very low as compared to the values from the other experiments with only two relationships with $C > 0.60$, namely for low temperature and low wind speed.

Table 4.4 Coefficient of determination, mean error, mean absolute error, agreement index and the confidence index coefficient of indices for the leaf temperature of the *F. microcarpa* at a distance from the station (2 m x 2 m) from 18th May to 20th May 2010

Weather parameter		R^2	ME (°C)	MAE (°C)	D	C	n
All data with uncorrected wind speed		0.24	-2.40	3.65	0.57	0.28	332
All data with zero wind speed values replaced by 0.0005		0.31	-1.38	2.50	0.70	0.39	332
Segregated net radiation (Wm^{-2})	Positive net radiation (day time)	0.18	0.28	2.53	0.69	0.30	115
	Negative net radiation (night time)	0.40	-2.26	2.49	0.71	0.45	117
Segregated relative humidity (%)	High relative humidity ($\geq 60\%$)	0.42	-1.51	2.27	0.76	0.49	277
	Low relative humidity ($< 60\%$)	0.01	-0.69	3.73	0.56	0.06	55
Segregated air temperature (°C)	High temperature ($\geq 15^\circ C$)	0.00	-0.39	2.95	0.53	0.03	137
	Low temperature ($< 15^\circ C$)	0.66	-2.08	2.19	0.83	0.67	195
Segregated wind speed (ms^{-1})	High wind speed ($\geq 1 ms^{-1}$)	0.05	-1.13	2.80	0.51	0.12	42
	Medium wind speed (< 1 and $> 0.0005 ms^{-1}$)	0.30	-1.14	2.48	0.70	0.38	53
	Low wind speed ($0.0005 ms^{-1}$)	0.75	-2.32	2.41	0.82	0.71	293

n: sample size in each category

The crown of the *F. microcarpa* was hemispherical and that the leaves that were used in the experiment were located in the interior of the crown. These leaves were not only shaded by other

leaves from the same tree and exposed to slower winds but could also be shaded by the other *F. microcarpa* trees. However, unlike the leaves of the tree, the *S. nicolai* plant was located in an open area and its leaves were fully exposed to the sun and elements all the time. The leaves of the *S. nicolai* were relatively large compared to that of the *F. microcarpa tree* (1680 cm² for *S. nicolai* versus about 8-10 cm²). Pedro and Gillespie (1982b) found that the shaded leaves in an apple orchard had more errors than exposed leaves.

The poor performance of the *F. microcarpa* could be related to the exposure. The *F. microcarpa* trees had a round and woolly canopy, such that when automatic weather station was 1-2 m from the tree trunk, it was positioned in such a way that the station was shaded by the trees. Moreover, the exposure of the three leaves were very different. The *F. microcarpa* leaves were mostly shaded and not horizontal, unlike *A. paraecox* and the *S. nicolai* which were more exposed to direct solar radiation and appeared more horizontal. Consequently the net radiation balance for the *F. microcarpa* was more complex and the net radiation measured was assumed to be different to the net radiation of the leaf. According to Haseba and Ito (1982) the leaf temperature of a plant is closely related to the meteorological conditions and the physical properties and physiological processes within the plant. Leaf temperature depends on air temperature, relative humidity, solar radiation, leaf resistance, and boundary layer resistance. Boundary layer resistance depends mainly on the shape and size of the leaf and wind speed. In this case, the leaves had different sizes. This means that using only weather conditions to predict leaf temperature could be prone to errors and could have caused the iteration method to under or overestimate calculated leaf temperature depending on the type of leaf.

4.5 Conclusion

It can be concluded that the iteration energy balance method offers an alternative method to calculate leaf temperature without the need to measure it directly. However, this method had a tendency of underestimating leaf temperature. A comparison of the calculated and measured leaf temperature shows that the calculated leaf temperature was generally less than the measured temperature in the three leaves of the different plants. However, the leaf temperature of plants with exposed leaves exhibited a better agreement with the measured temperature than the deep

shade tree leaves. There are two issues that require special attention. Firstly, there is need to establish a standard protocol for the measurement of weather parameters (to be used to compute leaf temperature) in terms of the sensors' placement (height as well as distance from the plant). Secondly, the exposure of the plant needs to be defined, since using the same weather parameters to compute leaf temperature for leaves with different exposures will not yield the same results.

Chapter 5

Determination of leaf wetness duration from simulation models

5.1 Introduction

Surface wetness has been recognized as a quantifiable component influencing plant disease development since the 1900s (Wallin, 1967), but surface wetness has always been difficult to quantitatively define. Attempts to directly detect surface wetness have been greatly hindered by the lack of a suitable sensor and lack of a standard exposure protocol. In addition, most sensors provide indirect measurement of surface wetness duration, have different physical properties from leaves and also require calibration to represent the phenomenon for a specific crop (Getz, 1991; Giesler et al., 1996). The precision and accuracy of the sensors is markedly affected by sensor size and shape, orientation, presence, colour and type of paint coating and even show variability among apparently similar sensors (Lau et al., 2000). Sensors also require seasonal calibration, regular maintenance, error checking and occasional sensor replacement. The collection and transfer of data from a field instrument to a database can be time-consuming and subject to errors. Bird excreta or dust may accumulate on sensors, and dataloggers may deplete their batteries at critical times. Lightning strikes can cause data-logger meltdowns.

Several studies have been conducted to investigate the performance of simulation models (both empirical and physical) in estimating leaf wetness duration. The Surface Wetness Energy Balance (SWEB) model, which uses a physical approach to predict leaf wetness duration, has been developed as a potential theoretical standard for surface wetness measurement. Studies of surface wetness indicate that the SWEB model performed better than sensors at three sites, two in New York and one in Australia (Dalla Marta et al., 2005; Magarey et al., 2006a). Although the model has been designed and used extensively to estimate leaf wetness duration mainly in grapevine, it can be calibrated to simulate wetness in other crop canopies. Dalla Marta et al. (2007) adjusted and applied the SWEB model for the simulation of leaf wetness duration on the canopy of sunflower. On the other hand, LWD can be simulated using an empirical model such as the relative humidity model. The purpose of this study was to evaluate the performance of the two models namely the SWEB model and a relative humidity model to estimate leaf wetness

duration in a Satsuma Mandarin citrus orchard by comparing each model's simulated leaf wetness duration with visually observed leaf wetness duration of the citrus canopy.

5.2 Theory

The surface wetness energy budget (SWEB) model is a physical model developed at Cornell University (USA) based on the "big leaf" concept. The model was designed for grapes and assumes that the canopy is a big leaf and simulates surface wetness based on a surface energy balance and water budget. Since the model has been designed for operational use, it was calibrated to the observed surface wetness duration under controlled environmental conditions (2005) and validated with visual observations of surface wetness duration at 3-year site combinations, two in Geneva, NY and one in Adelaide, Australia (Magarey, 1999; Seem et al., 2000; Magarey et al., 2005). The model satisfies most of the requirements for a suitable surface wetness model in terms of simplicity, utility, scalability, ease of adaptation to other crops and sites and calibration under controlled conditions (Magarey, 2005).

Three assumptions were made in constructing the model. First, the grape canopy is assumed to be one big leaf at the average height of the crop. The big leaf model is the simplest approach, because a multilayer approach would require serious modification each time it is moved to a new crop. Although the multilayer model may have a slight advantage over big leaf for estimating evaporation (Greenspan and Matthews, 1996), the SWEB may also be scaled to represent a layer in the crop canopy by adjusting the input parameters, with the exception that it cannot represent sunlit portions of the canopy due to the third assumption below. Second, it is assumed that inputs to the model are temperature, relative humidity at canopy height, precipitation, wind speed are measured above the canopy and the net radiation for the canopy. Third, net radiation does not contribute to evaporation on leaves inside the canopy, which are the slowest to dry and therefore the most important to plant disease studies. This last assumption is based upon the fact that the first sunlit leaf top layer in a grape canopy absorbs 94% of the incoming solar radiation (Smart and Robinson, 1991). Since net radiation is included during the night, the model can also simulate longer wetness durations caused by dew at the top of canopies.

The SWEB model is composed of four modules. The first module defines surface wetness and the surface water distribution on a plant surface which calculates the actual wet area of the canopy. The second module is the plant canopy water budget which is a function of the water storage and is added to by intercepted precipitation or condensation and subtracted from by evaporation. The water storage capacity is based on the properties of a single leaf scaled up to that of a canopy. The third module describes the surface energy balance based on a combination formulation developed by Tanner and Fuchs (1968) for evaporation or condensation from unsaturated surfaces. Evaporation is calculated solely from the aerodynamic term of the equation, since daytime net radiation is assumed not to contribute to evaporation. The assumption is based on the fact that the sunlit leaf layer in a grape canopy absorbs 94% of the incoming solar radiation (Smart and Robinson, 1991). During the night both evaporation and condensation are estimated from the energy budget equation. The fourth module is the transfer function scaled to the evaporation of drops and films. Appropriate values of the transfer coefficient that describe the drying of drops and films were identified under controlled conditions for a range of atmospheric variables and plant properties (Magarey et al., 2005). The transfer coefficient was based on Bird's generic transfer coefficient that was calibrated to surface wetness under controlled conditions, to account for the influence of windspeed and an object's shape and size.

On the other hand, LWD can also be estimated from empirical models such as the constant relative humidity (RH) threshold model. This model estimates LWD as the the number of hours with RH greater than or equal to a constant value. The RH model was developed from observations that condensation on grass began before saturation in the air was reached, when relative humidity ranged from 91% to 99% (Monteith, 1957). The author implied that the leaves were colder than air and condensation began when the leaf temperature reached the dew point of surrounding air. Empirical models are readily adaptable to agricultural uses because they generally depend on input weather variables which are commonly measured at most automated weather stations (Sutton et al., 1984; Sentelhas et al., 2008). Different threshold values of relative humidity have been used to simulate LWD. According to Crowe et al. (1978) and Sutton

et al. (1984), a relative humidity threshold of $\geq 90\%$ has been used for a long time to estimate LWD. Sentelhas et al. (2008) reported a RH model that utilized a RH threshold value $\geq 90\%$ and above had greater accuracy in estimating LWD than a model that used dew point depression as the threshold. Kim et al. (2010) also used this same threshold value to estimate LWD.

5.3 Materials and Methods

5.3.1 Models' input data

The observed leaf wetness and weather data collected in Chapter 2 was used to evaluate the performance of the two simulation models. To simulate leaf wetness in the top canopy using the SWEB model, values of 3.67 and 2.14 m were used as input parameters for leaf area index and crop height respectively. The measured leaf area index at the beginning of the field trial experiment was 3.67. It was assumed that the citrus canopy had 3 layers (top, middle and bottom) each with equal distribution to the leaf area index with a value of 1.22. The average height of the citrus trees was calculated from measured heights of five citrus trees where the wetness sensors were located. For the RH model, LWD was computed as the number of hours that canopy relative humidity was $\geq 75\%$. This value was the minimum relative humidity, which was recorded when the source of wetness was dew. The choice of the minimum relative humidity value as the threshold value was done to avoid underestimating LWD.

5.3.2 Data Analysis

To evaluate the performance of each of the simulation models, the upper and lower canopy positions were considered separately. The visual observations of wetness in each canopy position (the upper and lower canopy levels) and model estimated leaf wetness were compared to quantify the number of hours that were correctly classified as wet and dry using a dichotomous categorical verification (Wilks, 1995; Dalla Marta et al., 2005). A contingency table was compiled with the number of hours that were correctly or incorrectly estimated by each of the models. Table 5.1 shows the classification of the hourly observed and model simulated LWD.

Table 5.1 Classification of hits, misses, false alarms and correct negatives

	Estimated wet	Estimated Dry
Observed wet	Hits (X)	Misses (Y)
Observed dry	False alarm (W)	Correct negatives (Z)

Four statistical indices namely fraction of correct estimates (F_c), correct success index (C_{SI}), false alarm ratio (F_{AR}) and bias (B_s) were computed using wetness data according to table 5.1. According to Dalla Marta et al. (2005; 2007) and Sentelhas et al. (2008), F_c represents the fraction of the simulated estimates (wetness event occurred and non-event occurred (dryness)) correctly predicted whilst the correct success index C_{SI} measures the fraction of the wetness events occurring, that were correctly simulated by the models. Both indices range between 0 and 1, where 0 indicates no skill whilst 1 represents a perfect score. B_s shows the tendency of the model to under or overestimate the simulated phenomenon. A bias of less than one indicates underestimation. If the bias is equal to one, it means that the model has no tendency (no bias). The false alarm ratio (F_c) expresses the ratio of the wetness events occurring that were not predicted. This index varies from 0 to 1 and should be as small as possible

According to the authors, the statistical indices are calculated as follows:

$$F_c = \frac{X + Z}{X + Y + W + Z} ; C_{SI} = \frac{X}{X + Y + W} ; F_{AR} = \frac{W}{X + W} \text{ and } B_s = \frac{X + W}{X + Y} .$$

The same indices were also computed for all wet days, dew days and rain days considering only the upper canopy level. A comparison of the statistical indices comparing visual observations of leaf wetness duration with both the SWEB and relative humidity models for the lower and upper canopies was also computed.

Daily leaf wetness duration was computed from hourly leaf wetness data for the observed data as well as for each model and the sensors. This was done by summing the hourly LWD over a period of 24 hours for each canopy level. For the wetness sensors, the daily LWD was computed as the average value calculated using LWD measured by each sensor in that canopy level on that day. To compare the performance of the models as well as the sensors, a regression analysis was performed to compare daily observed and model predicted leaf wetness duration data by

calculating the correlation coefficient at 95% confidence level. Finally, all the daily with wet leaf data was divided into rainy-only days, dew-only days and days when wetness resulted from dew as well as rain and the coefficient of determination was calculated for the different days. A rainy-only day was defined as a day in which rainfall amount ≥ 0.25 mm was measured. Percentage error distribution was also computed for the different days (dew days, rain days as well as days when wetness resulted from dew as well as rain). The purpose of this analysis was to quantify the frequency of errors produced by each of models during different wetness events.

5.4 Results and Discussion

5.4.1 Analysis of hourly leaf wetness in the upper canopy for different wetness events

Generally the relative humidity model, had a higher correct fraction (F_c), higher correct success index (C_{SI}), and gave a lower false alarm (F_{AR}) than the SWEB model. When considering all the events, F_c and C_{SI} values of 0.78 and 0.60 were obtained in the comparison between observed and SWEB simulated hourly wetness. However, the same indices yielded values 0.84 and 0.68 respectively in the case of the relative humidity model. The same trend was exhibited during dew and rain only events. This means that the relative humidity model detected wet hours with higher accuracy than the SWEB model. Bias during all events as well as dew was close to 1 for both models, so there was approximately a balance between over and underestimates. When dew only days were considered, the SWEB had a tendency to overestimate (B_s), whilst the relative humidity model had a tendency to underestimate when considering all events. The higher false alarm of the SWEB model could be a result of its overestimation.

Table 5.2 Statistical indices comparing hourly visual observations of leaf wetness duration with both the SWEB and relative humidity models for different wetness events in the upper canopy

	SWEB model			Relative humidity model		
	All events	Dew events only	Rain events only	All events	Dew events only	Rain events only
F_c	0.78	0.64	0.73	0.84	0.66	0.76
C_{SI}	0.60	0.53	0.63	0.68	0.58	0.66
F_{AR}	0.30	0.20	0.16	0.17	0.13	0.09
B_s	1.15	1.16	0.86	0.95	1.01	0.77

During the rain events, the critical success index increased slightly and consequently resulted in the decrease of false alarm for both models. When wetness resulted from dew events, both the models exhibited a similar pattern and the critical success index (C_{SI}) decreased to 0.53 and 0.58 for the SWEB and relative humidity model respectively. The SWEB model incorrectly predicted wetness in 20% of all the hours that wetness occurred from dew, whilst the relative humidity wrongly predicted wetness with a lower frequency of 13%. These results indicated that the wetness data simulated by models are subject to errors and uncertainties. The performance of the relative humidity model seem to suggest that even the simple relative humidity can be very useful in simulating hourly leaf wetness, considering that relative humidity is a weather parameter which is measured in most standard weather stations. This could be the reason why some researchers have used relative humidity as a surrogate for leaf wetness duration and that adjusting the relative humidity threshold to account for local climate differences can result in leaf wetness duration that are highly accurate (Gleason et al., 2008).

5.4.2 Analysis of observed leaf wetness duration in both upper and lower canopy levels

Both models exhibited a similar pattern. The statistical indices suggest that the accuracy of both models was better for top than the bottom canopy for both models. Both models had higher C_{SI} in the upper canopy level (0.68 and 0.76) but this index dropped by about 20% in the lower canopy level for each of the model (Table 5.2). This indicated that the models were not so good at predicting wet events in the lower canopy. Other statistical indices such as the false alarm ratios were higher in the lower canopy position (0.43 and 0.29) as a confirmation that the both models poorly simulated wetness in the lower canopy.

Table 5.3 Statistical indices comparing visual observations of leaf wetness duration with both the SWEB and relative humidity models for the lower and upper canopies using all data

	Upper canopy level		Lower eastern canopy	
	SWEB	RH	SWEB	RH
F_c	0.76	0.88	0.75	0.80
C_{SI}	0.68	0.76	0.48	0.59
F_{AR}	0.32	0.04	0.43	0.29
B_s	1.46	0.81	0.85	1.10

5.4.3 Analysis of daily leaf wetness duration

Results of regression analysis, revealed a better agreement between the relative humidity model and observed leaf wetness duration. A weak but statistically significant relationship was obtained when observed leaf wetness was compared with leaf wetness duration simulated from the SWEB model. Comparison of the SWEB model and observed leaf wetness duration produced the strongest correlation ($R^2=0.55$) if the whole data set was considered (Table 5.4). During dew and rain days, the association between observed and SWEB simulated leaf wetness duration in the top canopy was almost the same ($R^2=0.45$ and 0.44 respectively). For the bottom canopy, the leaf wetness duration predicted by the SWEB model was poorly associated with observed leaf wetness. The highest coefficient of determination was low ($R^2=0.24$) but significant whilst the worst correlation was 0.04 which calculated with only four points was not even statistically significant. When considering days when wetness occurred due to both rain and dew, the association between observed and simulated wetness was very poor and not statistically significant for SWEB model (Table 5.4). All the coefficients of determination for the types of wetness decreased substantially in the lower canopy.

Table 5.4 Coefficient of determination (R^2) between observed and model simulated leaf wetness duration

Event	SWEB model		RH model	
	Top Canopy	Lower eastern canopy	Top Canopy	Lower eastern canopy
All days	0.55 ** (n=62)	0.24 ** (n=62)	0.79 ** (n=62)	0.54 ** (n=62)
Dew only days	0.44 ** (n=24)	0.10 ns (n=14)	0.65 ** (n=24)	0.11 ns (n=14)
Rainy days	0.45 ** (n=17)	0.20 ** (n=22)	0.46 ** (n=17)	0.39 ** (n=22)
Both rain as well as dew as a single event days	0.05 ns (n=10)	0.04 ns (n=4)	0.74 ** (n=10)	0.82 ns (n=4)
All wet days	0.43 ** (n=51)	0.07 ns (n=40)	0.55 ** (n=51)	0.35 ** (n=40)

ns=not significant, **= $P<0.05$, n=number of days in each calculation

The relative humidity model was relatively more accurate than the SWEB model (Table 5.4). Although the coefficients of determination between the top and the bottom exhibited a similar

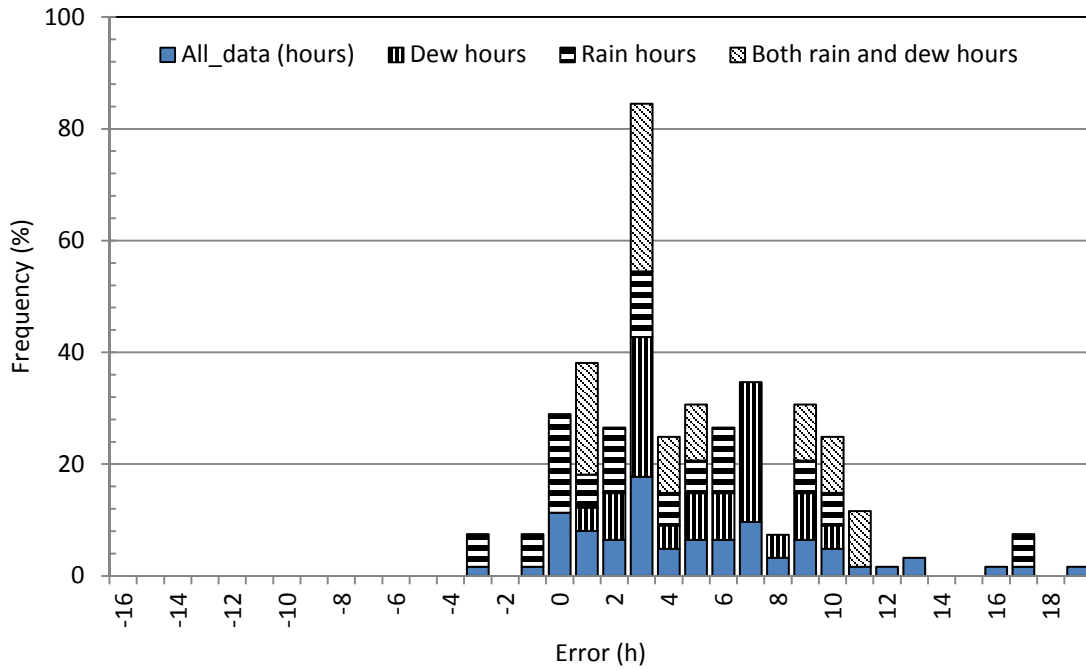
pattern, there was a better agreement between RH simulated and observed leaf wetness than with the SWEB model (Table 5.3). Unlike the SWEB model, the relationship between observed and simulated wetness during dew only days was stronger ($R^2=0.65$) as compared to that during rain days ($R^2=0.46$). A higher coefficient of determination ($R^2=0.74$) was obtained when wetness resulted from both rain as well as dew. In the lower canopy, the relationship between observed and that simulated by the model was mostly not statistically significant at 95% confidence level.

The regression analysis results seem to suggest that both models have a tendency to correctly simulate the behaviour for the upper layers, while it was not able to simulate the lower one. Similar results were obtained with wetness sensors (Chapter 2), where sensors placed in the upper level had a higher accuracy in measuring LWD than sensors located in the lower canopy levels. Dalla Marta et al. (2007) also found that the SWEB model seemed to simulate the behaviour of the upper layers while it was not able to correctly simulate the lower one when investigation leaf wetness duration in sunflower (*Helianthus annuus*). Sentelhas et al. (2005) also noted that the accuracy of estimating leaf wetness duration in apples using leaf wetness sensors also decreased from top to bottom.

5.4.4 Frequency of errors

Considering the top canopy, the SWEB model resulted in error distributions skewed towards overestimation, with a wide range of errors (Fig. 5.1 (a)). A comparison of dew days and rain days indicated some differences in terms of the distribution of the errors. The model overestimated daily wetness during all the days that wetness resulted from dew and all the errors had values as high as 10 h. The greatest number of errors occurred when the model overestimated wetness by 7 hours which accounted for 25% of all the errors that occurred during dew only days. During rainy days, the model correctly predicted wetness with a frequency of 18% and most of the errors were less than 6 h. When wetness resulted from both rain and dew, 30% of all the error had a magnitude of 3 h.

a)



b)

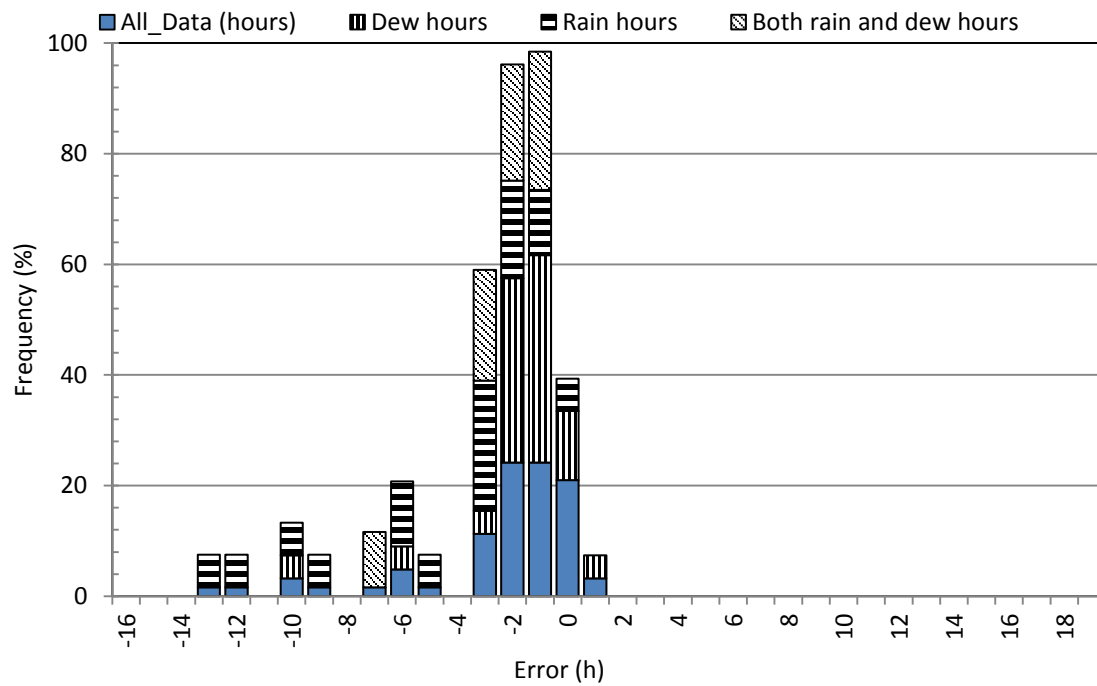


Fig 5.1 Frequency of errors in the top canopy from (a) SWEB model (b) relative humidity model for citrus orchard near Stellenbosch in 2012

For the same canopy, the relative humidity presented an opposite pattern to the SWEB model as this model exhibited a tendency of underestimation and a relatively smaller range of errors (Fig. 5.1(b)). This confirms that the relative humidity had a higher accuracy than the SWEB model as shown above. When all the days were considered, the model overestimated wetness by only 1 h with a frequency of 3%. The model performed better than the SWEB model, correctly predicting wetness with an accuracy of 21%. Most of the errors occurred due to the model underestimating wetness mostly between 3 h and 1 h. During dew only days, the model mostly underestimated wetness by 2 h and 1 h, which accounted for 33% and 37% respectively of all the errors. During rain days the model slightly underestimated wetness. The poor performance of the SWEB model could be attributed to the model parameter maximum water storage which was assumed to be constant during the field trial. As the plant grows and develops this parameters also changes. One well-known challenge to all net radiometers is that of keeping the thermopile surfaces or domes clean (Brotzge and Duchon, 2000). According to the authors, when precipitation and dew evaporate from the sensor surface, residual debris remains, which can alter the surface albedo and absorption properties. In addition, water droplets on the dome may refract, or reflect radiation, leading to incorrect values of net radiation. This could have been one source of error for the SWEB model since according to Kincaid and Cheney (1996) inaccuracy in a single input may greatly influence model performance because errors in input values can be preserved or amplified.

An analysis of the distribution in the lower canopy for both models indicated a different pattern to that of the upper citrus canopy (Fig. 5.2). In both models, the distribution of errors was approximately symmetrical and had a wider range, which seemed to indicate that the models were less accurate in predicting leaf wetness duration in the lower canopy as compared to the upper canopy (Fig. 5.2). The SWEB model overall overestimated leaf wetness duration during dew only days. However, when rain occurred, the model generally underestimated wetness duration. This same rainy days pattern prevailed during days when wetness was a result of both rain and dew showing that rain brought more moisture than dew. During dew only days, the most common error was an overestimation of leaf wetness duration by 2 h, which contributed to a 29% of all the errors that occurred during all the dew days (Fig. 5 2(a)).

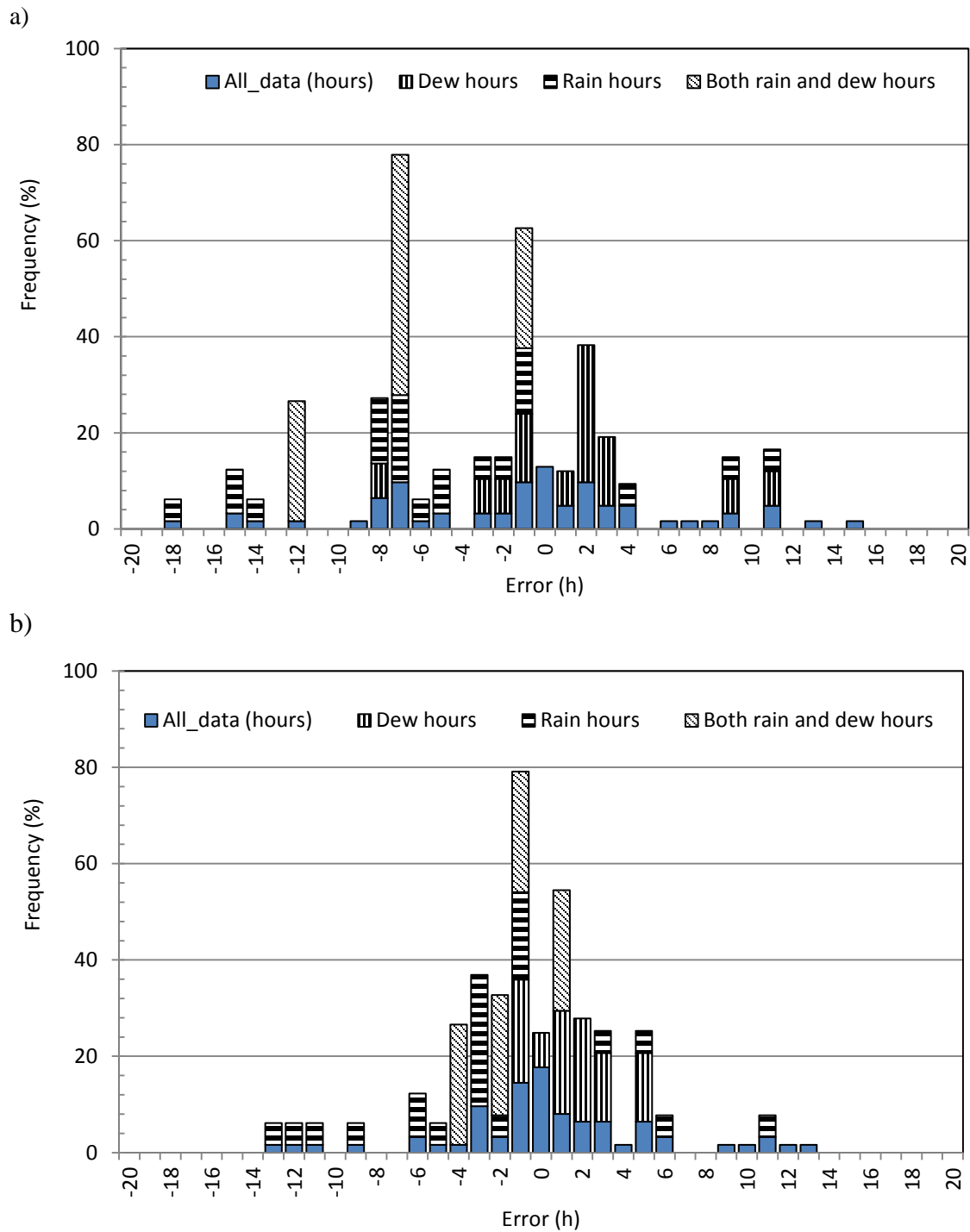


Fig 5.2 Frequency of errors in the lower canopy from (a) SWEB model (b) relative humidity model at at Welgenvallen Experimental Farm of the University of Stellenbosch for the citrus canopy

The relative humidity model also overestimated leaf wetness duration during dew days and largely underestimated wetness duration during rainy days (Fig. 5.2(b)). During days that wetness occurred due to both rain and dew events, the model also underestimated wetness duration. On the whole, the relative humidity model had more small errors occurring more frequently than the large errors. Most of the errors greater than 5 h, each contributed less than 5% to the total errors. In addition, during dew days, the model correctly predicted leaf wetness with a frequency of 7% unlike the SWEB model that failed to correctly predict leaf wetness duration (Fig. 5.2(b)).

5.5 Conclusion

The study supports the hypothesis that both physical and empirical models can be used to accurately predict leaf wetness duration. In this case, both the SWEB and relative humidity models can be a practical and useful tool for estimating leaf wetness duration in upper canopy of the Satsuma Mandarin citrus plants. The results confirm that even a simple relative humidity model has a potential to produce accurate leaf wetness duration provided the model is locally calibrated. The merit of the relative humidity model is that it only requires one measured input parameter, relative humidity, which is measured by most weather stations.

It is evident that leaf wetness is a variable that is difficult to measure and simulate and that even a physical model such as the SWEB cannot capture all the elements affecting dew formation and dissipation. This is because leaf wetness duration is not affected by a single type weather situation but also by plant structure, architecture, and height which affect the crop microclimate and height. The SWEB although designed for grapevine canopies can also be used to estimate leaf wetness duration in the citrus canopy. For example, because the model consistently overestimated leaf wetness duration of the top canopy, one of the descriptive parameters embedded in the model could be adjusted to represent the citrus canopy. Further studies are therefore required in order to determine these parameters.

Chapter 6

General discussion and recommendations

The visual observations of LWD within the citrus canopy in Stellenbosch, showed spatial heterogeneity between different canopy positions. This variable (LWD) is influenced by weather as well as other factors such as plant structure which allow different portions of the canopy to be wet for different lengths of time (Chapter 2). The spatial variability showed a constant pattern of longer LWD at the top of the citrus canopy on dew and rainy days. When the source of wetness was from dew, the mean LWD differences between the upper and lower canopy positions were greatest. However, in order to be able to completely characterize the spatial variability of LWD within the citrus canopy, there is a need to determine LWD at the middle canopy position and compare it with other canopy positions (upper and lower) of the citrus canopy.

The measurement of LWD in this middle layer would enable one to better characterize and increase knowledge about the vertical wetness structure of the canopy. Since it was observed that sensors placed in the upper canopy were estimators of LWD, one possible area that warrants further research would be to investigate the possibility of predicting LWD duration in the lower canopy level using LWD data measured in the upper canopy level. From a plant protection view point, data on LWD within a canopy can be very useful. For example in the case of the citrus canopy, it was observed that dew formed more frequently at the upper canopy level than in the lower canopy. Such information can be used to support various applications such as differential management of fungicide sprays (depending on the crop layer considered), which could be economically beneficial to the citrus growers and also reduce the use of chemicals which pose a risk to workers' safety and also contaminate the environment.

The performance of wetness sensors has demonstrated that both the Decagon and unpainted Campbell sensors, if correctly calibrated and installed in the upper canopy level of the citrus canopy can accurately measure LWD. Consequently, the decision to paint or not paint the sensors is one decision that users of Campbell sensors would appear to be unnecessary. Extension workers and grower organisations should therefore encourage growers to consider the use of the commercial sensors as part of a decision support system. However, the poor agreement

between visual observation and LWD measurements in the lower canopy level highlights the importance that users of such LWD (data measured by an unpainted Campbell or Decagon sensor) should be aware of this limitation, as it can be the source of error if used in disease warning systems. Sensors can provide accurate estimates of leaf wetness duration if used properly. The other advantage is that sensors can be calibrated to determine amount of dew deposition, which is also another important component of the water balance.

For some user and growers, it is not always convenient for a sensor to be placed within a grower's field, especially if it needs to be removed frequently for crop management such as spraying and other activities that can alter the performance of the sensors. If LWD is monitored based on a single sensor per orchard, then an alternative option would be to deploy a single sensor preferably close to the field. More research is also needed to identify the best protocol for the placement of such sensors that operationally measure LWD for decision warning systems. This protocol associated with an agricultural decision support system would include which kind of sensor to use, where to position the sensors including exposure and inclination and what type of response and how to use the data to correctly apply the decision support system

There is no single best method to acquire LWD data for disease-warning systems. The results of this study confirmed the hypothesis that empirical models can accurately predict leaf wetness as compared to commercial wetness sensors. Consequently, for citrus farmers who cannot afford to set-up up their own station, simulation can be a viable option especially if the input data is provided by the meteorological services. Many studies have been conducted to improve the understanding of the causes affecting LWD, however due to the extreme variability and complexity of the phenomenon, the best solution would be mutual agreement on an operational definition acceptable to the scientific community. The set-up of models should be based on standard protocols. The parameterization and validation of mechanistic models would be impossible without accurate *in situ* measurements of leaf wetness.

Leaf temperature is an important factor that has a bearing on the deposition of dew. Theoretically, dew deposition occurs whenever the leaf temperature falls below the ambient air

temperature. One of the objectives of the study was to evaluate the Newton-Raphson iterative method as an alternative approach in the indirect determination of leaf temperature from meteorological data (Chapter 4). To this end, three field experiments were conducted at two different sites at Cape Peninsula University of Technology (CPUT), Bellville Campus in Cape Town. Leaf temperature was computed using measured meteorological data and the Newton-Raphson iteration method and the estimated leaf temperature was compared with measured leaf temperature from *Ficus microcarpa*, *Strelitzia nicolai* and *Agapanthus praecox* plants. The results indicated this method has the potential to be used as an indirect approach in the determination of leaf temperature, although its accuracy varied among the three types of leaves. If canopy temperature could be determined from weather conditions, then it is more attractive to citrus growers and other growers because of the importance of leaf temperature in the process of dew deposition. Cost of the infra-red thermometer and its installation may not be attractive to citrus growers because it would require the use of other hardware such as dataloggers which are costly. The use of iteration to determine the leaf temperature can be extended to plants such as grapes and citrus and can also be used to predict moderate to severe plant water stress in citrus and other plants such as grapevines.

Growers of high value crops should be encouraged to set up or use available decision support systems such as a disease early warning system as the benefits of operating such systems have the potential to outweigh the costs of setting it up. Growers stand to lose more money from a disease outbreak causing reduced yield or lower the grade of quality of crop, than they might gain from saving a few pesticides by using a warning system. However, before setting up a disease warning system, the user should be aware of the limitations of either “do it yourself” or the use of LWD data which is produced by another user. It is therefore recommended that in setting up a disease warning system there are a number of factors that need to be considered. Firstly if the grower can afford to an automatic weather station on their farm, they should consult, seek advice and guidance from experts in the area.

The expertise in setting up such automatic weather stations can be obtained from meteorological services and extension workers or other technical experts. While the installation of other sensors

is not problematic, it is the wetness sensor that requires special attention. The placement of these within a canopy is crucial because of its high variability within a canopy, for the successful implementation of any disease warning system. If the calibration of the sensors is to be based on visual observation, there is a need to establish the number of leaf samples needed to obtain a representation of the field and also determine the wet/dry threshold. Consequently, the user should collect information about the crop and pathogens, cultivation and environmental conditions by interacting with various agents such as extension workers, agrometeorologists, plant pathologist, researchers, technicians and other experts who can advise on different aspects that are required to produce a reliable decision support system. The sensors would require routine regularly scheduled maintenance and error check to ensure high quality of the data to be collected.

If the grower cannot afford to set up his/her own weather station in the field, modelling offers a viable option especially if the data comes from a weather station operated by the meteorological services. Models usually require calibration and some of the models especially physical ones may require inputs that are not usually measured in a standard weather station. However there a major setback if the user is not operating his/her own weather station could be a delay in the routine availability of the input data, would also delay the operation of a disease warning system. For growers already operating disease warning system, they should keep on refining their systems. Alternatively, they can run a more sophisticated system in the background and compare it against their current system. Disease warning systems highlight the need for different expertise such as plant pathologists, agrometeorologists, researchers meteorologists, technicians and computer experts to be able to formulate a dependable disease warning system. However, such a decision support systems need to be packaged in format that fits the growers. SA citrus growers should consider the use of disease control tools such as prediction instead of depending on calendar spray schedule. The use of such models can result in reduced disease, large increases in fruit production and the elimination of unnecessary spray.

A future project could be to develop a special spatial model to integrate the leaves and calculate risk associated with them being wet. Another possible area of research is the development of an

early warning dew formation system based on standard meteorological parameters. Such a system may alert the grower the probability of dew formation that night based on forecasted weather parameters at a particular time before the actual dew formation. If such a system can be successfully developed, it can then be integrated into a disease warning system and will give growers a lead time to plan their spraying activities if necessary. Growers could be alerted by mobile phones, as a similar system is currently being implemented in SA to alert farmers about frost.

Dew condensation is also relevant to other industries. The effects of condensation can be problematic for the food industry, spray painting, medical and construction industries, as well as fogging in greenhouses. It is important that the stakeholders should take the necessary precautions so that the condensed moisture does not affect the quality of their products. In the food industry, previously refrigerated food such as milk or fruit left outside causes moisture to deposit on the outside of the container. Moisture that accumulates on the container may affect the quality and labelling on the container which may adversely affect the marketing of the product. Moisture may also be deposited on the surface of objects such as metal, which may cause spray painting not to be as efficient. This can cause the metal surface to be affected by rust. In the construction industry, moisture condensing on ceilings, walls, pipes and other kinds of installation produces a poor often unhealthy indoor climate, and is the main cause of rust, moulds and corrosion which decrease the lifetime of such products.

In the medical field, condensation on the inside lid of culture containers including petri dishes is a universal problem in a plant tissue culture laboratory (Finer and Finer, 2007). Condensation on the lids of petri dishes used to culture plant tissues often obscure the view of the contents of the dish and interfere with data collection. This occurs when the temperature of the inside lid or walls falls below the temperature inside the container itself and results in condensation that can take the form of either a light fog or large water droplets. When large droplets form, they can drop from the lid onto the contents of the container, displacing the contents and creating water soaked environment. Although light condensation can be somewhat frustrating for casual viewing of the contents of a petri dish, this same level of condensation can completely disrupt abilities to perform image analysis of the contents of a sealed petri dish over time. In this case,

condensation can be reduced or eliminated through modifications in shelf design. In cases where constant temperature is not required, circulation of heated air over the tops of the culture containers or forcing cool air underneath the containers can effectively keep the lid temperature above the container temperature, eliminating condensation problems.

Therefore, leaf wetness studies such as this one using a range of different methods (measurements, computing and modelling) could be usefully extended to industries other than the agricultural and horticultural sectors. In some such industries, condensation could be critical as a make or break factor in success of a certain project. Therefore these types of studies should be applied to provide such industrial situation with a problem solving and monitoring service, as there are many applications of research around the world.

References

- Acock, B., 2002. Methods of measuring leaf temperature. Symposium on the Techniques of Experimentation in Greenhouses. ISHS, Acta Hort. 7, 74-78
- Agam, N., Berliner, P., 2006. Dew formation and water vapor adsorption in semi-arid Environments - a review. J. Arid Environ. 65 (4), 572-590
- Anderson, M., Norman, J., Meyers, T., Diak, G., 2000. An analytical model for estimating canopy transpiration and carbon assimilation fluxes based on canopy light-use efficiency. Agric. For. Meteorol. 101, 265-289
- Anonymous, 1990. Conclusions and recommendations of the joint WMO/EPPO/NAPPO Symposium on Practical Applications of Agrometeorology in Plant Protection. EPPO Bull. 21, 699-700
- Armstrong, R., Bartkur, N.N., Norris, E., 1993. A comparative study of three leaf wetness sensors. Int. J. Biometeorol. 37, 7-10
- ARC-ISCW., 2013. Agricultural Research Council, Institute for Soil Climate and Water database. Pretoria, South Africa
- Aylor, D.E., 1986. A framework for examining inter-regional aerial transport of fungal spores. Agric. For. Meteorol. 38, 263-288
- Bailley, B.J., 1985. Microclimate, physical processes and greenhouse technology. Acta Hort. 174, 35-42
- Ballester, C., Jimenez-Bello, M.A., Castel, J.R., Intrigliolo, D.S., 2013. Usefulness of thermography for plant water stress detection in citrus and persimmon trees. Agric. For. Meteorol. 168, 120-129
- Batzer, J.C., Gleason, M.L., Taylor, S.E., Koehler, K.J., Montero, J., 2008. Spatial heterogeneity of leaf wetness duration in apple trees and its influence on performance of a warning system for sooty blotch and flyspeck. Plant Dis. 92, 164-170
- Bereford, W.R., Henshall, R.M., 1998. Field performance of wetness sensors used in apple scab forecasting. ICPP. Paper no 3.2.2
- Beysens, D., 1995. The formation of dew. Atmos. Res. 39, 215-237
- Beysens, D., Muselli, M., Nikolayev, V., Narhe, R., Milimouk, I., 2005. Measurement and modelling of dew in island, coastal and alpine areas. Atmos. Res. 73, 1-22

- Bhatia, A., Roberts, P.D., Timmer, L.W., 2003. Evaluation of the Alter-Rater model for timing of fungicide applications for the control of *Alternaria* brown spot of citrus. *Plant Dis.* 87, 1089-1093
- Boucher, J.F., Munson, A., Bernier, P., 1995. Foliar absorption of dew influences shoot water potential and root growth in *Pinus strobus* seedlings. *Tree Physiol.* 15(12), 819-823
- Brotzge, J.A., Duchon, C.E., 2000. A field comparison of a domeless net radiometer, two four-component net radiometers and a domed net radiometer. *J. Atmos. Oceanic Technol.* 17, 1569-1581
- Brutsaert, W., 1982. *Evaporation into the Atmosphere: Theory, History and Applications.* Riedel, Dordrecht
- Burrage, S.W., 1977. Dew on wheat. *Agric. Meteorol.* 10, 3-12
- Campbell Scientific., 1988. Model 237 leaf wetness sensor. Logan, Utah. pp 1-8
- Camargo, A., Sentelhas, P.C., 1997. Performance evaluation of different potential evapotranspiration estimating methods in the state of Sao Paulo, Brazil. *Braz. J. Agrometeorol.* 5, 89-97
- Carstens, E., Le Roux, H.F., Holtzhausen, M.A., Van Rooyen, L., Coetzee, J., Wentzel, R., Laubscher, W., Dawood, Z., Venter, E., Schutte, G., Fourie, P.H., Hattingh, V., 2012. Citrus black spot is absent in Western Cape, Northern Cape and Free State provinces. *S. Afr. J. Sci.* 108 (7/8), 876-882
- Challa, H., Bot, G.P.A., Nederhoff, E.M., Van de Braak, N.J., 1988. Greenhouse climate control in the nineties. *Acta Hort.* 230, 459-470
- Christian, R.S.C., Pria, M.D., Jesus, W.C, Amorin, L., Filho, A.B., 2009. Modelling the process of Asiatic citrus canker on Tahiti lime in relation to temperature and leaf wetness. *Europ. Plant Pathol.* 124, 1-7
- Clothier, B.E., Clawson, K.L., Pinter P.J., Moran, M.S., Rejinato, R.J., Jackson, R.D., 1986. Estimation of soil heat flux from radiation during the growth of alfalfa. *Agric. For. Meteorol.* 37, 319-329
- Cosh, M.H., Kabelo, E.R., Hornbuckle, B., Gleason, M.L., Jackson, T.J., Prueger, J.H., 2009. Observations of dew amount using in situ and satellite measurements in an agricultural landscape. *Agric. For. Meteorol.* 149, 1082-1086

- Crowe, J.M., Coakley, S.M., Emge, R.C., 1978. Forecasting dew duration at Pendleton, Oregon using simple weather observations. *J. Appl. Meteorol.* 17, 1482-1487
- Dalla Marta, A., Magarey, R.D., Orlandini, S., 2005. Modelling surface wetness duration and downy mildew simulation on grapevine in Italy. *Agric. For. Meteorol.* 132, 84-89
- Dalla Marta, A., Magarey, R.D., Martinelli, L., Orlandini, S., 2007. Leaf wetness in sunflower (*Helianthus annuus*): Analysis of observations, measurements and simulations. *Europ. J. Agron.* 26, 310-316
- Dalla Marta, A., Martinelli L., Orlandini, S., 2008. Leaf wetness spatial variability within a grapevine canopy. *Am. J. Enol. Vitic.* 59 (1), 78-82
- Dalla Marta, A., Orlandini, S., Ghironi, M., Sabatini, F., 2004. Influence of different sensor positions on leaf wetness measurements and their effect on the simulation of grapevine downy mildew (*Plasmopara viticola*). *Idoj.* 108, 253-263
- Davie, T., 2003. *Fundamentals of Hydrology*. Routledge, London
- Davis, D.R., Hughes, J.E., 1970. A new approach to record the wetting parameter by the use of electrical resistance sensors. *Plant Dis. Rep.* 54, 474-479
- Decagon Devices, 2007. *Dielectric leaf wetness sensor operator's manual*. Pullman, Washington. USA. pp 1-14
- Department of Agriculture, Forestry and Fisheries, 2011. *A profile of the South African citrus market value chain*. Arcadia, South Africa
- Ede, A.J., 1967. *An Introduction to Heat Transfer Principles and Calculations*. Pergamon Press, London. pp 287
- Finer, J.E., Finer, J.J., 2007. A simple method for reducing moisture condensation on Petri dish lids. *Plant Cel. Org. Cul.* 91, 299-304
- Fourie, P., Schutte, T., Serfontein, S., Swart, F., 2013. Modelling the effect of temperature and wetness on *Guignardia Pseudothecium* maturation and Ascospore release in citrus orchards. *Phytopathol.* 103 (3), 281-292
- Francl, L.J., Panigrahi, S., 1997. Artificial neural network models of wheat leaf wetness. *Agric. For. Meteorol.* 88, 57-65
- Fuchs, M., Tanner, C.B., 1966. Infrared thermometry of vegetation. *Agron. J.* 58, 597-601

- Gale, A., Manes, A., Poljakoff-Mayerber, A., 1970. A rapidly equilibrating thermocouple contact thermometer for measurement of leaf-surface temperatures. *Ecol.* 51 (3), 521-525
- Garratt, J.R., Segal, M., 1988. On the contribution of atmospheric moisture to dew formation. *Boundary layer. Meteorol.* 45, 209-236
- Gates, D.M., 1980. *Biophysical Ecology*. Springer, New York. pp 611
- Gates, D.M., Tibbals, E.C., Kreith, F., 1965. Radiation and convection for *ponderous* pine. *Am. J. Bot.* 52 (1), 66-71
- García-Tejero, I.F., Durán-Zuazo, V.H., Muriel-Fernández, J.L., Jiménez-Bocanegra, J.A., 2011. Linking canopy temperature and trunk diameter fluctuations with other physiological water status tools for water stress management in citrus orchards. *Funct. Plan. Biol.* 38, 106-117
- Getz, R.R., 1992. Report on the measurement of leaf wetness. Report to WMO (Commission for Instruments and Methods of Observation). CAgM No. 38. pp 10
- Gianessi, L., Williams, A., 2012. High-value South African citrus exports rely on fungicides. Crop Protection Research Institute, Washington. pp 1
- Giesler, L.T., Horst, G.L., Yuen, G.Y., 1996. A site-specific sensor for measuring leaf wetness duration within turf grass canopies. *Agric. For. Meteorol.* 81, 145-156
- Gillespie, T.J., Duan, R.X., 1987. A comparison of cylindrical and flat plate sensors for surface wetness duration. *Agric. For. Meteorol.* 40, 61-70
- Gillespie, T.J., Kidd, G.E., 1978. Sensing duration of leaf moisture retention using electrical impedance grids. *Can. J. Plant Sci.* 58, 179-187
- Gleason, M.L., 2001. Environment. In: Maloy, O.C., Murray, T.D. (Eds.), *Encyclopedia of Plant Pathology*. John Wiley & Sons, New York
- Gleason, M.L., Duttweiler, K. B., Batzer, J.C., Taylor, S.E., Sentelhas, P.C., Monteiro, J., Gillespie, T.J., 2008. Obtaining weather data for input to crop disease warning systems: Leaf wetness duration as a case study. *Sci. Agric.* 65, 76-87
- Gleason, M.L., Taylor, S.E., Loughin, T.M., Koehler, K.J., 1994. Development and validation of an empirical model to estimate the duration of dew periods. *Plant Dis.* 78, 1011-1016

- Greenspan, M.D., Matthews, L.E., 1996. On-site vineyard water status from simple and complex canopy models. *Proceedings of Int. Conf. on Evapotranspiration and Irrigation*. pp 650-655
- Griffiths, J.F., 1978. *Applied Climatology, An Introduction*. 2nd Edition. Oxford University Press
- Haasbroek, P.D., 2006. Refinement and improvement of a downy early warning system disease model for the Western Cape. MSc Thesis. University of the Free State, South Africa
- Hahn, F., 2009. Actual pathogen detection: Sensors and algorithms - a review. *Algorith.* 2, 301-338
- Haseba, T., Ito, D., 1982. Leaf temperature in relation to meteorological factors. *Agric. For. Meteorol.* 38(3), 269-277
- Hao, K., Li, C., Guo, B., Ma J., Ayup, M., Chen, Z., 2012. Dew formation and its long-term trend in a desert-riparian forest ecosystem on the eastern edge of the Taklimakan Desert in China. *J. Hydrol.* 472, 90-98
- Henshall, W.R., Beresford, R.M., Chynoweth, R.W., Ramankutty, P., 2005. Comparing surface wetness inside and outside grape canopy for region-wide assessment of plant disease risk. *Fruit Dis. Man.* 58, 80-83
- Heusinkveld, B.N., Berkowicz, S.M., Jacobs, A.F.A., Hillen, W., Holtslag, A.A.M., 2008. A new remote optical wetness sensor and its applications. *Agric. For. Meteorol.* 148, 580-591
- Hirst, J.M., 1954. A method for recording the formation and persistence of water droplets on plant shoots. *Quart. J. Roy. Meteorol. Soc.* 80, 227-231
- Hornbuckle, B., England, A., Anderson, M., 2007. The effect of intercepted precipitation on the microwave emission of maize at 1.4 ghz. *IEEE Trans. Geosci. Remote Sens.* 45 (7), 1988-1994
- Huband, N.D.S., Butler, D.R., 1984. A comparison of wetness sensors for use with computer or microprocessor systems designed for disease forecasting. *Proceedings of the British Crop Protection Conference - Pests and Diseases* 2, 633-638
- Huber, L., Gillespie, T.J., 1992. Modelling leaf wetness in relation to plant disease epidemiology. *Ann. Rev. Phytopath.* 30, 353-577
- Huber, L., Itier, B., 1990. Leaf wetness duration in a field bean canopy. *Agric. For. Meteorol.* 51, 281-92

- Jackson, R.D., Idso, S.B., Reginato, R.J., Pinter, P.J., 1981. Canopy temperature as a crop water stress indicator. *Water Resour. Res.* 17, 1133-1138
- Jackson, T.J., Moy, L., 1999. Dew effects on passive microwave observations of land surfaces. *Rem. Sens. Environ.* 70, 129-137
- Jacobs, A.F.G., Heusinkveld, B.G., Berkowicz, S.M., 2000. Dew measurements along a longitudinal sand dune transect, Negev Desert, Israel. *Int. J. Biometeorol.* 43 (4), 184-190
- Jacobs, A., Heusinkveld, B., Klok, E.J., 2005. Leaf wetness within a lily canopy. *Meteorol. Appl.* 12, 193-198
- Jacobs, A.F.G., Nieveen, J.P., 1995. Formation of dew and the drying process within crop canopies. *Meteorol. Appl.* 2, 249-256
- Jacobs, A.F.G., Van Pul, W.A.J., Van Dijken, A., 1990. Similarity moisture dew profiles within a corn canopy. *J. Appl. Meteorol.* 29, 1300-1306
- Jones, H.G., 1992. *Plants and Microclimate. A Qualitative Approach to Environmental Plant Physiology.* 2nd Edition. Cambridge University Press, New York. pp 9-44
- Kabela, E., Hornbuckle, B., Cosh, M., Anderson, M., Gleason, M., 2009. Dew frequency, duration, amount, and distribution in corn and soybean during smex05. *Agric. For. Meteorol.* 149, 11-24
- Kim, K.S., Taylor, S.E., Gleason, M.L., 2004. Development and validation of a leaf wetness duration sensor using a fuzzy logic system. *Agric. For. Meteorol.* 17, 53-64
- Kim, K.S., Taylor, S.E., Gleason, M.L., Koehler, K.J., 2002. Model to enhance site-specific estimation of leaf wetness duration. *Plant Dis.* 86, 179-185
- Kim, K.S., Taylor, S.E., Gleason, M.L., Nutter, F.W., Coop, L.B., Pfender, W.F., Seem, R.C., Sentelhas, P.C., Gillespie, T.J., Dalla Marta, A., Orlandini, S., 2010. Spatial portability of numerical models of leaf wetness duration based on empirical approaches. *Agric. For. Meteorol.* 150, 871-880
- Kincaid, D., Cheney, W., 1996. *Numerical Analysis: Mathematics of Scientific Computing.* 2nd Edition. Brooks, Pacific Grove, CA
- Kidron, G.J., 1999. Altitude dependent dew and fog in the Negev Desert, Israel. *Agric. For. Meteorol.* 96 (1-3), 1-8

- Kidron, G.J., 2005. Angle and aspect dependent dew and fog precipitation in the Negev desert. *J. Hydrol.* 301 (1-4), 66-74
- Klemm, O., Milford, C., Sutton, M.A., Spindle, G., Van Putten, E., 2002. A climatology of leaf surface wetness. *Theor. Appl. Climatol.* 71, 107-117
- Kotze, J.M., 1981. Epidemiology and control of citrus black spot in South Africa. *Plant Dis.* 65, 945-950
- Kreith, F., Sellers, W.D., 1975. General principles and natural evaporation. In: D.A. de Vries, N.H. Afgan (eds), *Heat and Mass Transfer in the Biosphere*. Scripta Book Company, Washington, D.C. pp 207-227
- Latina, R., Evans, K.J., 1996. Development and delivery of a forecaster for *Alternaria* leaf blight of muskmelon. *Phytopathol.* 86, 106-110
- Lau, Y.N., Gleason, M.L., Zriba, N., Taylor, S.E., Hinz, P.N., 2000. Effects of coating, deployment angle and compass orientation on performance of electronic wetness sensors during dew periods. *Plant Dis.* 84, 192-197
- Lomas, J., Shashoua, Y., 1970. The performance of three types of leaf wetness recorders. *Agric. Meteorol.* 7, 159-166
- Long, I.F., 1958. Some observations on dew. *Meteorol. Mag.* 87, 161-168
- Lulu, J., Sentelhas, P.C., Pedro, M.J., Pezzopane, J.R.M., Blain, G.C., 2008. Spatial variability of wetness duration in a Niagara Rosada vineyard. *Eng. Agric. Jabot.* 28, 104-114
- Luo, W.H., Goudriaan, J., 2000. Dew formation on rice under varying durations of nocturnal radiative loss. *Agric. For. Meteorol.* 104, 303-313
- Madeira, A.C., Kim, K.S., Taylor, S.E., Gleason, M.L., 2002. A simple cloud-based energy balance model to estimate dew. *Agric. For. Meteorol.* 111, 55-63
- Magarey, R.D., 1999. A theoretical standard for surface wetness estimation. Ph.D Thesis. Cornell University, Ithaca, NY
- Magarey, R.D., R.C., Russo, J.M., Seem, R.C., 2006a. Grape canopy surface wetness: Simulation versus visualization and measurement. *Agric. For. Meteorol.* 139, 361-372
- Magarey, R.D., Russo, J.M., Seem, R.C., 2006b. Simulation of surface wetness with a water budget and energy balance approach. *Agric. For. Meteorol.* 139, 373-381

- Magarey, R.D., Russo, J.M., Seem, R.C., Gadoury, D.M., 2004. Surface wetness duration under controlled environmental conditions. *Agric. For. Meteorol.* 128, 111-122
- Magarey, R.D., Seem, R.C., Weiss, A., Gillespie, T., Huber, L., 2005. Estimating surface wetness on plants. *Am. Soc. Agron. Monog.* 47, 199-225
- Magarey, R.D., Seem, R.C., Russo, J.M., Zack, J.W., Waight, K.T., Travis, J.W., Oudemans, P.V., 2001. Site-specific information without on-site sensors. *Plant Dis.* 85(12), 1216-1225
- Mannini, P., Anconelli, S., 2007. Leaf temperature and water stress in strawberry. *Acta Hort.* 345, 55-62
- Masakata, H., Wada, Y., Nemoto, H., 2006. Estimation of drought tolerance based on leaf temperature in Upland Rice breeding. *Breeding Sci.* 56, 47-54
- Miller, P.C., 1971. Sampling to estimate mean leaf temperature and transpiration rates in vegetative canopies. *Ecol.* 52(5), 885-889
- Miranda, R.A.C., Davie, T.D., Cornell, S.E., 2000. A laboratory assessment of wetness sensors for leaf, fruit and trunk surfaces. *Agric. For. Meteorol.* 102, 263-274
- Monteith, J.L., 1957. Dew. *Quart. J. R. Meteorol. Soc.* 83, 322-341
- Monteith, J.L., 1963. Dew: Facts and fallacies. In: A.J. Rutter., F.H. Whetehead (eds), *The Water Relations of Plants*. Wiley, New York. pp 37-56
- Monteith, J.L., Unsworth, M.H., 1990. *Principles of Environmental Physics*. Edward Arnold. London, England. Pp 21-35
- Muselli, M., Beysens, D., Marcillat, J., Milimouk, I., Nilsson, T., Louche, A., 2002. Dew water collector for potable water in Ajaccio (Corsica Island, France). *Atmos. Res.* 64, 297-312
- Nagel, J. F., 1962. On the measurement of dew. *Arch. Meteorol. Geophys. Bioclimatol.* 11, 403-423
- Noffsinger, T., 1965. Survey of techniques for measuring dew. In: A. Waxler (ed), *Humidity and Moisture*. New York, Reinhold. pp. 523-531
- Norman, J.M., 1979. Modelling the complete crop canopy. In: B.J. Barfield., J.F. Gerber (eds), *Modification of the Aerial Environment of Crops*. Am. Soc. Agron. pp 249-277
- Oberhuber, W., Edwards, G.E., 1993. Temperature dependence of the linkage of quantum yield of photosystem II to CO₂ fixation in C₃ and C₄ plants. *Plant Physiol.* 101, 507-510

- Orlandini, S., Giuntoli, A., Moriondo, M., 2001. Agrometeorological and ecophysiological approach to the analysis of grapevine response to downy and powdery mildew infections. *Adv. Hort. Sci.* 15, 92-96
- Pangga, I.B., Hanan, J., Chakraborty, S., 2011. Pathogenic dynamics in a crop canopy and their evolution under changing climate. *Plant Pathol.* 69, 70-81
- Papastamati, K., McCartney, H.A., Van den Bosch., 2004. Modelling leaf wetness duration during the rosette stage of oilseed rape. *Agric. For. Meteorol.* 123, 69-78
- Pedro, M.J., 1980. Relation of leaf surface wetness duration to meteorological parameters. Ph.D. Thesis. University of Guelph, Ontario, Canada
- Pedro, M.J., Gillespie, T.J., 1982a. Estimating dew duration. I. Utilizing micrometeorological data. *Agric. Meteorol.* 25, 283-296
- Pedro, M.J., Gillespie, T.J., 1982b. Estimating dew duration. II. Utilizing standard weather station data. *Agric. Meteorol.* 25, 297-310
- Penrose, L.J., Nicol, H.J., 1996. Aspects of microclimate variation within apple tree canopies and between sites in relation to potential *Venturia inequalis* infection. *J. Crop Hort. Sci.* 24, 259-266
- Pitblado, R. E., 1988. The development of a weather-timed fungicide spray program for field tomatoes. *Can. J. Plant Pathol.* 10, 371-280
- Potratz, K.J., Gleason, M.L., Hockmuth, M.L., Parker, S.K., Pearston, G.A., 1994. Testing the accuracy and precision of wetness sensors in a tomato field and on turf grass. *J. Iowa Acad. Sci.* 101, 56-60
- Priestley, C., Taylor, R., 1972. On assessment of surface heat flux and evaporation using large-scale parameters. *Mon. Weath. Rev.* 100, 81-92
- Qin, Z., Berliner, P., Karnieli, A., 2002. Numerical solution of a complete surface energy balance model for simulation of heat fluxes and surface temperature under bare soil. *Appl. Math. Comput.* 130, 171-200
- Rao, R.S., Gillespie, T.J., Schaafsma, A.W., 1998. Estimating wetness duration on maize ears from meteorological observations. *Can. J. Soil Sci.* 78, 149-154
- Richards, K., 2009. Adaptation of a leaf wetness model to estimate dewfall amount on a roof surface. *Agric. For. Meteorol.* 149, 1377-1383

- Rizzo, D, M., Mouser, P, J., Whitney, D.H., Mark, C.D., Magarey, R.D., Voinov, A.A., 2006. The comparison of four dynamic system-based software packages: Translation and sensitivity analysis. *Environ. Mod. Soft.* 12, 1491-1502
- Royle, D.J., Butler, D.R., 1986. Epidemiological significance of liquid water in crop canopies and its role in disease forecasting. In: P.G. Ayres, L. Boddy (eds), *Water, Fungi and Plants*. Cambridge University Press, Cambridge. pp 139-156
- Sachs, R.M., 1991. Stress-adapted landscapes save water, escape injury in drought. *Cal. Agric.* 45 (6), 19-21
- Sadler, E.J., 1996. Considerations for determining leaf wetness using infra-red thermometry in humid regions. Proceeding 12th Conference on Biometeorology and Aerobiology. J. 3, 6-7. American Meteorology Society, Boston, MA
- Santos, E.A., Sentelhas, P.C., Pezzopane, J.M., Angelocci, R., Monteiro, J., 2008. Spatial variability of leaf of leaf wetness duration in cotton, coffee and banana crop canopies. *Sci. Agric.* 65, 18-25
- Santillán-Núñez, V.N., 2009. Spatial variability of leaf wetness duration within a citrus canopy. MSc Thesis. University of Florida, Florida
- Savage, M.J., 2012. Estimation of leaf wetness duration for short-grass surface. *South African J. Plant and Soil.* 29, 183-189
- Schmitz, H.F., Grant, R.H., 2009. Precipitation and dew in soyabean canopy: Spatial variations of leaf wetness and implications for *Phakopsora pachyrhizi*. *Agric. For. Meteorol.* 149, 1621-1627
- Scherm, H., Van Bruggen, A.H.C., 1993. Sensitivity of simulated dew duration to meteorological variations in different climatic regions of California. *Agric. For. Meteorol.* 66, 229-245
- Schneebeil, M., Wolf, D, Kunert, N., Eugester, W., Matzler, C., 2011. Relating the x-band opacity of a tree canopy to a sapflow, rain interception and dew formation. *Rem. Sens. Environ.* 115, 2116-2125
- Seem, R.C., Magarey, R.D., Zack, J.W., Russo, J.M., 2000. Estimating disease risk at the whole plant level with general circulation models. *Environ. Pollut.* 108, 389-395

- Sentelhas, P.C., Dalla Marta, A., Gillespie, T.J., Orlandini, S., Santos, E.A., Gillespie, T.J., Gleason, M.L., 2008. Suitability of relative humidity as an estimator of leaf wetness duration. *Agric. For. Meteorol.* 148, 392-400
- Sentelhas, P.C., Gillespie, T.J., Batzer, J.C., Gleason, M.L., Monteiro, J., Pezzopane, J.R., Pedro, M.J., 2005. Spatial variability of leaf wetness duration in different crop canopies. *Int. J. Biometeorol.* 49, 363-370
- Sentelhas, P.C., Gillespie, T.J., Gleason, M.L., Monteiro, J., Helland, S.T., 2004a. Operational exposure of leaf sensors. *Agric. For. Meteorol.* 126, 59-72
- Sentelhas, P.C., Monteiro, J., Gillespie, T.J., 2004b. Electronic leaf wetness duration sensor: Why it should be painted. *Int. J. Biometeorol.* 48, 202-205
- Shaw, R.H., 1973. Dew duration in central Iowa. *Iowa State J. Res.* 47, 219-227
- Sirjusingh, C., Sutton J.C., 1996. Effects of wetness duration and temperature on infection of Geranium by *Botrytis cinerea*. *Plant Dis.* 80, 160-165
- Slatyer, R.O., 1967. Plant water relationships. Academic Press. pp 378
- Smart, R.E., Robinson, M.D., 1991. Sunlight into Wine: A Handbook for Winegrape Canopy Management. Hyde Park Press, Adelaide, South Australia. pp 88
- Smith, L.P., 1958. The duration of surface wetness. *Proc. Int. Hort. Congr.* 15, 478-484.
- Soil Classification Working Group, 1991. Soil Classification: A Taxonomic System for South Africa. Department of Agricultural Development, Pretoria
- Sutton, J.C., Gillespie, T.J., Hilderbrand, P.D., 1984. Monitoring weather factors in relation to plant disease. *Plant Dis.* 68, 78-84
- Taylor, S., 1975. Optimal leaf form. In: D.M Gates, R.B. Schmerl (eds), In Perspectives of Biophysical Ecology. Springer, New York. pp 73-86
- Tanner, C.B., Fuchs, M., 1968. Evaporation from unsaturated surfaces: A generalized combination method. *J. Geophys. Res.* 73, 1299-1304
- Timmer, L.W., Darhower, H.M., Bhatia, A., 2001. The Alter-Rater, A new based weather-based model for timing fungicide sprays for *Alternaria* control. Publication No. SP-175. University of Florida, Gainesville, Florida
- Timmer, L.W., Zitko, S.E., 1996. Evaluation of a model for prediction of postbloom fruit drop of citrus. *Plant Dis.* 80, 380-383

- Truter, M., 2010. Epidemiology of citrus black spot in South Africa and its impact on phytosanitary trade restrictions. Ph.D Thesis. University of Pretoria, South Africa
- Van Jaarsveld, J.A., 1995. Modelling the long-term atmospheric behaviour of pollutants on various spatial scales. Ph.D Thesis, Utrecht University, Netherlands
- Vincent, A., Garcia-Jimenez, J., 2008. Risk of establishment of non-indigenous diseases of citrus fruit and foliage in Spain: An approach using meteorological databases and tree canopy climate data. *Phytoparasit.* 36(1), 7-19
- Wallin, J.R., 1963. Dew, its significance and measurement in phytopathology. *Phytopathol.* 53, 1210-1216
- Wallin, J.R., 1967. Agricultural aspects of dew. *Agric. Meteorol.* 4, 85-102
- Wei, Y.Q., Bailey, B.J., Stenning, B.C., 1995. A wetness sensor for detecting condensation on tomato plants in a greenhouse. *J. Agric. Eng. Res.* 61, 197-204
- Wichink Kruit, R.J., Jacobs, A.F.G., Heusinkveld, B.G., 2004. Comparison of four methods to estimate leaf wetness duration caused by dew on grasslands. In: Conference on Agricultural and Forestry Meteorology, American Meteorological Society, Vancouver
- Wichink Kruit, R.J., Jacobs, A.F.G., Holstlag, A.A.M., 2008. Measurements and estimates of leaf wetness over grassland for dry deposition modeling of trace gases. *Atmos. Environ.* 42, 5304-5316
- Wilks, D.S., 1995. *Statistical Methods in the Atmospheric Sciences*. Academic Press, New York, pp 467
- Willmott, C.J., Ackleson, S.G., Davis, R.E., Feddeme, J.J., Klink, K.M., Legates, D.R., O'donnell, J., Rowe, C.M. 1985. Statistics for the evaluation and comparisons of models. *J. Geophys. Res.* 90, 8995-9005
- Wittich, K.P., 1995. Some remarks on dew duration on top of an orchard. *Agric. For. Meteorol.* 72, 167-180
- Yang, X., Short, T.H., Fox, R.D., Bauerle, W.L., 1990. Transpiration, leaf temperature and stomatal resistance of a greenhouse cucumber crop. *Agric. For. Meteorol.* 51, 197-209
- Ye, Y.H., Zhou, K., Song, S.J., Jin, J. H., Peng, S.L., 2007. Dew amounts and its correlations with meteorological factors in urban landscapes of Guangzhou, China. *Atmos. Res.* 86, 21-29

- Zangvil, A., 1996. Six years of dew observations in the Negev Desert, Israel. *J. Arid. Environ.* 32, 361-371
- Zarco-Tejada, P., Gonzalez-Dugo, V., Berni, J.A.J., 2012. Fluorescence, temperature and narrow-band indices acquired from a UAV platform for water stress detection using a micro-hyperspectral imager and a thermal camera. *Rem. Sens. Environ.* 117, 322-337
- Zhang, Y., Gillespie, T.J., 1990. Estimating maximum droplet wetness duration on crops from nearby weather station data. *Agric. For. Meteorol.* 51, 145-158
- Zhuang, Y.L., Ratcliffe, S., 2012. Relationship between dew presence and *Bassia dasyphylla* plant growth. *J. Arid Lands.* 4 (1), 11-18