

**Web-based teaching, learning and research using real-time data from field-
based agrometeorological measurement systems**

by

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Preface

The research contained in this dissertation was completed by the candidate while based in the Soil-Plant-Atmosphere Continuum Research Unit, Discipline of Agrometeorology, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The research was financially supported by the University of KwaZulu-Natal Teaching and Learning Office and the (ex) Faculty of Science and Agriculture, Water Research Commission, and the National Research Foundation.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

Signed: CS Everson

Date: 31st January 2014

Declaration 1: Plagiarism

I, Michael John Savage, declare that:

- (i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;
- (ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;
- (iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;
- (iv) this dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
 - a) their words have been re-written but the general information attributed to them has been referenced;
 - b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;
- (v) where I have used material for which publications followed, I have indicated in detail my role in the work;
- (vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

(vii) this dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

Signed: MJ Savage

Date: 31st January 2014

Declaration 2: Publications/conference contributions/awards

The Abstracts, published papers and press releases emanating from this work appear in the Supplementary materials (pages SM1 to SM43). The * indicates corresponding author.

Chapter 2

1. Grant BR, Savage MJ* 2013. Estimation of sunshine duration from solar irradiance measurements for implementation into a Web-based environmental monitoring system. Paper presentation to Combined Congress 2013, South African Society for Horticultural Sciences, Weed Science Society, Crop Production Society and Soil Science Society of South Africa, 21st to 24th Jan, 2013, Durban, South Africa. Presented by MJ Savage.
2. Kaptein ND, Savage MJ* 2013. A Web-based microclimatic measurement and evaporative cooling control system in a forestry nursery. Paper presentation to Combined Congress 2013, South African Society for Horticultural Sciences, Weed Science Society, Crop Production Society and Soil Science Society of South Africa, 21st to 24th Jan, 2013, Durban, South Africa. Presented by ND Kaptein.
3. Savage MJ*, Abraha MG, Moyo NC, Babikir ESN 2012. Web-based teaching and learning early-warning system for real-time data and information for the agricultural, earth and environmental sciences. Sixth Annual University Teaching & Learning Conference, UKZN, Durban, South Africa, 25th to 27th September 2012. Presented by MJ Savage.
4. Savage MJ*, Abraha MG, Moyo NC, Babikir ESN 2013. Web-based system for near real-time agrometeorological applications. Paper presentation to Combined Congress 2013, South African Society for Horticultural Sciences, Weed Science Society, Crop Production Society and Soil Science Society of South Africa, 21st to 24th Jan, 2013, Durban, South Africa. Presented by MJ Savage.
5. Savage MJ*, Abraha MG, Moyo NC, Babikir ESN 2014. Web-based teaching, learning and research using accessible real-time data obtained from field-based agrometeorological measurement systems. *South African Journal of Plant and Soil*. In press.
6. Savage MJ 2013. Air temperature measurement errors. Paper presentation to the South African Society of Atmospheric Sciences Conference 2013, 26th to 27th Sept, 2013, Durban, South Africa. Paper presented by MJ Savage.
7. Strydom S, Savage MJ* 2013. A near real-time fire danger index measurement system. Paper presentation to South African Society of Atmospheric Sciences Conference 2013, 26th to 27th Sept, 2013, Durban, South Africa. Paper presented by S Strydom.
8. Award of the Board Floating Trophy for the Best Paper Presentation at Combined Congress 2013 (Durban, South Africa) of the Horticultural Society of Southern Africa, South African Crop Production Society, Soil Science Society of Southern Africa and the Weed Science Society of Southern Africa.

The paper (2014, in press) and conference paper presentations stem from the Web-based data and information system established at the Agrometeorology Instrumentation Mast (AIM) grassland site, Agrometeorology site, University of KwaZulu-Natal. I was responsible for the work, collected and analysed data, wrote the paper, developed slide shows, wrote the abstracts and presented the papers apart from that by BR Grant, ND Kaptein and S Strydom (honours students). Dr MG Abraha, Mr NC Moyo and Dr ENS Babikir, Agrometeorology Discipline, were instrumental in setting up Masts 1 and 2 and the radio of Mast 1 including installation of net radiometers, soil temperature and soil heat flux instrumentation. Mr Moyo assisted with the datalogger network wiring for serial communication between the different dataloggers.

Chapter 3

9. Savage MJ 2012. Estimation of frost occurrence and duration of frost for a short-grass surface. *South African Journal of Plant and Soil* 29, 173–181.
10. The paper, based on Chapter 3, was judged the best published paper in the South African Journal of Plant and Soil. The award was by the Board of the South African Society of Crop Production at the 2014 Combined Congress of Soil Science, Crop Science, Horticultural Science and Weed Science Societies in Grahamstown, South Africa.

This paper is an analysis of data collected at Mast 1 of the AIM system. I designed the experiment and collected and analysed the data and wrote the paper.

Chapter 4

11. Savage MJ 2012. Estimation of leaf wetness duration for a short-grass surface. *South African Journal of Plant and Soil* 29, 183–189.

This paper is an analysis of data collected at Mast 1 of the AIM system. I designed the experiment and collected and analysed the data and wrote the paper.

Chapter 6

12. Savage MJ 2012. Web-based near real-time surface energy balance for short grass using surface renewal, temperature variance and dissipation theory. Poster presentation to ASA, CSSA and SSSA Annual Meetings (Cincinnati, Ohio, USA, 21st to 24th October, 2012).

This is an analysis of data collected at Masts 1 and 2. I designed the experiment, wrote the datalogger program, maintained sensors, collected and analysed the data and wrote the poster.

Signed: MJ Savage

Date: 31st January 2014

Acknowledgements

A number of special acknowledgements deserve specific mention:

Meryl A Savage, my wife, for her support;

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Professor Colin S Everson of the UKZN for supervision;

the Agrometeorology 210 and 212 undergraduate students of 2011 to 2013, that were used as "guinea pigs", for testing and evaluation of the system in their lectures, practicals, tutorials and projects;

the Geography honours students that I supervised, Bryan Grant (sunshine duration), David Kaptein (measurement and control of an evaporative cooling system in a shadenet nursery) and Sheldon Strydom (fire danger), for which the Web-based system was used to generate new ideas and display of data and information;

the anonymous reviewers of the published papers (Chapters 2, 3 and 4) and conference abstract and extended abstracts and peer-reviewed conference proceedings stemming from this work;

the various agencies for funding and in particular the UKZN Teaching and Learning Office, Water Research Commission, and the National Research Foundation;

staff from the UKZN: Mr Guy M Dewar (Electronics Centre) and Mr Kamenthren Govender (Technical Manager, School of Agricultural, Earth and Environmental Sciences).

Chapter 2 (Web-based teaching, learning and research using accessible real-time data obtained from field-based agrometeorological measurement systems)

Funding from the UKZN Teaching and Learning Office, the UKZN College of Agriculture,

Engineering and Science, the South African National Research Foundation is gratefully acknowledged. The Water Research Commission is also acknowledged for previously funding equipment used in this project. We also acknowledge the administrative and technical support of Jothi Manickum (ex Agrometeorology Discipline, UKZN), electronic support of Guy Dewar (Electronics Centre, UKZN) for construction of the various electronics items used and his advice at important stages of the project, the support of the hundreds of UKZN students and in particular the AMET211_212 classes of 2011-2013, the AMET210 classes of 2012-13 and honours students Nkosinathi (David) Kaptein, Bryan Grant and Sheldon Strydom who used the system in the preliminary stages of development, the staff of Goodweld Engineering for their patience and expertise in the manufacture of the stands and masts used, the late Martin Voges (Information and Communication Services Division (ICS), UKZN), for writing the html script for toggling the various data and information Internet screens on a remote PC and Dale Peters (ICS, UKZN) for her early comments and suggestions on our project proposal and Meryl Savage for assistance with administrative tasks.

Chapter 3 (Estimation of leaf wetness duration for a short-grass surface)

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Chapter 4 (Estimation of frost duration for a short-grass surface)

Funding from UKZN (Teaching and Learning Office, College of Agriculture, Engineering and Science and Research Office) and South African National Research Foundation is gratefully acknowledged. The Water Research Commission is also acknowledged for previously funding equipment used. Administrative and technical support of Jothi Manickum and technical support of Dr Michael G Abraha, Nicholas C Moyo and Dr Eltayeb SN Babikir (Agrometeorology Discipline, UKZN) and electronic support of Guy Dewar (Electronics Centre) and the support of the UKZN AMET212 students of 2011 is also acknowledged.

Chapter 5 (Nowcasting of grass-surface, grass and air temperature minima based on sub-hourly pre-dawn measurements)

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Chapter 6 (Web-based near real-time surface energy balance for short grass using surface renewal, temperature variance and dissipation theory)

Financial support from the UKZN Teaching and Learning Office, NRF and WRC is acknowledged. Assistance in this and the maize study was provided by Dr Michael G Abraha and Mr Nicholas C Moyo.

Genesis 1: 1 In the beginning God created the heaven and the earth. And the earth was without form, and void; and darkness was upon the face of the deep. And the Spirit of God moved upon the face of the waters.

Abstract

Agrometeorology is a difficult subject for undergraduate students to relate to initially since most have never met many of the important concepts before. Furthermore, many students studying introductory agrometeorology have a mother tongue for which the words "meteorology" and "agrometeorology", for example, do not exist. In general, university students have a poor conception of the environment and of climate change, poor numeracy ability, and poor interpretation of graphical data representing the agro-environment and limited ability of statistically manipulating large data sets. Often, this is due to a lack of exposure to such data. A Web-based teaching, learning and research system was therefore developed for near real-time agrometeorological and environmental applications, data visualisation, visual literacy and to serve as a data resource for various disciplines. The main station, five inter-connected datalogger stations including three masts formed the basis for the system and was set up at the Agrometeorology site (altitude 684 m, latitude 29.628° S, longitude 30.403° E) on the Pietermaritzburg campus of the University of KwaZulu-Natal, KwaZulu-Natal, South Africa.

The Web-based system displays sub-hourly data, predominantly agrometeorological data, encompassing the agricultural and environmental sciences. The displayed data, updated every ten minutes, are in the form of tables and graphs. Field-based measurement systems included automatic weather station (AWS) sensors with additional solar radiation sensors (including an adjustable shadow band for diffuse irradiance), a closed-path carbon dioxide and water vapour analyser, four- and two-component net radiometers, leaf wetness and soil water content sensors, and an infrared thermometer. For short-grass reference evaporation (ET_o), energy balance and radiation balance components were either measured or calculated and displayed in near real-time. Carbon dioxide and water vapour concentrations were also displayed. Measurements included air temperature profile data for every 1-m to a height of 8 m and included AWS measurements in a forestry nursery, and spatial and temporal measurements in a misted and evaporatively cooled polycarbonate greenhouse. Fire danger index, frost duration, human comfort heat and wind chill indices, leaf wetness duration, soil water content and sunshine duration were displayed in various information screens (<http://agromet.ukzn.ac.za:5355>) and updated every ten minutes. The system also included an air temperature measurement comparison station as well as a solar irradiance measurement comparison station.

The main aim of the research was the development of the Web-based system for selected near real-time agrometeorological applications and also included environmental applications mainly for use by undergraduate and postgraduate Agriculture, Human Sciences

and Science students. This aim included the development, testing and evaluation of use of the Web-based teaching, learning and research early-warning system for selected agrometeorological applications, data visualization, visual literacy, and the development of a real-time agricultural, earth and environmental sciences data and information system that allowed students to access a real-time measurement system using the Internet – via a LAN connection, Bluetooth or Web-enabled cell phone. The system displayed graphics of real-time and recent weather data, but not exclusively so, using near real-time applications appropriate for second-year to research students. For example, applications included: 1. estimation of leaf wetness duration for a short-grass surface; 2. estimation of frost duration; 3. nowcasting of grass-surface, grass and air temperature minima based on sub-hourly pre-dawn temperature measurements; 4. surface energy balance using surface renewal, temperature variance and dissipation theory; 5. measurement of forestry nursery microclimate, and control of evaporative cooling sprinklers; 6. the spatial and temporal variations of the microclimate of a misted polycarbonate greenhouse; 7. fire danger index; 8. sunshine duration.

The Web-based system was useful for demonstrating, to under- and postgraduates, different agrometeorological and environmental applications and served as a data resource. In a questionnaire for which there were 63 respondents out of a potential total of 95, more than 80 % indicated that use of the system had improved their appreciation of the ranges of the various weather elements. More than 60 % of the respondents indicated that they benefited from use of the system, that they had improved their ability to manipulate data in a spreadsheet and/or display data in graphic or table form, improved their appreciation/awareness of global climate change and/or global warming aspects and improved their appreciation/awareness of the graphical display, and trends, of agro-environmental and environmental data. In a subsequent questionnaire (79 respondents), 89 % indicated that the system had improved their appreciation of ranges. More than 75 % of the respondents indicated that the graphical display of data had enabled further understanding of the agro-environmental concepts irrespective of language. There is an urgent need to create a list of isiZulu technical terms specific to Agrometeorology and allied disciplines.

To increase the value of AWS measurements, AWS systems should include grass temperature using an exposed temperature sensor for frost determination and possibly also to estimate leaf wetness duration if relative humidity measurements are available. Furthermore, timeous email and SMS alerts with near real-time sub-hourly data and graphics of leaf wetness duration for the current day, week and month displayed on the Internet, as used in this investigation, would considerably enhance the data product. Dielectric leaf wetness sensors and a grass minimum thermometer were used for frost and leaf wetness duration. The leaf wetness sensor method was consistent for determining leaf wetness duration. The leaf wetness sensor method for determining frost was problematic, while the grass- and/or infrared

thermometer temperature methods proved more desirable for frost duration estimation. Both leaf wetness duration and frost duration data were displayed in near real-time using the Web-based system.

The applicability of sunset to sunrise exponential and square root diurnal temperature models, the former inverted so as to nowcast minimum air temperature from sub-hourly air temperature measurements, was investigated. The models were also applied using grass temperature data from an exposed temperature sensor and to grass-surface temperature data from an infrared thermometer. The relative accuracy of the four temperature model methods tested was investigated using historic data from selected locations in South Africa and the USA at different altitudes and different data frequencies. The Web-based system, employing the various models using real-time temperature measurements, was used to display the results.

Shortened surface energy balance components were measured in near real-time using surface renewal, temperature variance, and surface renewal-dissipation theory micrometeorological methods. For surface renewal, a real-time iterative procedure was used. Net irradiance and soil heat flux measurements and the surface renewal sensible heat flux were used to determine evaporation for the short-grass surface in near real-time.

The Web-based system has proved to be a useful resource for teaching, learning and research, and a vehicle for reporting in an open system many agro-environmental measurements, and in particular, adverse weather in near real-time. From an agrometeorological point of view, the system has been used to illustrate to undergraduates important concepts such as the radiation balance, the energy balance, Brunt's law, Stefan-Boltzmann law, ETo and to postgraduates, complex concepts such as minimum air temperature nowcasting and surface renewal. The system was also a useful aid for research, illustrating measurement comparisons in near real-time. This allowed for easy decision making with regard to measurement methods and data comparisons.

Initially, the Web-based system consisted of a single AWS mast but has been expanded to eight stations over a period of less than two years with more than 300 students exposed to the system. The system enabled further understanding of agro-environmental concepts irrespective of language through the emphasis of visual literacy. The system is now used regularly by undergraduate and postgraduates with the potential for use in junior and high schools.

Extended abstract

Web-based teaching, learning and research using accessible real-time data obtained from field-based agrometeorological measurement systems

Agrometeorology is a difficult subject for undergraduate students to relate to initially since most have never met many of the important concepts before. Furthermore, many students studying introductory agrometeorology have a mother tongue for which the words "meteorology" and "agrometeorology" do not exist. Many university students have a poor conception of the environment and of climate change, poor numeracy ability, and poor interpretation of graphical data and limited ability of statistically manipulating large data sets. Often, this is due to a lack of exposure to data representing the environment. Students, for example, lack a basic understanding of concepts such as temperature, temperature scales, and graphical display of information. Often, students find it difficult to "read" graphs and lack the ability to display data graphically. Experience has shown that many students also do not appreciate the difference between temporal and regression graphs. Such deficiencies are particularly noticeable in second-year when students collect or use data for tutorials, scavenger hunt exercises, practicals and projects and then cannot interpret collected data or data made available. The Web-based project described here uses near real-time field-based measurement systems, including an automatic weather station (AWS) and radiation and air temperature station, to collect and display frequently-updated current and previous data in graphs/tables, using the Internet. An important feature of the project was that it enabled real-time display in the lecture room or laboratory via Bluetooth, Internet or Web-enabled cell phone. The real-time Web-based early-warning teaching and learning system encompassed the agricultural, earth and environmental sciences. It was a valuable data resource tool for many disciplines.

The main aim of the research was the development of the Web-based system for selected near real-time agrometeorological applications and also included environmental applications mainly for use by undergraduate and postgraduate Agriculture, Human Sciences and Science students. This aim included the development, testing and evaluation of use of the Web-based teaching, learning and research early-warning system for selected agrometeorological applications, data visualization, visual literacy, and the development of a real-time agricultural, earth and environmental sciences data and information system that allowed students to access a real-time measurement system using the Internet – via a LAN connection, Bluetooth or Web-enabled cell phone. The main objectives are to present the details of the system that was and is currently used by undergraduate and postgraduate students, as well as staff, to access a real-time agricultural and environmental measurement

system using the Internet for tutorials, practicals, projects and lectures. The system displayed graphics of real-time and recent weather sub-hourly data, but not exclusively so, using a variety of examples from second-year to research applications. Data can be extracted and manipulated, thereby reinforcing computer literacy, numeracy – including statistical ability – and graphical capabilities. An objective was to ensure that these abilities are improved while at the same time obtaining a deeper understanding of the environment. An example of the use of the system as one that can provide timely and crucial information to planners of activities involving strenuous activity is given. In a questionnaire for which there were 63 respondents out of a potential total of 95, more than 80 % indicated that use of the system had improved their appreciation of the ranges of the various weather elements. More than 60 % of the respondents indicated that they benefited from use of the system, that they had improved their ability to manipulate data in a spreadsheet and/or display data in graphic or table form, improved their appreciation/awareness of global climate change and/or global warming aspects and improved their appreciation/awareness of the graphical display, and trends, of agro-environmental and environmental data. The questionnaire also highlighted some of the weaknesses of the software used for displaying the graphics, in particular text enhancements, resolution and system interactivity. In a subsequent questionnaire, 89 % of respondents indicated that the system had improved their appreciation of ranges with more than 75 % of respondents indicating that the graphical display of data had enabled further understanding of the agro-environmental concepts irrespective of language. The Web-based system has proved to be a useful and contemporary resource for teaching and learning and has the potential to become a very useful research tool. There is an urgent need to create a list of isiZulu, and possibly isiXhosa, technical terms specific to Agrometeorology and allied disciplines.

Estimation of leaf wetness duration for a short-grass surface

The measurement of leaf wetness duration (LWD) was investigated using sub-hourly dielectric, infrared grass-surface temperature, dewpoint temperature, grass temperature and relative humidity (RH) measurements. Near real-time LWD data and information displays and alerts were made available timeously via a Web-based system. The data and information leaf wetness display was also used by undergraduate students, registered for second-year Agrometeorology modules, as part of their lecture, practical and project material. LWD was estimated for a short-grass surface using five methods: dielectric leaf wetness sensors (LWS); a constant RH for which wetness events were registered for RH greater than 87 %; RH between 70 and 87 % if RH increased by more than 3 % in 30 min; and two dewpoint depression based methods for which surface-measured temperature, using an infrared thermometer (IRT), and grass temperature, were compared with the dewpoint at either 0.1 or 2 m. The RH methods generally overestimated LWD compared to the other methods. There

was reasonable agreement between IRT- and grass-temperature methods if rain days were excluded but these methods showed poor agreement with LWS measurements of LWD. Microclimatic and radiative conditions, during nocturnal condensing events, are reported. Data from an AWS system would have more value if grass temperature was included for determination of LWD by comparison of grass temperature with a measured dewpoint, with timeous alerts and Web-based display of near real-time LWD data and graphics. The use of the Web-based data and information system for use by students in understanding the measurement of leaf wetness was described.

Estimation of frost duration for a short-grass surface

The estimation of frost duration (FD) was investigated using sub-hourly measurements from dielectric leaf wetness sensors, a grass-surface infrared thermometer and a freely exposed grass thermometer. Near real-time FD data and information displays and alerts were also made available via a Web-based system. FD was estimated using a dielectric leaf wetness sensor (LWS) method, for which the sensor voltage was between 274 and 284 mV with a voltage rate of change less than 10 mV h^{-1} for a 4-min period, and two temperature methods for which infrared thermometer (IRT) and grass temperatures were compared with 0°C . The estimation of FD using the LWS method ensured that most of the transitional dry-to-wet and wet-to-dry events were not included in the FD count. Generally, the IRT method yielded the largest estimate of FD, grass temperature method lower and LWS method lowest. Micrometeorological measurements showed consistent air temperature gradients of $2.25^\circ\text{C m}^{-1}$ for cloudless nocturnal frosted conditions with few air temperature measurements at 1 m and none above indicating frost occurrence. At the very least, AWS systems should contain a grass thermometer or preferably an IRT for determination of FD with near real-time sub-hourly data and graphics displayed, including timeous alerts of frost occurrence and FD, using the Internet.

Nowcasting of grass-surface, grass and air temperature minima based on sub-hourly pre-dawn measurements

Technological advances over the past several decades now allow AWS systems to perform sub-daily, even sub-hourly, temperature measurements including surface, grass and air temperatures. One valuable application of the temperature dataset used is in the area of timely nowcasting of the minimum temperature for each day. For this purpose, four temperature models were tested, using 12-months of historic data from four locations varying in altitude, for their ability to nowcast, 4-h or 2-h-ahead of sunrise, the minimum temperature. The models used employed either the exponential or square root function to describe the rate of

nighttime temperature decrease. The models were also used in real-time using the Web-based system:

<http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Daily%20minimum%20temperature%20nowcasting>

for which 4-h and 2-h nowcasts were made for one location with email alerts used for nowcasting of temperatures close to 0 °C. Model 1 (exponential) for which the AWS datalogger used covariance and variance calculations to determine the necessary coefficients for the predicted temperature reduction yielded root mean square error (RMSE) values less than 1 °C for the 2-h-ahead nowcasts. Model 2 (also exponential) for which a constant model coefficient was used was usually slightly less accurate but the RMSE was also less than 1 °C. For the 4-h-ahead nowcast, the RMSEs increased to less than 2 °C for all locations. Model 3 (square root) yielded good 2-h-ahead comparisons between nowcasted and actual daily minimum air temperature for the Marianna (Florida, USA) and Cedara (KwaZulu-Natal, South Africa) locations with the RMSE less than 1 °C, but for the remaining locations RMSEs for this model increased to around 2 °C in some cases. The 4-h-ahead nowcasts generally yielded increased RMSEs. For Pietermaritzburg (KwaZulu-Natal, South Africa), two-min surface, grass and 2-m air temperature data were used. All model nowcasts for the surface and grass daily minimum exhibited increased RMSE compared to those for air temperature at 2 m. Model 1 (exponential) applied to the historic data and data collected using the Web-based real-time system yielded reasonable nowcasts 2 h ahead of time with an increase in the variability for the 4-h nowcasts.

Web-based near real-time surface energy balance for short grass using surface renewal, temperature variance and dissipation theory

Increasingly, near real-time evaporation and surface energy fluxes are required, for example, for comparison with satellite flux estimates or for use when remotely-sensed estimates are compromised by the occurrence of cloud, particularly for summer-rainfall areas. Net irradiance and soil heat flux components of the shortened surface energy balance for short grass were measured with the sensible heat flux (H) determined in near real-time using surface renewal (SR) and temperature variance (TV) methods and using a surface renewal-dissipation theory (SRDT) method. Measurements of air temperature from an unshielded fine-wire thermocouple placed at a height of 0.46 m above the soil surface were obtained at 10 Hz. From these measurements, the following air temperature statistics were determined every 30 min: mean, variance, skewness, and air temperature structure functions of order 2, 3 and 5 for lag times of 0.4 and 0.8 s. For cloudless conditions, the 0.4-s lag corresponded to the maximum of the negative of the structure function of order 3 divided by the time lag and this lag was therefore used for the calculation of H using the SR and SRDT methods. The SR

method requires calculation of the air temperature ramp amplitude and the quiescent and ramping periods for a 30-min period. For the air temperature ramp amplitude, the roots of a cubic polynomial were obtained in real-time using a datalogger program employing an iterative procedure for which the ramp amplitude was determined to within 0.005 °C from which H was determined using an SR weighting factor of 1. For the TV method, the direction of H was determined from the sign of the third-order air temperature structure function and the magnitude of H determined from the mean, variance and skewness of air temperature with adjustments for skewness applied for positive skewness and unstable events. The SRDT method, which uses the square of the SR ramp amplitude, the ramp period and the variance of air temperature, tended to underestimate H compared to SR and TV methods (for the SRDT vs SR method: slope = 0.771, coefficient of determination (R^2) = 0.990, RMSE = 3.1 W m⁻²) using data from 1 June to 28 July 2012. With adjustment for skewness, the TV method showed good agreement with the SR method (slope = 1.035, R^2 = 0.905, RMSE = 13.2 W m⁻²). A shortened surface energy balance was used to determine the latent energy from measured net irradiance from two- and four-component net radiometers, the measured soil heat flux and H , the latter using SR, TV and SRDT methods. The component fluxes, updated half-hourly, are displayed on the Web-based system:

<http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Energy%20balance>

Half-hourly energy balance components are tabulated.

The Web-based system has proved to be a useful resource for teaching, learning and research and a vehicle for reporting in an open system many agro-environmental measurements. From an agrometeorological point of view, the system has been used to illustrate to undergraduates important concepts such as the radiation balance, the energy balance, Brunt's law, and the Stefan-Boltzmann law and to postgraduates, complex concepts such as minimum air temperature nowcasting and surface renewal. The system was also a useful aid for research, illustrating measurement comparisons in near real-time. This allowed for easy decision making.

The Web-based system stemmed from years of frustration of being unable to provide timely weather to students for lectures, practicals and projects. Initially, the system consisted of a single AWS mast which has now been expanded to eight stations over a period of less than two years with more than 300 students exposed to the system. The system enabled further understanding of agro-environmental concepts irrespective of language through the emphasis of visual literacy. The system is now used regularly by undergraduate and postgraduates with the potential for use in junior and high schools.

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1 Introduction

Agrometeorology, as an applied discipline, is challenging to undergraduate students and even postgraduate students including those in their preliminary research years (honours) or masters and PhD students. The teaching of agrometeorology presents significant challenges due the use of mathematics, physics, and meteorology in agricultural and environmental applications. In South Africa, many undergraduate University students do not have English as their mother tongue. This presents even greater difficulties to teaching and learning of agrometeorology since for example, in isiZulu and isiXhosa, words for "meteorology" and "agrometeorology" do not exist.

At the undergraduate level, aside from the language issue, students often have a poor conception of the environment and of climate change, poor numeracy ability, and poor interpretation of graphical or tabled data and limited ability of statistically manipulating large data sets. Experience over many years has shown that this is due to a lack of exposure to data representing the environment. When data are made available, students fail to appreciate their meaning and are unable to represent it, using graphs and/or tables, in a meaningful manner. Students, for example, lack a basic understanding of concepts such as temperature, temperature scales, and graphical display of information. Often, students find it difficult to "read" graphs and lack the ability to display data graphically. Experience has also shown that many students often do not appreciate the difference between line graphs, scatter plots, temporal and regression graphs. Such deficiencies are particularly noticeable in second year when students collect or use data for tutorials, scavenger hunt exercises, practicals and projects and then they cannot interpret collected data or data made available.

The Web-based project described here, together with selected agrometeorological applications, uses near real-time field-based measurement systems, including an automatic weather station (AWS). The system displays agrometeorological and environmental information, graphics and tables that can then be used for lectures, tutorials, practicals, projects and research.

From a research point of view, an online system that automatically captures data in near real-time and plots pre-specified linear regressions and/or temporal plots can be a very useful guide for research planning and possibly implementing changes in measurement protocols. If the data displays are shared, as is the case with Web-based displays, this would allow groups of students to automatically view the plots and therefore research interaction between group members is encouraged.

Furthermore, the accessibility of data and information, updated regularly, is useful for many applications. A system, such as that used and tested here, could be used to ground truth satellite model estimates of sensible heat flux and evaporation in near real-time, or be used as an early-warning system for frost or, for example, plant disease. The system can be used for many applications as demonstrated by those described in this work.

1.1 Nature and scope of study and brief history

The study entailed setting up an open access real-time Web-based early-warning teaching, learning and research system that encompassed selected agricultural, earth and environmental sciences applications. The system is based on a field-based AWS but not exclusively so. The potential of the system as a data resource tool for many disciplines was investigated. System use, as an early-warning system and provider of information and data in an open system to planners of events involving strenuous activity, was also investigated.

Field measurements were conducted during the period April 2011 to June 2013 at the Agrometeorology research site (Figure 1.1), University of KwaZulu-Natal, in Pietermaritzburg, KwaZulu-Natal, South Africa (altitude 684 m, latitude 29.628° S, longitude 30.403° E). The site consisted of two, 3-m tall lattice masts (referred to as Mast 1 and 2,

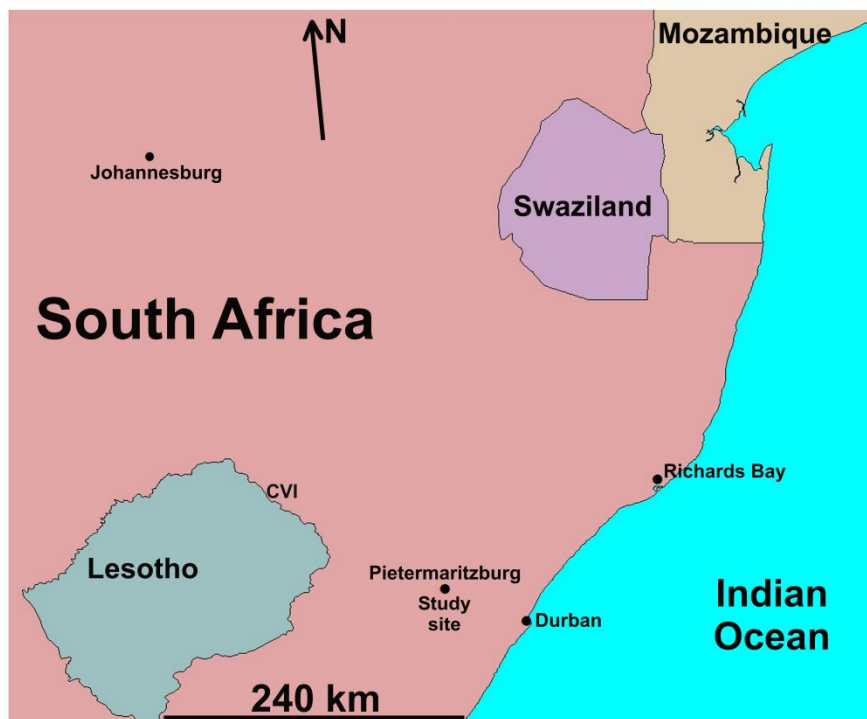


Figure 1.1 A map showing the location of the Pietermaritzburg study site in KwaZulu-Natal, South Africa. The site is in the Scottsville suburb (29.628° S, 30.403° E).

Figure 1.2), 21 m apart, and each fitted with AWS instruments. Mast 2 (recording from December 2011) acted as a backup of the Mast 1 measurements (recording started in April 2011). The Mast 1 (Figure 1.3) sensors, instruments and measurements were: AWS sensors, a profile of Gill radiation shields and thermocouples for air temperature, four- and two-component net radiometers, an infrared thermometer (IRT), barometer, carbon dioxide/water vapour infrared analyser (since March 2012) and a Yagi antenna at the top of the main pole for data telecommunication. In addition measurements of the following were performed: leaf wetness, soil water content, and thermocouples for measuring grass-minimum temperature and soil temperature at various depths. Mast 2 also supported thermocouples for sensible heat flux measurements (since July 2012). The radiation station (Figure 1.2) included pyranometers and a manually-adjusted shade band (weekly) for diffuse irradiance. The forestry nursery (Figure 1.2) micrometeorological measurement and irrigation control system commenced in December 2011 and was completed in February 2013. The Web-based system was extended in May 2013 to a greenhouse (Figure 1.2, polycarbonate, wet-walled, fans and misters) of the Controlled Environment Facility (CEF) of UKZN for monitoring micro-meteorological conditions within. An air temperature station, designed to compare various methods for measuring air temperature and for use by undergraduate and postgraduate stud-



Figure 1.2 The Agrometeorology Instrumentation Mast (AIM) system showing two masts, (21 m apart) the horizontal-pole air temperature station, the ICFR nursery, radiation station and polycarbonate greenhouse (acknowledgement: Google Maps).



Figure 1.3 Mast 1 with the added pole for attachment of sensors, instruments and equipment before attachment of a 5-m extension pole.

ents, was established in June 2011.

Commercially available software was used to create a radio and datalogger network and the Web-based display of the sub-hourly data and information in near real-time. The RS232 datalogger network and cabling for all stations, apart for the forestry nursery station which used a radio, was in place in January 2012.

1.2 Aim and objectives

The main aim of the research was the development, testing and evaluation of use of a Web-based teaching, learning and research early-warning system for selected agrometeorological and environmental applications, data visualization and visual literacy, so as to provide a near real-time agricultural, earth and environmental sciences data and information resource system mainly for use by undergraduate and postgraduate Agriculture, Human Sciences and Science students.

The objectives included the development, testing and evaluation of use of a Web-based teaching, learning and research early-warning system. Applications included the determination of the radiation and energy balances of a short-grass surface, determination of frost duration and leaf wetness, nowcasting of the daily minimum grass-surface temperature and air temperature, fire danger and human comfort indices, for example. The objective included the development of a real-time agricultural, earth and environmental sciences information system that allows students to access a real-time measurement system using the Internet – either via a LAN connection, Bluetooth or Web-enable cell phone. The intent was to display real-time graphics and recent weather data but not exclusively so.

The intention was that students, both undergraduates and postgraduates, should be able to extract data needed for manipulation, thereby reinforcing their computer literacy, numeracy – including statistical ability – and graphical capabilities. An objective was to ensure that these abilities were improved while at the same time manipulating agricultural, earth and environmental sciences data that expressed their environment.

The applications chosen to demonstrate system use ranged from being relevant to second- to honours-year students but also included agrometeorological research applications that demonstrated the utility of the system. Use of the system for early warning was also an essential component.

We are unaware of any similar system in Africa for the purposes described. The system developed at Utah State University (<http://weather.usu.edu/htm/publicity>), the first of

its kind on a university campus and also launched in 2011, focusses on the reporting of agro-environmental measurements but does not allow data downloads by students.

1.3 Specific objectives

A number of specific objectives are listed:

- the development, use and evaluation of a Web-based teaching, learning and research early-warning system (Chapter 2) for selected agrometeorological and environmental applications. The evaluation of system use through questionnaires included investigating the role of language as a specific sub-objective. At the commencement of this investigation, there was little information and description of methodologies and experience available that could be used as a guide for developing the Web-based system. The system enabled the display of near real-time data and information for the agricultural, earth and environmental sciences. It incorporated a field-based, meteorological, agricultural and environmental sciences system, linked via radio telecommunication to a laboratory computer, connected to the Internet with regular uploading of data in table form and graphics. An example of the use of the system, as one that can provide timely and crucial information to planners of activities involving strenuous activity, is given;
- an investigation of the measurement of leaf wetness duration (Chapter 3) using dielectric, infrared grass-surface temperature, dewpoint temperature, grass-minimum temperature and relative humidity sub-hourly measurements with near real-time data and information and alerts made available timeously via a Web-based system. Also, the use of the Web-based teaching and learning data and information system as part of an undergraduate student practical focussed on leaf wetness sensors and leaf wetness is described;
- determination of the occurrence of frost and frost duration (Chapter 4) for a short-grass surface for the relatively high relative humidity Agrometeorology site using various measurement methods, that may be applied at any location, including dielectric, infrared grass-surface temperature and grass temperature methods. An additional objective was the demonstration of the importance of including a grass thermometer with a normal AWS for determining frost occurrence and frost duration. For the purpose of timeous email and SMS alerts for early-warning of frost using the different methods, and for teaching and research purposes, the Web-based display of collected sub-hourly data and graphics was used to enhance the use of the data and their display;
- the early nowcasting of daily minimum air temperatures (Chapter 5), using (sunset to sunrise) exponential and square root models, the former inverted so as to determine

the minimum air temperature from sub-hourly temperature measurements. The application of these models in near real-time so as to allow nowcasting of the minimum air temperature based on the sub-hourly air temperature measurements, and therefore the rate of temperature decrease, several hours before sunrise, was also investigated. The models were also applied to nowcasting grass-minimum temperature and grass-surface temperature using IRT measurements. The relative accuracy of the four model methods tested was investigated using historic data from selected locations at different altitudes and different data frequencies. Furthermore, the implementation of a Web-based system employing the various models using real-time temperature measurements was described;

- the near real-time determination of the components of the shortened energy balance and evaporation (Chapter 6) for short grass and their display on the Web-based system using surface renewal, temperature variance and dissipation theory methods. An important sub-objective of this work was to obtain in near real-time the real roots of a cubic polynomial and hence the calculation of surface renewal sensible heat fluxes for stable and unstable conditions.

1.4 Structure of dissertation

Each chapter is mostly self-contained, containing a literature review, materials and methods, results and discussion and conclusions. The description, application and user-assessment of the Web-based data and information system (Chapter 2) are central to all chapters. The result of each chapter is one or more Web-based screens devoted to one or more aspects of that particular chapter.

Chapter 2 discusses the rationale for the system, system development and implementation. The evaluation results of three open questionnaires on use of the system are presented. There is also a description of some of the applications, such as the lowveld fire-danger index, heat index, sunshine duration, and others. Other applications are described in more detail in the remaining chapters. Further details of the applications are also provided in the Supplementary Materials which appears after the final chapter.

Chapter 3 focuses on the measurement of leaf wetness duration (LWD) using sub-hourly dielectric, infrared grass-surface temperature, dewpoint temperature, grass-minimum temperature and relative humidity measurements. Emphasis is also on the near real-time LWD data and information display and alerts via the Web-based system and display and data use by undergraduate students as part of their lecture, practical and project material.

Chapter 4 is devoted to the estimation of frost duration (FD) using dielectric, infrared grass-surface temperature and grass-minimum temperature sub-hourly measurements as well as the near real-time FD data and information displays and alerts made available via the Web-based system.

In Chapter 5, four temperature models are tested, using 12-months of historic sub-hourly data from four locations varying in altitude, for their ability to nowcast 2-h or 4-h-ahead of sunrise, the minimum temperature. The models were also used in near real-time using a Web-based system for which 4-h and 2-h nowcasts were made for one location with email alerts used for nowcasting of temperatures close to 0 °C.

Chapter 6 focuses on a Web-based near real-time surface energy balance for short grass using surface renewal, temperature variance and dissipation theory. Central to this work as far as surface renewal is concerned is a methodology for the real-time iterative solution of a cubic polynomial for the air temperature ramp amplitude and evaporation estimation.

The final chapter, Chapter 7, integrates the work and provides conclusions and documentation of the contributions of this research. Future teaching, learning and research possibilities including middle and senior school initiatives are presented.

2 Web-based teaching, learning and research using accessible real-time data obtained from field-based agrometeorological measurement systems¹

2.1 Abstract

Agrometeorology is a difficult subject for undergraduate students to relate to initially since they have never met many of the important concepts before. Furthermore, many students studying introductory agrometeorology have a mother tongue for which the words "meteorology" and "agrometeorology" do not exist. Many university students have a poor conception of the environment and of climate change, poor numeracy ability, and poor interpretation of graphical data and limited ability of statistically manipulating large data sets. Often, this is due to a lack of exposure to data representing the environment. Students, for example, lack a basic understanding of concepts such as temperature, temperature scales, and graphical display of information. Often, students find it difficult to "read" graphs and lack the ability to display data graphically. Experience has shown that many students also do not appreciate the difference between temporal and regression graphs. Such deficiencies are particularly noticeable in second-year when students collect or use data for tutorials, scavenger hunt exercises, practicals and projects and then cannot interpret collected data or data made available. The Web-based project described here uses near real-time field-based measurement systems, including an automatic weather station and radiation and temperature station, to collect and display frequently-updated current and previous data in graphs/tables, using the Internet. An important feature of the project was that it enabled real-time display in the lecture room or laboratory via the Internet, Bluetooth or a Web-enabled cell phone. The real-time Web-based early-warning teaching, learning and research system encompassed the agricultural, earth and environmental sciences. It was a valuable data resource tool for many disciplines. The main aim of the research was the development, testing and evaluation of use of a Web-based teaching, learning and research early-warning system for selected agrometeorological and environmental applications, data visualization and visual literacy, so as to provide a near real-time agricultural, earth and environmental sciences data and information resource system mainly for use by undergraduate and postgraduate Agriculture, Human Sciences and Science students. The system displays graphics of real-time and historic weather data but not exclusively so. Data can be extracted and manipulated, thereby reinforcing computer literacy, numeracy – including statistical ability – and graphical capabilities. The objective was to ensure that these abilities are improved while at the same time obtaining a deeper understanding of the environment. An example of the use of the

¹ Based on Savage *et al.* (2012, 2013, 2014), Grant and Savage (2013), Kaptein and Savage (2013), Savage (2014) and Strydom and Savage (2013)

system as one that can provide timely and crucial information to planners of activities involving strenuous activity is given. In a questionnaire for which there were 63 respondents out of a potential total of 95, more than 80 % indicated that use of the system had improved their appreciation of the ranges of the various weather elements. More than 60 % of the respondents indicated that they benefited from use of the system, that they had improved their ability to manipulate data in a spreadsheet and/or display data in graphic or table form, improved their appreciation/awareness of global climate change and/or global warming aspects and improved their appreciation/awareness of the graphical display, and trends, of agro-environmental and environmental data. The questionnaire also highlighted some of the weaknesses of the software used for displaying the graphics, in particular text enhancements, resolution and system interactivity. In a subsequent questionnaire, 89 % of respondents indicated that the system had improved their appreciation of ranges with more than 75 % of respondents indicating that the graphical display of data had enabled further understanding of the agro-environmental concepts irrespective of language. The Web-based system has proved to be a useful and contemporary resource for teaching and learning and has the potential to become a very useful research tool. There is an urgent need to create a list of isiZulu, and possibly isiXhosa, technical terms specific to Agrometeorology and allied disciplines.

Keywords: *language and graphics, seeing data; shared biophysical agro-environmental measurement system; visual literacy*

2.2 Introduction

Undergraduate students studying agrometeorology find the subject matter difficult at first since many of the key concepts are new to them. Also, many of the students have a first language for which the words "meteorology" and "agrometeorology" do not exist. Climate change is a very topical issue and yet many students have a poor conception of their environment, poor numeracy ability, poor interpretation of graphically displayed data and limited ability of statistically manipulating data. Often, this poor conception is due to a lack of exposure to important elements making up the environment. Students are not adequately exposed to the state of the environment around them and therefore leave University with a degree that has not sufficiently equipped them with a first-hand understanding of the environment and they are therefore unable to easily relate to the problems of our uncertain agricultural and environmental future. Students also lack a basic understanding of concepts such as temperature, temperature gradient, temperature scales, for example, and more complex concepts such as solar irradiance, rate of change of population density and the graphical display of information in various forms. Often students have difficulty in "reading"

graphs (Lowe, 2000), and the differences between a temporal graph and a regression graph, for example, are not appreciated. These deficiencies are particularly noticeable at the second-year level when students start to collect data for their practicals and projects or are assigned tutorials.

According to Aoyama and Stephens (2003) and Aoyama (2006), students cannot "read beyond the data into graphs because of a lack of understanding". This is particularly the case for the applied sciences and agricultural sciences for which numeric literacy needs to be heightened due to the requirement of computer literacy, mathematical literacy and statistical manipulation of data, for example. Kirk (undated) recommends that students work through data sets to discover for themselves the rate and extent of environmental change. And yet, even in second year, students usually have not been sufficiently exposed to their environment simply because such systems of exposure, including data, are not easily available to them. Also relevant to the current study and pertinent to South African students, is the question: does the use of graphics and data in teaching and learning transcend language differences between students and between student and staff, more than does written text and other resources?

Lowe (2000) and Felten (2008) used the term "visual literacy", stating that it is an essential component of science and technology education although this could also apply for example to human sciences students who are interested in or have a concern for the environment. Mention has been made of the lack of understanding by students of how to interpret the data that they have collected or data made available for practicals, projects or tutorials. Arcavi (2003) refers to this lack of interpretation of data as "seeing the unseen – in data" and that "... seeing..., with the aid of technology... may also sharpen our understanding, or serve as a springboard for questions which we were not able to formulate before". Using observationally-based climatic data sets and focusing on the (possible) cause(s) of global warming, Schweizer and Kelly (2005) found that students used observationally-based climatic data sets supplied in a variety of ways – such as "(for) supporting their own argument; negating the argument of the opposing side; presenting challenges to the opposing side; and raising new scientific questions".

This research reported here attempts to link environmental measurement systems to collected data and to their display via graphs and tables in a very real way that is easily accessible to undergraduate and postgraduate students and staff for a range of disciplines. The implemented system allowed the student more exposure to data representing the environment, "seeing data" and "visual literacy" through interweaving computer literacy, mathematical manipulation and basic statistical manipulation to near real-time agricultural, earth and environmental sciences data that also allowed early warnings to be issued.

Currently, Web-based real-time agricultural and environmental data and information systems dedicated to or used for teaching and learning are rare. This project aims to some extent to address that lack. Experiential learning is an important application of education (Clark *et al.*, 2010). Experience has shown that students learn more quickly and have increased interest when using real and very recent data relevant to their chosen discipline/major/programme. The intermeshing of data and graphical displays including data analyses reinforces computer, mathematical and statistical methods and skills. System integration across many disciplines results in enhancement of the quality of teaching and learning. Furthermore, a data resource, updated regularly, is more likely to maintain student interest. It can also be a useful resource for academic staff for lecture preparation or for use during lectures to illustrate a current environmental event and useful for tutorials including developing topical scavenger hunt exercises, practicals and projects.

In a recent paper discussing the next decade of environmental science in South Africa, Shackleton *et al.* (2011) state: "new graduates will be ill-equipped to deal with the new environmental challenges and thinking as they emerge, and research programmes will be unable to contribute to meaningful knowledge frontiers or solutions. This places a particular responsibility on universities to adopt a dynamic approach to teaching and research around environmental science, as well as the need for frequent stock taking and alignment of environmental science programmes with the latest developments internationally." The Web-based system reported on here (<http://agromet.ukzn.ac.za:5355>) is pillared on the approach of "a dynamic approach to teaching and research" relevant to a range of disciplines. Hundreds of students have been exposed via the system to near real-time events of the environment via the Web or other medium in a very direct way. The approach could easily be extended to other important but not adequately populated disciplines in South Africa such as atmospheric chemistry and water chemistry. These approaches to teaching and learning are in keeping with the recent Council for Higher Education (2013) report that: "The conditions on the ground dictate a fundamental systemic review of the undergraduate curriculum." The work described in this dissertation has redefined the teaching approaches – specifically those used for the teaching of agrometeorology at undergraduate level, and redefined the approach used for undergraduate and honours projects.

An open-ended questionnaire was used to assess the value and use of the system and for what purpose and to invite comments on improvements for the future. Much of the literature has concluded that: "Open-ended questions on questionnaires elaborate responses to closed questions and offer insights or issues not captured in the closed questions" (Cerritos College, undated). Close-ended questions are usually much easier to analyse but do not allow the respondent to answer in their own words. Open-ended questions give the respondent the

opportunity to express their own thoughts (Sawer, 1992) but since the answers are many and varied, the analysis is usually difficult or at least very time-consuming. Open-ended questions were chosen since they gave the opportunity of varied answers particularly in the case here where the aim was to obtain comment on usage, purpose of usage and access in an unbiased manner.

Open questionnaires are often analyzed using the Likert (1932) rating scale developed for analyzing the attitude of people in response to set questions. The Likert rating scale assumes that the response from "strongly disagree" to "strongly agree" vary linearly with the mode and not the mean being used (McLeod, 2008) due to the discrete nature of the categories used. The open questionnaire was preferred to one for which the respondent could only indicate yes or no to particular preconceived answers could limit the range of responses.

The implementation of a near real-time Web-based teaching, learning and research system is described. The system allows undergraduates (and post-graduates and academic staff) to view data, in table and graphical form, and extract data for downloading. Tutorial-type worksheets that students complete can easily be developed, including spreadsheet-based exercises. The results of a questionnaire are presented. The questionnaire addressed system usage, friendliness and improvement, and the role of graphics in aiding understanding of agrometeorological concepts irrespective of language. Specifically, the system allowed lecture material to be directly accessed using near real-time and historical data relevant to the following disciplines: agricultural plant sciences (crop science, horticultural science, irrigation science, and plant pathology), agricultural engineering, agrometeorology, biological sciences (ecology), environmental science, geography, geology, hydrology, soil science and others. The product was a field-based, meteorological, agricultural and environmental sciences system linked via radio telecommunication to a laboratory computer connected to the Internet with regular uploading of data in table form and graphics. Pre-programmed alerts, based on near real-time measurements and calculations, are in various forms including emails, FTP (File Transfer Protocol) or indicator buttons displayed by the graphical uploads to the Internet.

The innovation of the work was the integration of the various applications across many disciplines and accessibility of near real-time agricultural and environmental data and information in a laboratory, LAN laboratory, lecture room or using a cell phone or Bluetooth. We are unaware of any similar system in Africa for the purposes described. The system developed at Utah State University (<http://weather.usu.edu/htm/publicity>), the first of its kind on a university campus and also launched in 2011, focusses on the reporting of agro-environmental measurements but does not allow data downloads by students.

2.3 Materials and methods

System design, whatever its form, should allow for expansion in time and space and for a variety of uses and users. The core of the Web-based system was an automatic weather station (AWS) system. Data from such a system, unless made freely and easily accessible via a number of different forms – including Internet, email, FTP, Bluetooth, cell phone, SMS, public display, etc. – may be of limited use. Furthermore, data from a traditional AWS system may have limited scope and hence the system designed included many purposes and a whole host of sensors and measurements rarely found at a standard AWS system (Table 2.1, **Sensors row**).

As a result of the many different sensors used, a 3-m mast with a pole extending to a height of 8 m (Figure 1.3) was used for attachment of sensors, enclosure, antenna and desiccant. Two masts were used: the main mast for data and information for the Web-based system, and the second mast for data for undergraduate and postgraduate/staff projects (Figure 1.2). The AWS data from the second mast were also used to cross-check that from the main mast. In addition, a temperature station and a radiation station were used for teaching, learning and research purposes. A fifth station consisting of two dataloggers in a shadenet forestry nursery was also used to monitor the microclimatic conditions and control evaporative cooling and sprinkling irrigation of nursery seedlings for a year. The fifth station was replaced by a station in a wet-walled misted polycarbonate greenhouse involving a micrometeorological study of the internal environmental conditions (Figure 1.2). At all stations except the shadenet nursery, students and staff were able to add additional stations by connecting additional dataloggers to the input/output or RS232 ports of any of the existing dataloggers using a three-core cross-over cable (Table 2.1, **Inter-datalogger hardwiring row**). This allowed for easy additions, of sensors and/or environments requiring monitoring/control.

The setup screen of the Web-based system is shown (Figure 2.1). Each datalogger was set to a proprietary address protocol (for dataloggers and attached peripherals), similar to the Internet Protocol (IP), with a baud rate of 38400. This limit, less than that possible, was imposed by the broad-spectrum 2.4 GHz radios used for telecommunication (Table 2.1, **Communication method row**). However, this lower baud rate ensured reliable data transfers with a relatively slower speed that did not negatively impact on the system operation. This proprietary address protocol allowed seamless and transparent communication between the base station PC to and/or from dataloggers. The communication address of each datalogger had to be known and unique. Of note is that the datalogger at the main mast with connected antenna and radio acted as the "master" datalogger with all others set up as "slave" dataloggers (Figure 2.1, **left side**). The slaves did not require an antenna and radio but used

Table 2.1 Details of the various parts of the Web-based system located in the field.

Stations	Mast 1 (main mast)²	Mast 2	Temperature station	Radiation station	Polycarbonate greenhouse
Sensors	Solar irradiance (CM3 ³), relative humidity and air temperature (combination instrument ⁴), wind speed and direction instrument ⁵ model 03001, raingauge ⁶ , SDI relative humidity and air temperature instrument placed at 100 mm above soil surface in seven-plate radiation shield (combination instrument model CS215 ⁷), infrared thermometer ⁸ , barometric pressure sensor (model CS106 ⁴), carbon dioxide/water vapour infrared analyser ⁹ , leaf wetness sensor ¹⁰ , soil water content ¹¹ , four-component net radiometer (CNR1 ³), two component net radiometer (CNR2 ³), 16 differential type-E thermocouples for measuring: grass minimum temperature, air temperature in seven-plate radiation shields at	Solar irradiance (CM3 ³), relative humidity and air temperature (combination instrument ⁵), wind speed and direction instrument ⁶ (connected to CR1000 ⁷); surface renewal thermocouples (Mengistu and Savage, 2010) connected to CR3000 ⁷	Relative humidity and air temperature (combination instrument ⁴), aspirated and radiation shielded air temperature thermocouples (models 43502 ⁵ (one) and two of ASPTC ⁷), in-house constructed thermocouple and aspirated and radiation shielded air temperature thermocouples (30-gauge) also placed in seven plate and 12-plate Gill shields ⁵ and unshielded and naturally ventilated sensors ¹² including fine-wire type-E	Radiation instruments for measurement of solar irradiance (CM11 ³ secondary radiation standard, CMP3, CM3 ³ , EP07 ¹⁴) and diffuse irradiance using a CM3 shaded by an in-house radiation band requiring adjustment every ten days	Solar irradiance (CM3 ³), relative humidity and air temperature (combination instrument ⁴ placed in an in-house constructed aspirated radiation shield), wind speed and direction instrument ⁵ , model 03101, raingauge ⁶ with 1-mm resolution

² Located at the Agrometeorology site (29.6277 °S latitude, 30.4025 °E longitude, 671.3 m altitude) near the Rabie Saunders Building of UKZN, Pietermaritzburg, South Africa. The other mast and stations and polycarbonate greenhouse and nursery were in close proximity (Figure 1.2)

³ Kipp & Zonen B.V., Delft, The Netherlands

⁴ Vaisala Oyj, Helsinki, Finland

⁵ RM Young Company, Traverse City, Michigan, USA

⁶ Pronamic RAIN-O-MATIC consumer raingauge with attachment that results in 0.254 mm resolution (www.pronamic.com)

⁷ Campbell Scientific Inc., Logan, Utah, USA

⁸ Apogee IRT model IRR-P with a half angle of 22°, Apogee Instruments Inc., Logan, Utah, USA

⁹ Model LI-840A, LI-COR Inc., Lincoln, Nebraska, USA

¹⁰ Model LWS, Decagon Devices Inc., Pullman, Washington State, USA

¹¹ Stevens HydraProbe – SDI model, Stevens Water Monitoring Systems Inc., Beaverton, Oregon, USA

¹² The thermocouples, thermistors and PT1000 sensors were constructed in-house with the thermistors and PT100 sensors sealed in metal tubes

Stations	Mast 1 (main mast) ²	Mast 2	Temperature station	Radiation station	Polycarbonate greenhouse
	heights of 0.1, 1, 2, 3, 4, 5, 6, 7, and 8 m above soil surface and soil temperatures at 0.01, 0.02, 0.05, 0.1 and 0.2 m as well as the average soil temperature between 0.02- and 0.06-m depths		thermocouples (12.5, 25 and 75 μ m diameter), thermistors (model NTC ¹³ epoxy bead, 30 k Ω at 25 °C, 0.3 °C interchangeability) and PT1000 resistance thermometers ¹³ (model 362-9907, class A, interchangeability of 0.15 °C) placed in a Stevenson screen and in the various aspirated radiation shields		
Logging equipment and power details	CR1000 (PakBus address 101) and multiplexer connected to two 14 A h batteries and a 40 W solar panel	CR1000 (102) and AM16/32A multiplexer ⁷ CR3000 (301)	CR1000 (103) connected to two 120 A h deep-cycle batteries, one 14 A h battery, a 40 W solar panel and a mains battery charger	CR800 ⁷ (801) connected to a 14 A h battery and a mains battery charge	CR3000 connected to a 14 A h battery and main battery charger
Communication method	RF416 ⁷ (broad-spectrum base station radio, 2.4 GHz) with attached panel antenna ¹⁵ in line-of-sight with base station antenna allowing 1.5 km transmission range under ideal conditions – a higher gain directional antenna could allow transmission distance of	Hardwired RS-232 communication with CR1000 at Mast 1, between the two loggers at Mast 2 and between the CR1000 at Mast 2 with the Temperature	Hardwired RS-232 communication with Mast 2 CR1000 datalogger and with the Radiation station datalogger	Hardwired RS-232 communication with the Temperature station	Hardwired RS-232 communication with the Radiation station datalogger

¹⁴ Middleton Instruments, Yarraville, Victoria, Australia

¹³ RS Components, Midrand, Gauteng, South Africa

¹⁵ Poynting panel antenna 2.4 GHz 14 dBi (model) POY-A-PANL-0005 with 10-m cable (HDF195): Poynting Direct (Pty), Johannesburg, Gauteng, South Africa

Stations	Mast 1 (main mast) ²	Mast 2	Temperature station	Radiation station	Polycarbonate greenhouse
	15 km. The antenna was mounted at a height of 8 m. CR1000_101 (hardwired RS-232 communication with Mast 2)	station datalogger			
Inter-data-logger hard wiring ¹⁶	CR1000_control port 8 (C8) to Mast 2_CR3000_C7 CR1000_C7 to Mast 2_CR3000_C8 CR1000_control ground (G) to Mast 2_CR3000_G	CR3000_C6 to Mast 2_CR1000_C7, CR3000_C5 to Mast 2_CR1000_C8, CR3000_G to Mast 2_CR1000_G CR1000_C6 to Temperature station_CR1000_C7, CR1000_C5 to Temperature station_CR1000_C8, CR1000_G to Temperature station_CR1000_G	CR1000_C7 to Radiation station_CR800_C8, CR1000_C8 to Radiation station_CR800_C7, CR1000_G to Radiation station_CR800_G	Further expansion is possible via a multiplexer and/or logging devices connected to the logger control ports to a Phytotron complex or the Institute for Commercial Forestry Research	
Grounding	The antenna was connected to an N-type radio frequency polymer arrestor (AL-LSXM surge protector (iPolyPhaser), source unknown but the equivalent is from Clearline, Gauteng, South Africa, model 12-00105) which in turn was connected to the RF415 radio; the datalogger earth was connected via a very	The datalogger earth was connected via a very thick copper cable to a grounding rod banged into ground to as deep a depth as possible	The datalogger earth was connected via a very thick copper cable to a grounding rod banged into ground to as deep a depth as possible	The datalogger earth was connected via a very thick copper cable to the grounding cable for the building	The datalogger earth was connected via a very thick copper cable to a grounding rod banged into ground to as deep a depth as possible

¹⁶ In addition to the hard-wiring, all dataloggers were set to be Pakbus-aware with a baud rate of 38400, and the relevant COM ports (usually C5 to C8) set to RS232 with a baud rate of 38400, a beacon interval of 15 s and a verify interval of 15 s. One datalogger was connected to another by, for example, connecting C7 (TX) of CR1000_102 to C8 (RX) of CR3000_301 and C8 (RX) of CR1000_102 to C7 (TX) of CR3000_301. In each case, the Pakbus address of the nearest datalogger neighbours could also be specified. These settings could be done using a datalogger keyboard (CR1000KD⁷ in the case of the CR800/CR1000) after which the datalogger recompiles – recovery of data before changing settings is therefore essential. Note: future expansion is possible at each mast/station through COM port connections or through connection of logger to logger using a DE male to DE male cross-over cable via the logger RS232 port (pin 2 (RX) of logger 1 to pin 3 (TX) of logger 2, pin 3 of logger 1 to pin 2 of logger 2, pin 5 (G) of logger 1 to pin 5 of logger 2)

Stations	Mast 1 (main mast) ²	Mast 2	Temperature station	Radiation station	Polycarbonate greenhouse
	thick copper cable to a grounding rod banged into ground to as deep a depth as possible				
Base station used for connecting to all field stations	Battery-powered (with mains changer in parallel) RF416 radio (with 8-m antennae and surge-protector) was connected to serial port of a USB to serial cable via a 50-m cable connected to a computer. The computer was in turn connected to the Internet. The ipconfig DOS command was used to determine the IP address of the base station computer and the netstat DOS command was used to determine an unused http port address. This address was unblocked by the Webmaster to allow open access. The computer was connected to an uninterruptable power supply in turn connected to mains				
Software ¹⁷	The base station software included 1. LoggerNet ⁷ version 4.1 for automatic and scheduled connection to all loggers and download of data at 11-minute intervals; 2. RTMC Pro ⁷ development version 3.1 to create the graphics and data tables used for the Web-based system with the run-time version used for toggling the various displays of the graphics and data tables. The graphics and data tables are updated according to the LoggerNet schedule. The RTMC Pro software also allows for the creation of alerts/alarms, via email, based on current measurements; 3. RTMC Pro WebServer ⁷ version 3.1 software, once the IP and http port addresses have been specified, uploads the RTMC Pro screens to the Internet – about 100 kbyte per screen				
Access to data and information – visually and other-wise	The base station had two connected monitors – one in the laboratory and another in the nearby corridor for which the various screens containing data and information are displayed and toggled every 30 s. This allowed passers-by immediate visual display of information The Internet data tables may be opened, as html information, stored and opened in Excel. Row sorting is required to remove the page display headers. The graphic items are self-contained in the entire screen image and may be stored as snapshots. Some of the screens may contain hotspots allowing automatic movement to other parts of the Internet and back again. Once the information is available on the Internet, it can be viewed via an Internet or Bluetooth connection or Web-enabled cell phone				

¹⁷ Other software with similar functionality was not tested. However, LoggerNet is required for communication with the field stations

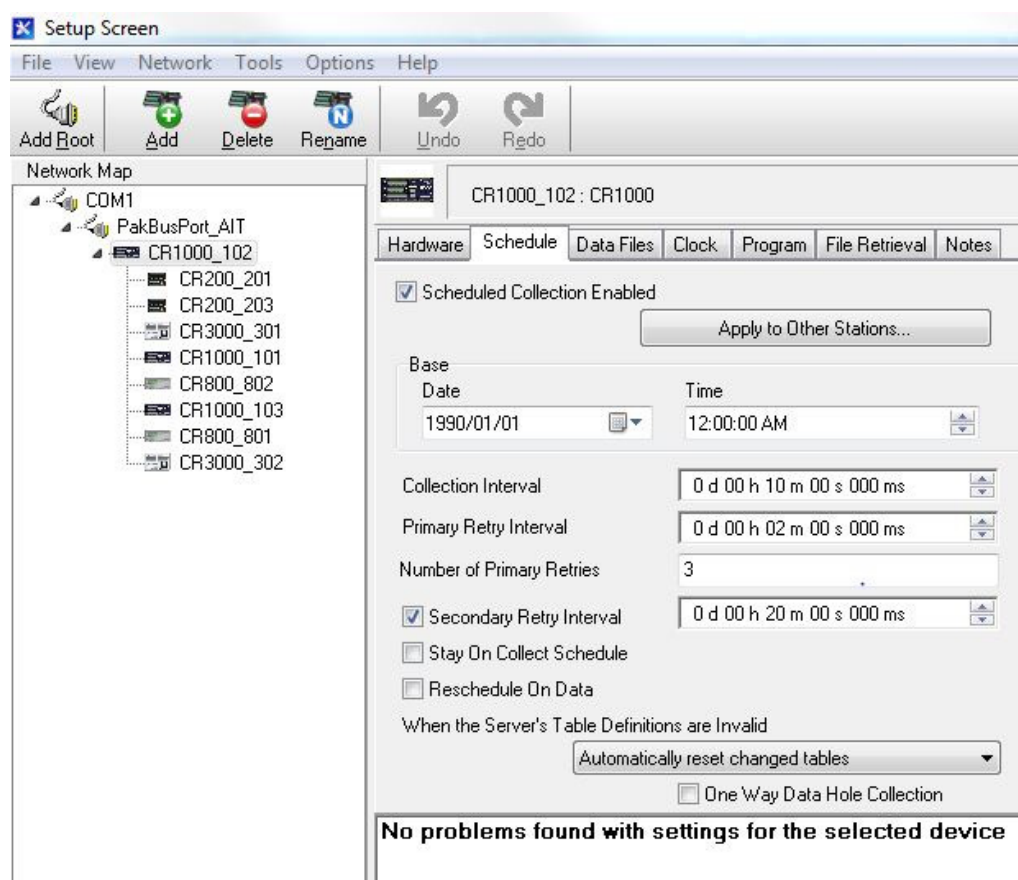


Figure 2.1 The setup screen at the base station computer for the nine dataloggers used in the Web-based data and information system. On the right is shown the details of a typical schedule applied to one of the dataloggers, the "master" datalogger.

two control ports configured for RS232 communication both at a 38400 baud rate, one port for sending (TX) and the other for receiving (RX) information, for connection of one datalogger with another, saving the cost of an antenna and radio for each added datalogger (see Table 2.1 footnote 16 for further details for configuring the control ports). The datalogger in the shadenet nursery was too far from other stations for direct-wire connection. Its antenna was, however, in line-of-sight of that of Mast 1. The nursery datalogger was therefore also set up as a "slave" (Figure 2.1).

For each datalogger, a schedule protocol was defined (right side of Figure 2.1, for example). In the case shown, the datalogger communication software enabled communication and downloads of data every 10 min with three primary retries 2 min after the collection interval had expired and a second retry interval of 20 min. For each datalogger, the output data files included in the scheduled collection are specified (Figure 2.2) – as shown, the information was appended to the relevant data file(s) previously updated. The Public file is usually not collected. For communication to take place, the data table definitions of each datalogger matched those known to the base station computer. Different frequency output files (2 min, 60 min, 24 h, for example) were used for different purposes.

On any Web-enabled computer the Web version of the various data and information screens remained at the selected screen, requiring user intervention to pass from one screen to another. Therefore, html script code was written that allowed the toggling of the various screens (Appendix 2.1). The other way of displaying snapshots and components of a screen was to use FTP – at the same update time interval. Similarly, data reports could be emailed and/or sent via FTP.

More than one version of the WebServer software, used to upload the graphics and tables created to the Internet (Table 2.1, **Software row**), may be executed on the base station PC. Each version needs to have unique RTMC Pro file and http port settings (with different security settings optional) for each version to be associated with a unique Web URL. The Webmaster has to allow open access of the http port(s) which then allows open use of the data and information on any Web-enabled computer. The advantage of running multiple versions of RTMC Pro was that different data and information systems, targeted for undergraduates, postgraduates and/or staff with screens dedicated for particular purposes, could be displayed.

Although the system described here was based on a local AWS and other hard-wired measurement systems, other remote measurement systems or even systems beyond the borders of South Africa, could be added using the proprietary datalogger communication software (Table 2.1, **Software row**). Such systems would usually have a GSM (Global System for Mobile Communications) modem attached to the datalogger with the software

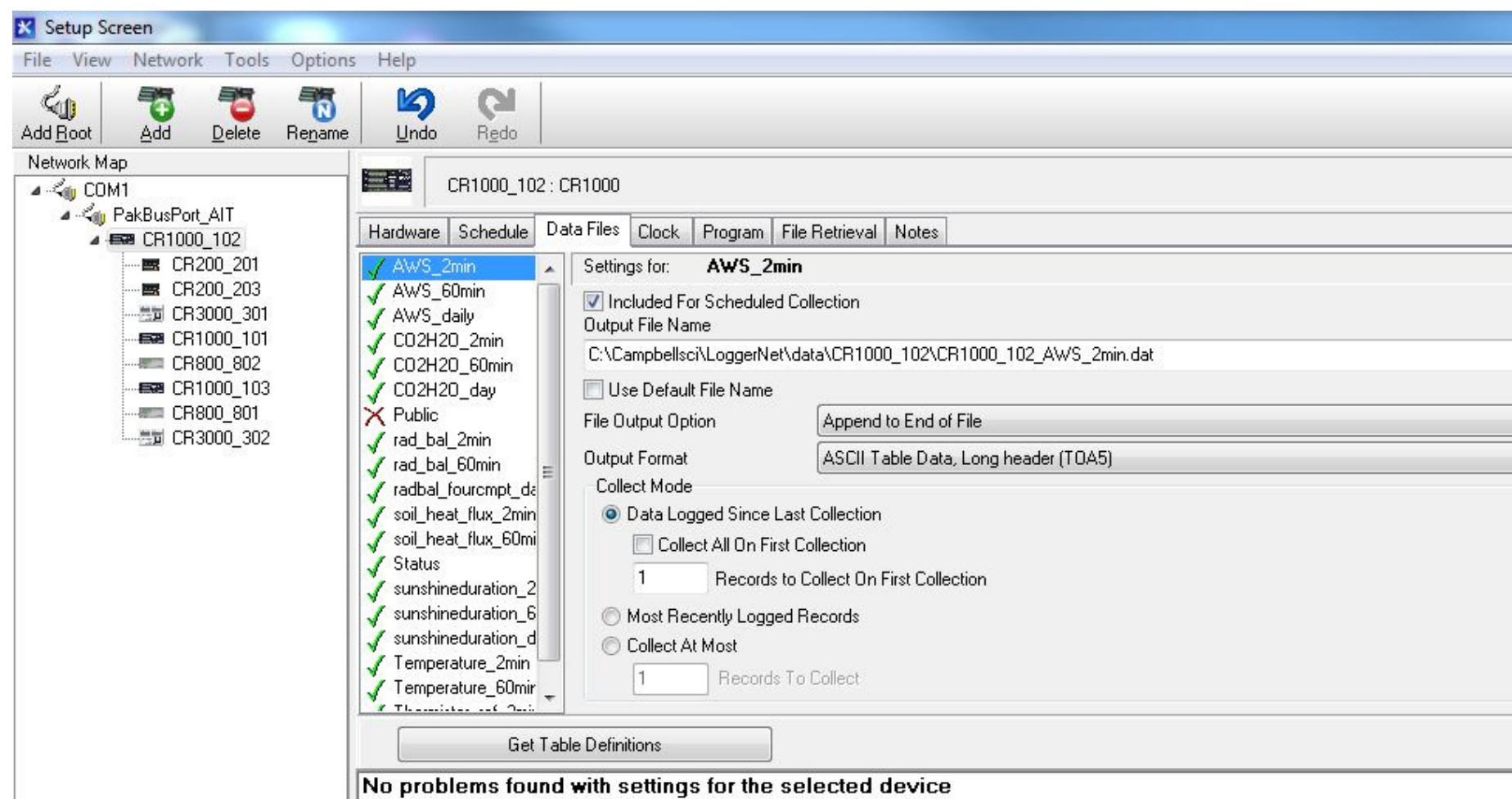


Figure 2.2 The data file screen of the system lists the various output data files of the "master" datalogger, not all of which are included in the schedule, as well as the file output and file format options specified.

scheduled to dial in for data downloads at regular intervals but at a much lower schedule frequency than when using radios so as to reduce dial-in costs. Datalogger-initiated alerts or data transmission based on defined real-time environmental conditions could, however, also be included in the datalogger program.

An open questionnaire¹⁸ was designed to gauge the response to usage of the system as well as to obtain feedback for improvement (Appendix 2.2). The paper version of the questionnaire was given to a total of 60 undergraduate students. The electronic version was emailed to a total of 65 staff and postgraduate students on 29th October 2012. A two-week period was given for completion and respondents were given two reminders, the last one four days before the deadline for return. A second survey of a larger group (79 respondents) was conducted in May 2013. Similar questions to the first questionnaire were used but there were two questions related to language. Specifically, respondents were asked: "Do you think that the graphical display of data has enabled your further understanding of the agro-environmental concepts irrespective of language? Please elaborate." A third questionnaire, conducted in November 2013, included a third question probing further the language of instruction issue: "What language are you comfortable with?"

2.4 Results and discussion

Various and varied themes that encompass both agrometeorology and the agricultural, earth and environmental sciences as far as possible were developed (Table 2.2) to construct the screens used in the development of the system. Selected themes are discussed in more detail as examples of the scope of the Web-based system.

2.4.1 Contemporary data

For tutorials involving use of the system, one significant advantage was that the data used contains current data which may be compared with historic data through graphical display of both historic and current data that is regularly updated (Figure 2.3; Table 2.2, **CO2 row**). Students would immediately note that the current carbon dioxide concentrations, denoted [CO₂] in the **CO2** screen, of around 425 $\mu\text{mol mol}^{-1}$ and shown in the temporal graph at the top left of Figure 2.3, consistently exceeded that depicted in the 1960 to 2011 data set plotted at the bottom right, taken from NOAA (Thoning *et al.*, 1989; Table 2.2, **CO2 row**).

¹⁸ UKZN Protocol Reference Number HSS/0549/013

Table 2.2 A list of the various screens (themes), in alphabetic order by theme, displayed on the Internet via the Web-based data and information system.

Screen name, theme	Details of theme	Target
Air temperature comparison: A comparison of various air temperature measurement methods	The air temperature station consists of 24 different methods for measuring air temperature ranging from unshielded fine-wire thermocouples (Table 2.1) to shielded and aspirated and radiation-shielded sensors and sensors placed in 6-plate and 12-plate radiation shields and in a Stevenson screen. Air temperature data are displayed as temporal plots and temperature difference plots for easy identification of differences using the various methods	Second year students for their projects
Astronomical: Graphical and digital display of astronomical parameters	Sunrise, sunset, daylength, dawn and dusk times are displayed. Solar angle is shown in a temporal plot	Agrometeorology, environmental science, geography and hydrology students
AWS current: Current AWS measurements	Display of temperatures (air, grass, grass-surface using infrared thermometer), wind speed, wind direction, relative humidity, solar irradiance, rainfall, leaf wetness duration and grass reference evaporation (ET _o) (Allen <i>et al.</i> , 2006). Screen also contains an hourly data table	High school learners, public and most University students at an introductory level
AWS yesterday: AWS measurements for yesterday	Display of yesterday's maximum and minimum temperatures (air, grass, surface using infrared thermometer), wind speed, wind direction, relative humidity and total solar irradiance, rainfall, leaf wetness duration and ET _o . Screen also contains a daily data table	All users
Berg winds: Micrometeorological factors during and after Berg winds	This screen presents six simultaneous criteria for the occurrence of Berg winds and the micrometeorological conditions for a typical Berg wind are displayed. A table of data of 2-min AWS data is also displayed	Agricultural plant sciences, agrometeorology, biological sciences, environmental science, geography, High school learners and hydrology students
Chill units	This screen presents the Richardson chill unit values. Other chill unit calculations such as the dynamic and positive chill units are planned	Research and undergraduate student project
Climate change 1: Discussion of historical temperature data for 1880 to 2012	These two information screens focus on the temporal plots of the Global Historical Climatology Network temperature for the period 1880 to 2012 (Peterson and Vose, 1997: http://data.giss.nasa.gov/gistemp/tabledata/ZonAnn.Ts+dSST.txt). The second screen shows the statistical result that the rate of increase in the temperature anomaly: 1. for the period 1971 to 2012 is statistically much greater than that for the period 1880 to 1970 for both hemispheres; 2.	Agricultural plant sciences, agrometeorology, biological sciences, chemistry, environmental science, geography, hydrology and soil science students
Climate change 2:		

Screen name, theme	Details of theme	Target
Statistical analysis of historical temperature data	for the northern hemisphere is more than double that for the southern hemisphere for the period 1971 to 2012	
CO ₂ : Historic and current record of [CO ₂]	Figure 2.3. The historic record of [CO ₂] (Thoning <i>et al.</i> , 1989: ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2_weekly_mlo.txt , Keeling <i>et al.</i> , 2005) and the definition of a greenhouse gas in relation to the return of infrared irradiance to the earth's surface. Current [CO ₂] and [H ₂ O] are plotted and tabled. This screen (Table 2.2) contains some information about the record of [CO ₂] and its role as an important greenhouse gas. A temporal plot of recent measurements of [CO ₂] and [H ₂ O] is shown (top left) as well as their standard deviation (top right). Tabled hourly concentrations and the measured infrared components of the radiation balance are included (bottom left of screen) as well the historic trend in [CO ₂] from the Mauna Loa dataset (bottom right)	Agricultural plant sciences, agrometeorology, biological sciences, chemistry, environmental science, geography, hydrology and soil science students
CO ₂ check: Infrared analyser checks	Measurements of [H ₂ O] using normal AWS capacitive hygrometers at Masts 1 and 2 are plotted in a temporal graph and compared with that obtained using the CO ₂ /H ₂ O infrared analyser	System manager
Definition of terms: Definition of terms used in the various screens	This information screen discusses the various factors quantifying the microclimate. The concept of air temperature measurement being a measurement in shade or radiation shield is stressed	All users
Diffuse radiation: Graphical display of diffuse irradiance	Temporal plots of solar irradiance, diffuse irradiance (measured using a shaded thermopile solarimeter) together with solar elevation are displayed. Included at the bottom of the screen is a data table of the 2-min data	Agrometeorology, environmental science and geography students, honours project student, agrometeorology staff
Energy balance (Chapter 6)	The shortened energy balance is discussed, including a definition of closure. Temperature-based methods are used to determine sensible heat flux density – including surface renewal, temperature variance and surface renewal-dissipation theory methods	Agrometeorology, hydrology, irrigation science and soil science students
ET _o : Grass reference evaporation	Figure 2.4. Definition of Penman-Monteith ET _o (Allen <i>et al.</i> , 1999) and display of latest hourly ET _o and that in the ICFR nursery and display of ET _o totals for yesterday and today. Table of hourly data available for downloading the AWS data and short-grass and tall-crop ET _o	Agricultural engineering, agricultural plant sciences, agrometeorology, hydrology, irrigation science and soil science students
Fire danger index	This screen displays in near real-time the lowveld fire danger index. Elements of it include the methodology for calculating a burning index, based on a nomogram, which for the near real-time estimation purposes, was converted into an equation. The burning index (BI, Willis <i>et al.</i> , 2001)	Agricultural engineering, agricultural plant sciences, agrometeorology, ecology, grassland science and hydrology students

Screen name, theme	Details of theme	Target
	was calculated hourly using air temperature and relative humidity and a wind speed adjustment applied. From the adjusted BI and the elapsed days since last rainfall, FDI is calculated. A high FDI is conducive of fire likelihood. Two graphs of BI and FDI are shown in the display, one for a week and one for the current day	
Flood: Displaying rainfall and soil water conditions	Recent rainfall, accumulated rainfall and soil water content are presented in temporal graphs as well as in table form. Rainfall total for today, yesterday, and the current week and month are displayed	Agrometeorology, environmental science, geography, High school learners, hydrology and soil science students
Fronts: Detecting the passage of frontal weather	Temporal plots of atmospheric pressure and atmospheric pressure adjusted to sea level as well as wind speed are depicted. Small temporal plots of wind direction and air temperature together with the other plots allow for the easy identification of the passage of high or low pressure systems	Agrometeorology, environmental science and geography students
Frost: Definition of frost and display of relevant measurements for today and yesterday (Chapter 4)	The various types of frost are defined as well as the atmospheric conditions required for radiative frosts. Emphasis is given to the importance of atmospheric conditions near the earth's surface for possible prediction of frost, including the use of a dielectric leaf wetness sensor and the grass minimum temperature. Values for the current air temperature, air temperature profile gradient, wind speed, grass minimum and the grass-surface temperature are displayed	Agricultural engineering, agricultural plant sciences, agrometeorology, biological sciences, environmental science, geography and hydrology students
Global warming: A natural phenomenon but focussing on its enhancement through human activities	This information screen discusses global warming as a natural phenomenon, the role of greenhouse gases and the role of the radiation balance and in particular the impact of increased [CO ₂] on the radiation balance. Included is a discussion of the global warming potential and the increasing importance of methane and nitrous oxide	Agricultural plant sciences, agrometeorology, biological sciences, chemistry, environmental science, geography, hydrology and soil science students
Human comfort: Presentation of current heat index and wind chill and that for yesterday	Human comfort indices heat index and wind chill are defined and current, minimum and maximum values presented. Hotspots to the NOAA Web sites are given for further details as is an hourly data table of the indices (http://www.hpc.ncep.noaa.gov/html/heatindex.shtml and http://www.nws.noaa.gov/om/windchill/index.shtml)	All users
ICFR nursery: Graphical and digital display of the current and previous five	Hourly temporal plots of air temperature inside the shadenet and outside (Mast 2) are presented. Air temperature inside is via an in-house constructed aspirated radiation shield. Also plotted is the temperature difference between inside and outside, the solar irradiance inside and outside as	Honours project focussing on control of inside conditions through evaporative cooling when conditions inside are too hot

Screen name, theme	Details of theme	Target
days of conditions in the shadenet (screen removed on completion of honours project)	well as current and total values of leaf wetness, wind speed and ETo for the inside and outside environments	and sprinkling irrigation to avoid frost; staff of the Institute for Commercial Forestry Research
Leaf wetness (Chapter 3)	Display of information and measurements/totals of leaf wetness using different methods	All
Minimum temperature nowcasting (Chapter 5)	Display of the results of different model methods for nowcasting the daily minimum temperature for frost incidence	All
Polycarbonate greenhouse (three screens)	Investigation was for comparing inside and outside conditions as well as to investigate the spatial (N-S and E-W) and temporal variation of the inside conditions	Research and undergraduate student project
Radiation balance: Grass-surface radiation balance	Figure 2.5. A temporal plot of the four components of the grass-surface radiation balance as well as the estimated downward infrared flux calculated using Brunt's equation (Ld_Brunt). The corrected Brunt downward infrared flux, Ld_Brunt_today is also shown. The 2-min data table of the various components is shown at the bottom	Agrometeorology and hydrology students
Solar radiation comparisons: Calibration facility for various solarimeters	Figure 2.6. Scatter plots, temporal plots, difference and percentage difference plots are used to highlight measurement differences in solar irradiance measured using a number of different thermopile solarimeters including a secondary standard and two second-order solarimeters	Agricultural engineering, agricultural plant sciences, agrometeorology, biological sciences, environmental science, geography, hydrology and soil science students
Sunshine	Sunshine duration calculations are presented on this screen	Research and honours student project
Temperature: Graphical display of temperature from surface to 8 m and sky temperature	Figure 2.7. The temporal record of air temperature profile in graphical and table form are displayed as well as soil temperature in table form	Agrometeorology, environmental science, geography, hydrology and soil science students
Wind velocity: Wind velocity and wind rose	The wind rose plot is explained and plotted for the past 24 h and past month. Wind velocity is defined and current and measurements for yesterday displayed	Agricultural plant sciences, agrometeorology, environmental science, geography, High school learners, hydrology and soil science students

The record of carbon dioxide concentration dating back as far as 1740 is shown below (bottom of screen) as is the more recent record from 1960 to present. From these graphs, it is clear that CO₂ concentration has increased significantly.

Carbon dioxide is an important greenhouse gas - that is, it effectively absorbs infrared irradiance from the earth and then returns a significant amount. This causes warming.

The problem is that our human activities have led to a drastic increase in the concentration of carbon dioxide. But without CO₂ and water vapour, the temperature of the earth would decrease from its current average of about 16 to -16 °C!!!

The graph below (left) is the measured 2-min mean concentration of two important greenhouse gases, viz., carbon dioxide and water vapour. The concentration of carbon dioxide, denoted [CO₂], is so small compared to that of water vapour that it is expressed in ppm (parts per million). Commonly, this is the amount of CO₂ in μmol in a unit amount of air (1 mol). Thus, [CO₂] is expressed in $\mu\text{mol}/\text{mol}$ whereas [H₂O] is expressed in mmol/mol . The hourly data for [CO₂] and [H₂O] are contained in the table below (left).

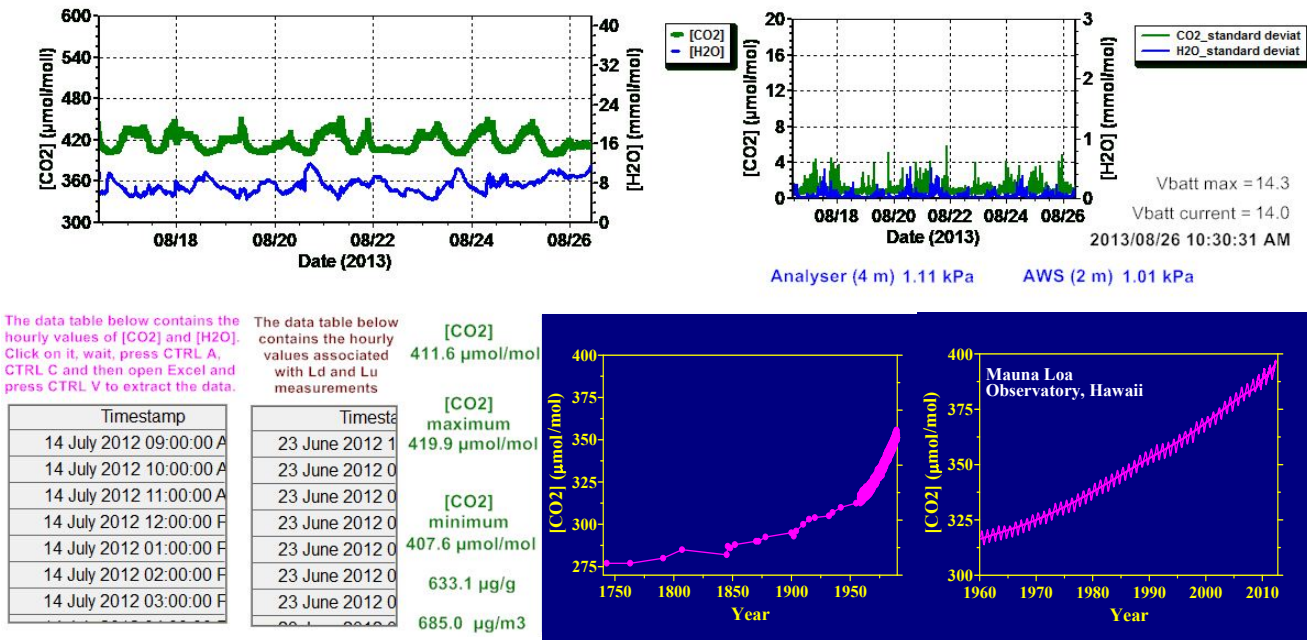


Figure 2.3 The CO₂ screen (Table 2.2) containing some information about the record of [CO₂] and its role as an important greenhouse gas. A temporal plot of recent measurements of [CO₂] and [H₂O] is shown (top left) as well as their standard deviation (top right). Tabled hourly concentrations and the measured infrared components of the radiation balance are included (bottom left) as well the historic trend in [CO₂] from the Mauna Loa dataset (bottom right, Thoning *et al.*, 1989).

ETo is referred to as short-grass reference evaporation. It represents the evaporation from short green grass not limited by water or nutrients

Four factors that quantify the microclimate include solar irradiance (W/m^2), air temperature ($^{\circ}\text{C}$), atmospheric water vapour pressure and wind speed. These are usually measured at an automatic weather station. Often, the dominant factor affecting evaporation is the solar irradiance. Historically, the crop factor approach has been used for estimating evaporation based on class-A pan (or Symon's tank) evaporation and a crop factor determined using simultaneous pan and lysimeter evaporation measurements. Recently, Allen et al. (2006) showed how to estimate hourly reference evaporation (for short grass and a so-called tall-crop, the later corresponding to lucerne) from hourly data from an AWS.

Commonly, crop evaporation (LE) is estimated from grass reference evaporation (Allen et al., 1998: FAO 56; Allen et al., 2006) based on point atmospheric measurements at a single level, usually at 2 m, at an automatic weather station from measurements of solar irradiance, air temperature, water vapour pressure and wind speed. In addition, a crop factor is used as a multiplying factor for reference evaporation to obtain LE, the crop factor effectively distinguishing the vegetation under consideration from a grass reference crop. The dual crop factor approach uses one crop factor for the soil surface and another for the basal crop cover. The extension of reference evaporation from daily (Allen et al., 1998) to hourly estimates has been recommended (Allen et al., 2006) for both grass (0.1-m tall) reference evaporation and tall vegetation (0.5-m lucerne).

Allen et al. (2006) recommend that for application of the FAO-PM ETo method from FAO56 applied for hourly or shorter time intervals for short grass, a surface resistance $r_s = 50 \text{ s/m}$ is recommended for daytime and $r_s = 200 \text{ s/m}$ for nighttime periods and an aerodynamic resistance of $208/U_2$ is used, where U_2 is the horizontal wind speed at a height of 2 m. These adjustments are based on best agreements with computations made on a 24-h time step basis lysimeter measurements. The daytime value of $r_s = 50 \text{ s/m}$ recommended by Allen et al. (2006) is also in agreement with that found by Savage et al. (1997) for a short grass surface.

Also for hourly or shorter time intervals for a 0.5-m tall canopy, $r_s = 30 \text{ s/m}$ for daytime and $r_s = 200 \text{ s/m}$ for nighttime periods and an aerodynamic resistance of $118/U_2$ is recommended. Allen et al. (2006) based these adjustments on best agreement with 24-h time-step lysimeter measurements.

The partitioning of the available energy flux density, $R_{\text{net}} + S$ where R_{net} is the net irradiance and S the soil heat flux density, is slightly different for short grass reference evaporation than that for tall-crop reference evaporation. For short grass, $S = 0.1 R_{\text{net}}$ when R_{net} is positive (daytime) and $S = 0.5 R_{\text{net}}$ for the nighttime. For tall-crop reference evaporation, it is assumed that $S = 0.04 R_{\text{net}}$ when $R_{\text{net}} > 0$ (daytime) and $S = 0.2 R_{\text{net}}$ for nighttime.

Totals for periods indicated (or datalogger reset)

Total ETo (mm) for current week	18.4 mm	Total ETo tall (mm) for current week	24.0 mm
Total ETo (mm) for current month	18.4 mm	Total ETo tall (mm) for current month	24.0 mm

References

1. Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. United Nations Food and Agriculture Organization, Irrigation and Drainage Paper 56. Rome, Italy, 300 pp.
2. Allen R.G. et al. 2006. A recommendation on standardized surface resistance for hourly calculation of reference ETo by the FAO56 Penman-Monteith method. Agric. Water Mgt. 81: 1-22.
3. Savage, M.J., C.S. Everson and B.R. Metelerkamp, 1997. Evaporation measurement above vegetated surfaces using micrometeorological techniques. Water Research Commission Report No. 349/1/97, p248, ISBN 1-86845-363-4.

Hourly ETo (mm/h) for Mast 1 (and AWS data)

Timestamp	Day_of
27 August 2013 10:00:00 PM	

Hourly ETo (mm/h) for high humidity greenhouse (Unit U)

Timestamp	Day_of_year_number
23 August 2013 12:00:00 PM	234.5

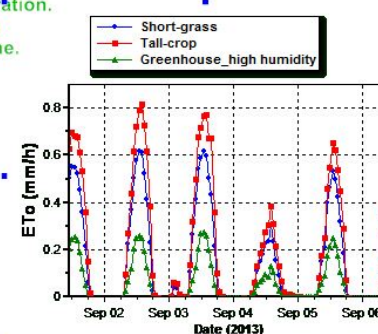
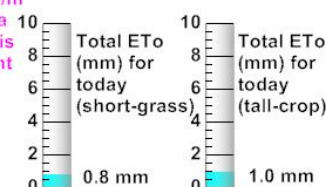
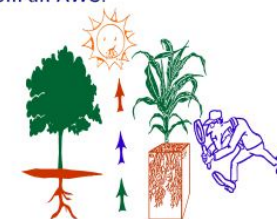


Figure 2.4 The ETo screen for hourly and daily short-grass and tall-crop reference evaporation. Detailed information is given about the calculation of daily and hourly ETo, and gauges for ETo for Mast 1 and the high humidity greenhouse as well as a temporal plot of hourly ETo. The hourly data used for calculating ETo is given, for both locations.

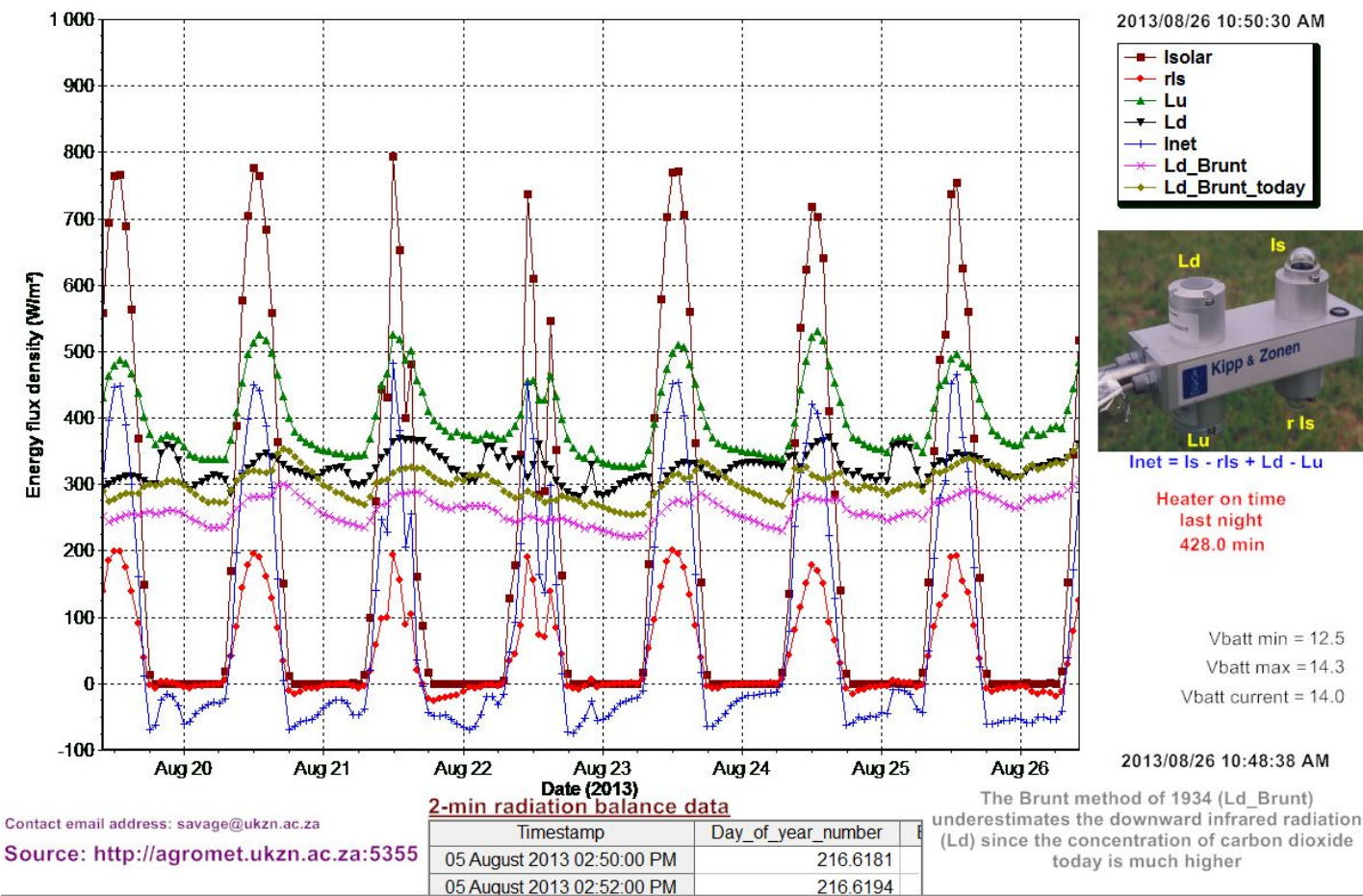


Figure 2.5 A temporal plot for hourly data of the four components of the grass-surface radiation balance as well as the estimated downward infrared flux calculated using Brunt’s equation (Ld_Brunt). The corrected Brunt downward infrared flux, Ld_Brunt_today is also shown. The 2-min data table of the various components is shown at the bottom.

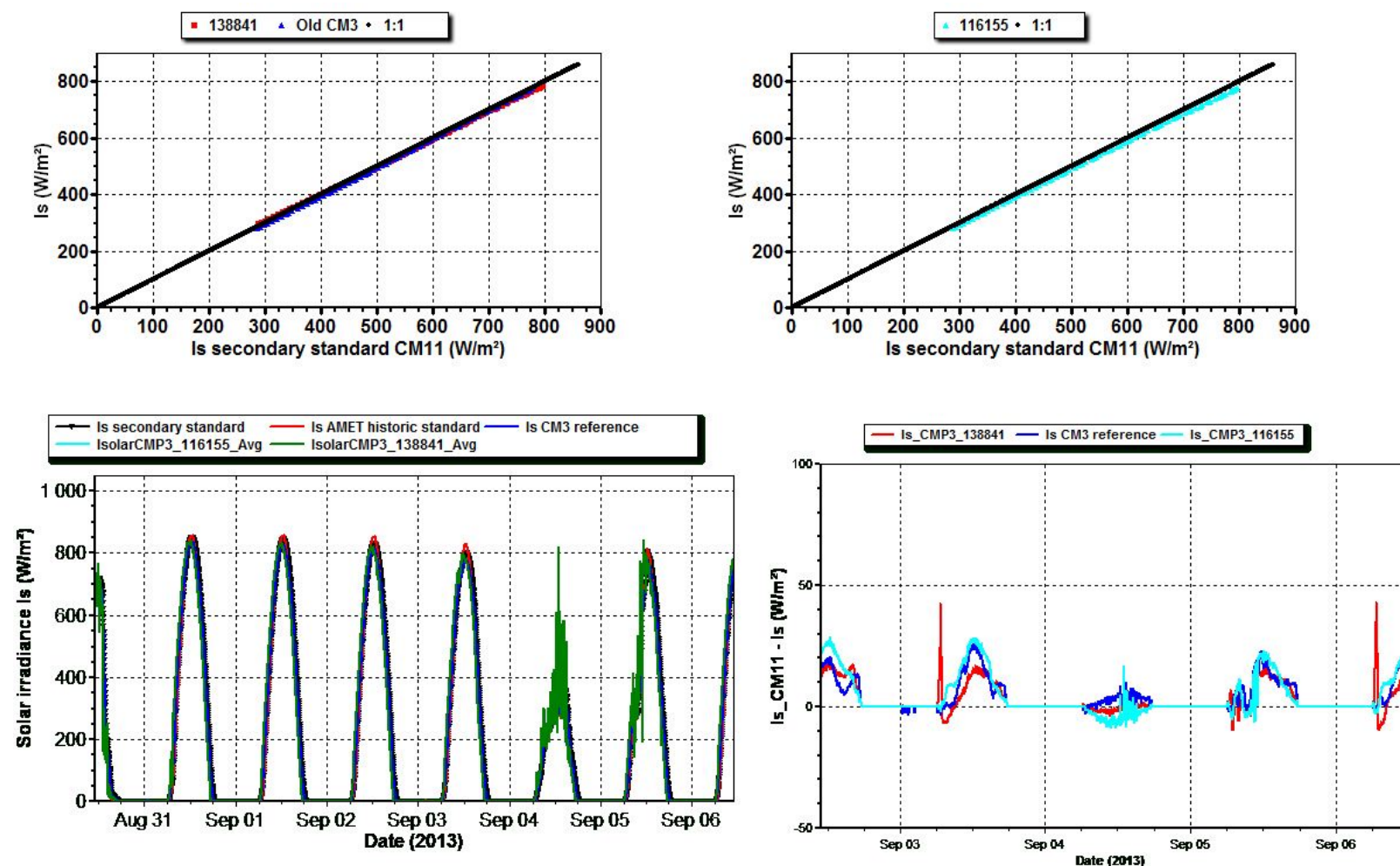


Figure 2.6 Upper: Scatter plot of solar irradiance measured using three sensors against that measured using a secondary standard thermopile solarimeter; lower left: temporal plot of solar irradiance using the four solarimeters; lower right: temporal difference and % difference plots that more conveniently illustrate the differences between the various solarimeter measurements.

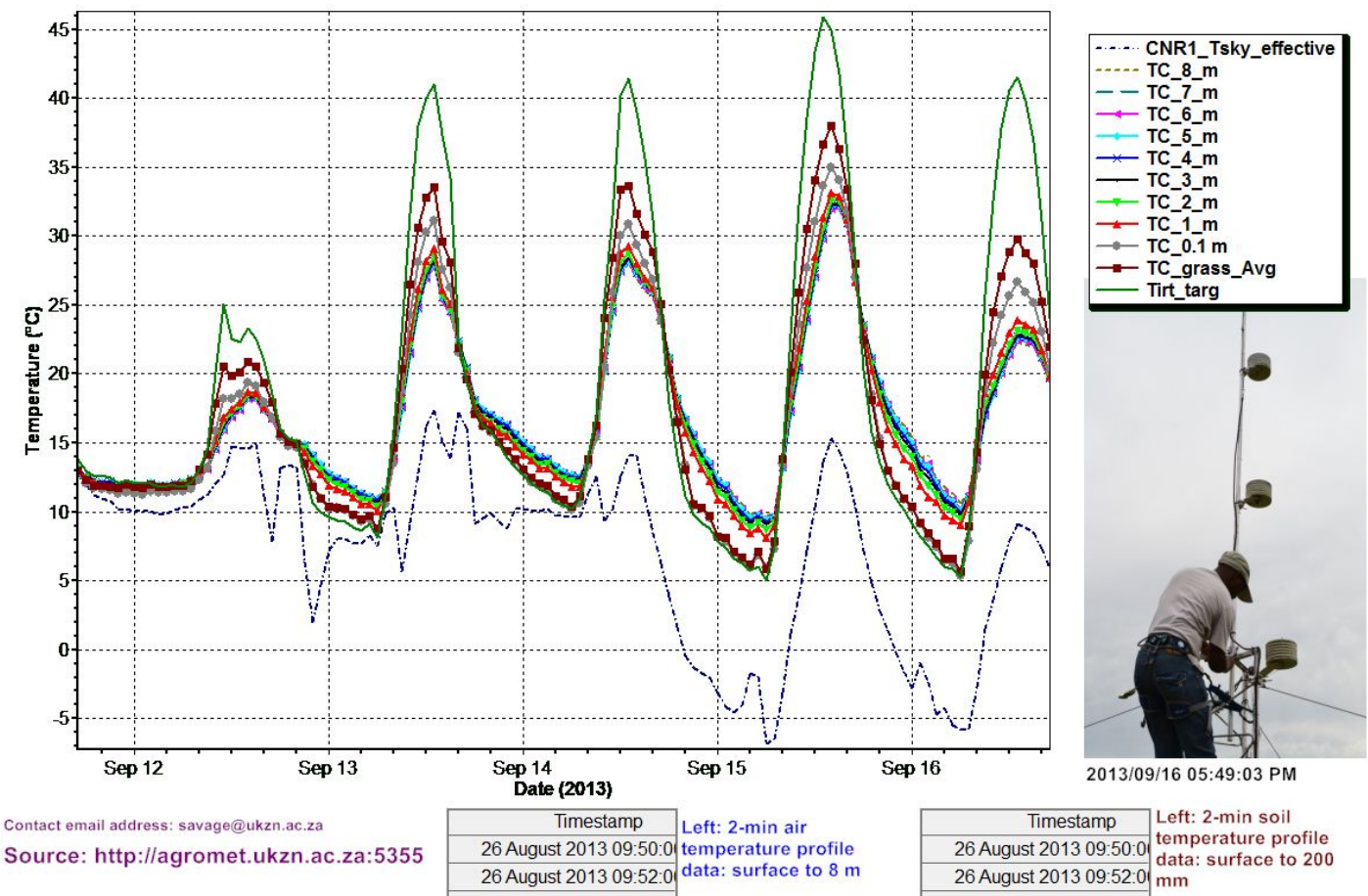


Figure 2.7 A temporal plot of various hourly temperatures from grass-surface temperature using an infrared thermometer, unshielded temperature of grass and air temperature at 0.1, 1, 2, 3, 4, 5, 6, 7, and 8 m and sky temperature. The data tables at the bottom include 2-min air temperature profile data as well as soil temperature.

In this particular example, chemistry students could download the hourly data table (at the bottom left of Figure 2.3), and through a tutorial, learn how to convert carbon dioxide concentration from one unit to another (e.g., to mg L^{-1} , $\mu\text{g g}^{-1}$ etc.). Agricultural plant sciences students could be challenged to explain the shape of the diurnal carbon dioxide and water vapour concentration trends in terms of the differences in the exchange of these gases between plants and the atmosphere through stomata during day- and nighttimes. Agrometeorology, environmental science, geography and hydrology students could explore the current and historic $[\text{CO}_2]$ and the possible impact of the current levels on global climate change. Students studying crop modelling could use the daily weather data and $[\text{CO}_2]$ for modelling crop growth.

2.4.2 Critical examination of data

As an example of stressing the need to critically examine data directly relate it to climate change, the surface radiation balance for short grass was depicted in the **Radiation balance** screen (Figure 2.5; Table 2.2, **Radiation balance row**) for a week. This need is illustrated by using the equation of Brunt (1934) for calculating the returned infrared irradiance L_d (W m^{-2}) for cloudless nighttimes from the measured air temperature T_z ($^{\circ}\text{C}$) and water vapour pressure e_z (kPa) at height z using:

$$Ld_Brunt = \sigma(T_z + 273.15)^4(0.44 + 0.08\sqrt{10 \cdot e_z})$$

$\longleftrightarrow \longleftrightarrow$
 Contribution Contribution
 due to $[\text{CO}_2]$ due to $[\text{H}_2\text{O}]$

where $\sigma = 5.6704 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ is the Stefan-Boltzmann constant. Through the display of Ld_Brunt and the measured Ld (Figure 2.5) using measurements from a four-component net radiometer (Figure 2.5; Table 2.1, **Sensors row**), it was immediately obvious that the Ld_Brunt estimate consistently underestimated measured Ld . Through a guided tutorial, students explored why this was the case and also explored the linear relationship that Brunt (1934) proposed between $Ld/\sigma(T_z + 273.15)^4$ and $\sqrt{10 \cdot e_z}$ for cloudless nighttimes and developed new coefficients that expressed the significantly increased $[\text{CO}_2]$ between 1934 and today. Cloudless nighttimes could be determined by examining the nighttime decrease in air temperature. Uniform nighttime air temperature decreases would indicate possible cloudless conditions. The revised version, Ld_today , was also be added to the system for students to compare with the measured Ld and Ld_Brunt (Figure 2.5).

2.4.3 Web-based system as a multi-disciplinary teaching and research tool

Evaporation estimation is a multi-disciplinary topic central to many disciplines in the applied environmental and agricultural sciences. The concept of grass reference evaporation, ETo , was discussed in the **ETo** screen (Figure 2.4; Table 2.2, **ETo** row) with the relevant hourly data for two environments, Mast 1 and inside a polycarbonate greenhouse, appearing at the bottom of the screen. The data tables contained both short-grass and tall-crop reference evaporation (Allen *et al.*, 2006). Through a guided worksheet, students could be asked to plot both hourly short-grass ETo and tall-crop reference evaporation for a week and comment on their differences and their variation for days with different environmental conditions.

2.4.4 Visual reinforcement of concepts

Atmospheric stability is a concept central to agrometeorology, environmental sciences, geography and hydrology students. The concept of atmospheric stability is also part of the grade 12 Geography syllabus. The diurnal heating of the earth's surface during daytime and nighttime cooling was demonstrated using five days of IRT measurements of the short-grass surface (Figure 2.7; Table 2.1, **Sensors** row) and the radiation-shielded and naturally-ventilated air temperature measurements between 0.1 and 8 m. Around midday on the cloudless days, the surface was the hottest with cooler temperatures away from the surface and the reverse for the nighttime. The table of data shown at the bottom of Figure 2.7 could be used to calculate the air temperature gradient for each layer of the lower atmosphere from 0.1 to 8 m. These gradients could be plotted as a function of time of day to demonstrate the change in atmospheric stability for each hour of the day for each layer. The magnitude of the air temperature gradients could be used to probe the extent of the stability or instability of the atmosphere at particular times and the impact of these gradients on atmospheric pollution. Also, the early-morning differences in temperature of several °C between the grassland surface and that measured at 2 m, the normal AWS height, could be explored in relation to frost occurrence.

2.4.5 Visual reinforcement of measurements and measurement ranges

Visual reinforcement of data is possible when measurements and measurement ranges are associated with easily recognisable images. A useful feature of the Web-based RTMCPPro software used was the application of the Basic Alarm component. The requirements of the component are the datalogger station, data table and the selected data element (Figure 2.8a). In addition, an image may be displayed when a defined measurement condition is met and

another image when the condition is not met. For example, a person shading themselves could be displayed when air temperature is between 24 and 28 °C. This component could be superimposed on another for which an image of a person at a beach on a sunny day is displayed if air temperature exceeds 28 °C and otherwise no image is displayed. In the latter case, the "no image" would need to be transparent. To ensure that unusually high nighttime air temperatures do not display a sunny-beach image, a third component would need to be superimposed. This third superimposed component could be activated based on a solar irradiance less than a small set value – such as 15 W m⁻². As a separate but not superimposed component, for air temperatures less than 10 °C, an image of a shivering person with gloves, woollen hat and jersey could be displayed. Each image except for the "nighttime" image would need to be transparent when not activated. In other words, the "off condition" needs to be the transparent.gif file (Figure 2.8b). The nighttime image would need to be the translucent.png file when the condition is satisfied (i.e., nighttime) and the transparent.gif file when not satisfied (i.e., daytime). The "nighttime" image needs to be superimposed on the "shivering person with gloves" image.

The visual reinforcement of measurements and measurement ranges could allow the Web-based system to be used in a junior or high school. Through the use of images based on a combination of measurements, the complexity of the agro-environment could be made much simpler through the use of data or data combinations shown as simple visuals including graphics associated with near real-time events. These graphical reinforcements also allow the system to be used in a multi-language environment.

2.4.6 Web-based system as an innovative research tool

The continual and automatic graphical display of research data allows for a dynamic and visual interrogation of measurements which can assist in developing ideas for more detailed displays or detecting data trends that in turn assist in developing further ideas. This process can be aided by temporal graphs, scatter plots and/or temporal plots of differences between two sensors/methods say, of the data (Figure 2.6, **Solar radiation comparison screen**; Table 2.2). Experience with the system demonstrated its use in examining collected data online with little intervention. Graphical plots mentioned aid not only in developing new ideas, possibly revising plotted graphs, easily comparing instruments and also identifying sensor or data problems. Through the Web, the data and information is easily accessible to all members of the project team. These methods were applied and were particularly useful in the case of the air temperature mast (Supplementary Materials, page SM34) and the identification of the air temperature system with the least radiation error.

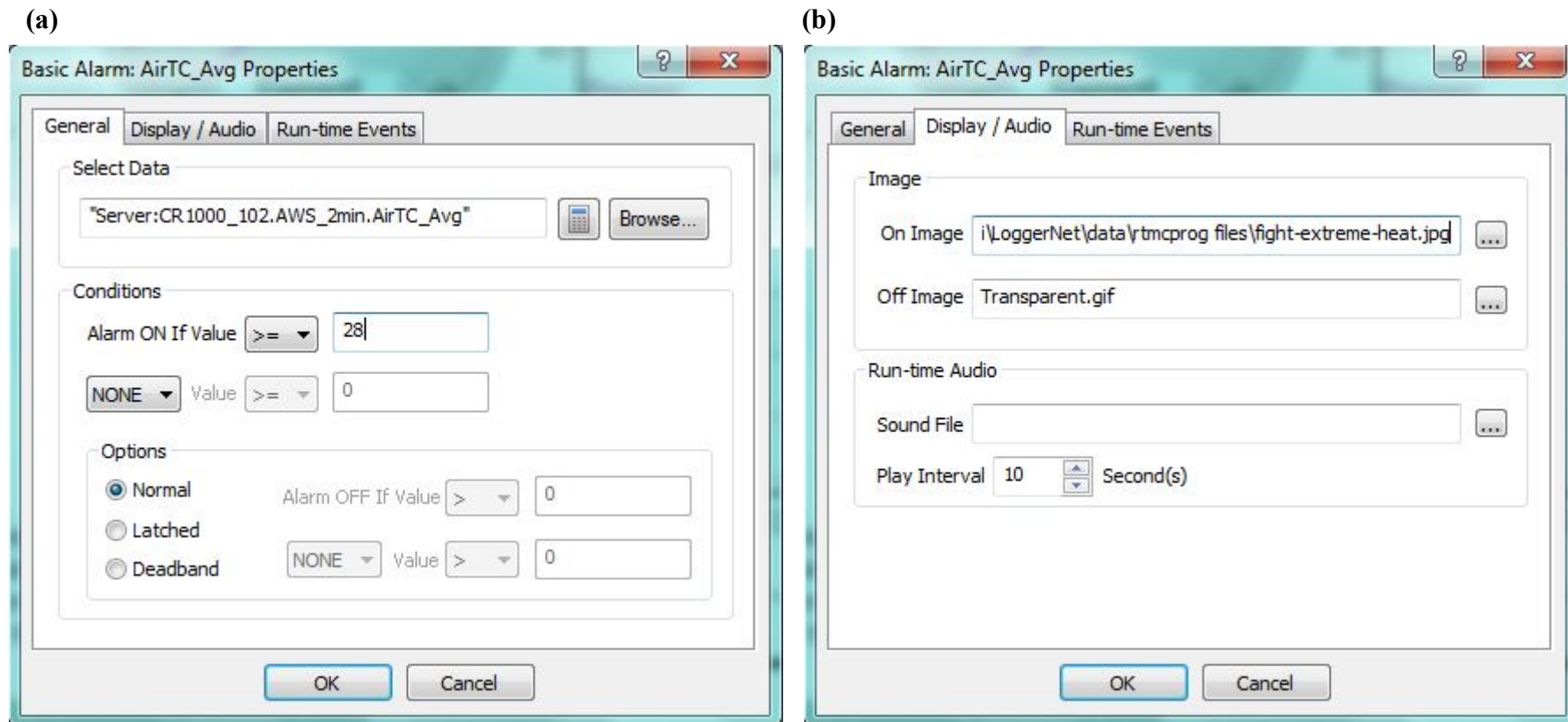


Figure 2.8 The properties of the Basic Alarm component. At left, (a), the requirements for the General Properties tab are shown. At right, (b), the requirements for the Display/Audio tab are shown.

In a recent experiment in greenhouse U (Figure 1.2), the spatial (and temporal) microclimate conditions and data were made available to users via a web-based research, teaching and learning system

(<http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Greenhouse%20tunnel%20U>, for example) (Savage *et al.*, 2014). The web-based system described was useful in providing greenhouse users, including the greenhouse manager, the capability of monitoring spatially-varying conditions online in near real-time so as to apply adjustments to equipment or to reposition plants used for experimental purposes (Savage, 2014).

2.4.7 Web-based early-warning system

A simple example of early-warning was that of low battery voltage warning for one or more of the dataloggers. An alert via email or FTP could be sent to the system manager based on a test of a 2-min or 60-min battery voltage compared to a fixed value of 10 V, say. Alerts of adverse weather events may also be applied to Berg winds, frost and also to the human comfort indices of heat index and wind chill as well as fire danger indices based on one or more measurements (Table 2.2). However, use of SMS was a more direct way of alerting and it was possible to use an incoming email to set up a rule to email or SMS others of an environmental event. In the case of the shadenet nursery (Table 2.2, **ICFR nursery row**), the datalogger was programmed to control the on/off status of a solenoid valve and based on the measured atmospheric conditions, it was set to apply water to evaporatively cool plants, avoid frost, remain on, or switch off. In all cases for all stations, it was possible to view the near real-time data, graphics and events, and also the solenoid status at least to within 10 min.

The lowveld fire danger index (FDI) is determined from air temperature, relative humidity, wind speed and elapsed days since last rainfall (taken to be 0.5 mm or more in a day). A nomogram, converted into an equation, was used for determining the burning index BI and a wind speed adjustment is applied (Willis *et al.*, 2001). From the adjusted BI and the elapsed days since last rainfall, FDI is calculated. A high FDI is conducive of fire likelihood. Two graphs of FDI are shown in the Web-based system

(<http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Fire%20danger%20index>), one for a week and one for the current day. A threshold FDI of 75 is shown by a red line. The wind speed adjusted BI, which is always less than FDI, is also shown. The calculations for BI, BI adjusted for wind speed, FDI and FDI adjusted for elapsed days since last rainfall were all performed in the datalogger programme. Hourly plots of FDI and other meteorological measurements allow users to follow in near real-time the conditions that would affect fire danger. It would be a simple matter to include alerts, based on the FDI calculated, air

temperature, relative humidity, wind speed and the like, that could be emailed to a predefined user list.

An aspect that has not been explored in detail is the use of the Web-based system as a fuzzy-logic system for nowcasting of, for example, fire danger, floods or frost. Rules for floods could be based on the measured rainfall intensity and the soil water content at both depths (Table 2.1, **Sensor row**) in relation to the saturation soil water content. Rules for fire danger could be a set similar to that used to define Berg wind conditions, the latter being very warm conditions with lower than usual atmospheric pressure, winds generally from the north, greater than usual wind speeds, drier than normal atmospheric conditions, etc. These rules could be included in the datalogger program or the WebServer software used (Table 2.1, **Software row**). The advantage of applying the rules using the WebServer software was that it is easier to gather data from different dataloggers for use in applying the rule(s), and frequent rule changes during development did not reset the datalogger data tables and therefore also reset the display graphs. This project is currently the basis of an honours project (Supplementary Materials, page SM38).

2.4.8 Provision of timely project data

The provision of timely project data for students in the applied sciences, for example in the agricultural, biological and environmental sciences, is a daunting task for a lecturer responsible for a second-year class with close to or more than 100 students or even a third-year class with more than 20 students. The Web-based system allowed easy creation of data tables (and hotspots for easy navigation from the system to other parts of the Internet and back again) that were used by groups of students for group projects, postgraduates and staff for lecturing aids, practical and/or tutorial material. Besides using the data as a basis for their projects, students regularly maintained the sensors that required cleaning or calibration and provided evidence of such visits in their report by including photographs obtained using their cell phones.

To date, the system has been used for three honours projects, two of which resulted in conference presentations by Grant and Savage (2013) and Kaptein and Savage (2013), Supplementary Materials, pages SM26 and SM28 respectively. One honours project (2013) involved the development of a near real-time fire danger index system (Supplementary Materials, page SM38).

2.4.9 System deficiencies and future opportunities

One problem with the system during the initial testing phase was that whenever the datalogger program of the master datalogger was altered, the tables and graphics directly associated with the master datalogger were reset. Web users requiring previous data, therefore, had to email their requests for data. During implementation, there were many and frequent changes to the master datalogger program and at one stage even a change in datalogger, due to the addition of more sensors. We could not find a way of attaching data tables of previous (historic) data to the Web-based system. A work-around would be to store the data in a separate directory on the base station server and make that data available on the Internet. This would, however, require an additional http address.

The other deficiency of the current system was the availability of sensors. We have been unable to source inexpensive and yet reliable sensors for, for example, methane concentration, ultra-violet irradiance and hail and lightning incidence. Also, we have not explored the possibilities of directly sending an SMS to warn of an environmental event. This is possible using code in the datalogger and would be useful to visually-impaired students who do not have access to the various graphics screens. The SMS could be voice-synthesized by the SMS receiver and sent, even to a normal landline, when activated as an alert by datalogger code. The need for this has not arisen.

Many primary and high schools cannot afford a weather station, even a simple one. The implemented system could relatively easily be tailored for use by scholars and particularly teachers through selected subjects. The requirement for access would be a PC with an Internet connection. This aspect should be explored in the future.

2.4.10 Role of language

Even for the teaching of children, a teaching strategy is "As you conduct a science lesson, include visuals that illustrate the subject matter" (Buck, 2000). According to Herr (2007, Chapter 24, Section 24.7.2): "Regardless of linguistic background, people around the world can interpret mathematical equations and musical scores. In addition, they can also interpret pictures, and with minimal linguistic skills, can interpret charts and graphs. Visual literacy, or the ability to evaluate, apply, or create conceptual visual representation, is relatively independent of language, and is therefore invaluable to learning science...".

The role of language in the use of the system is an interesting question that was not addressed in the original funding proposal for this project or in the first questionnaire. It was, however, assumed that graphical and table displays of data tend to reduce the role of language

and assist in the cognitive retention of information. This hypothesis was confirmed in a subsequent literature search and in the second questionnaire (May 2013) which will be discussed later.

2.4.11 Use of the open system for planners and information about adverse weather

An example of the use of the system in providing timely and crucial information to planners of activities involving strenuous activity is given. This example was chosen since had the information been available to the organizers, lives may possibly have been saved. Two articles on adverse weather were published in a local newspaper (The Witness, 2nd and 10th January 2013). These communications (Appendix 2.3, Figures A2.1 and A2.2 respectively) were two-fold. Firstly, they provided information about the open system. They also served to raise the profile of the system for use as an open data and information resource.

Air temperature is measured in the shade so when humans are exposed to direct sun, they are subjected to temperatures higher than this. Also, the measurement of air temperature does not include the influence of relative humidity. Humans perceive the combination of the air temperature and relative humidity. For air temperatures greater than 27 °C and relative humidity greater than 40 %, the heat index calculation kicks in with heat indices greater than air temperature. Using the USA National Oceanic and Atmospheric Administration formulation for heat index based on Steadman (1979), the heat index on Thursday [29th December 2012] reached a high of 33.7 °C which is a category-3 (extreme caution) heat index for which heat exhaustion could occur with prolonged exposure and/or physical activity (Environmental Protection Agency, 2006). On Friday [30th December 2012], the heat index high was 30.8 °C (category 4, caution) and on Saturday it was much worse at 38.6 °C (category 3). The heat index, air temperature and relative humidity are displayed in near real-time at the UKZN Agrometeorology open-access Website:

<http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Human%20comfort>

(Table 2.2, **Human comfort row**) and organisers of events, including events at schools, involving strenuous outdoor activities are urged to make sure that conditions are not hazardous to participants.

2.4.12 Analysis of three open questionnaires on use of the Web-based data and information system

Three surveys were undertaken – SURV1 (2012, second semester), SURV2 (2013, first semester) and SURV3 (2013, second semester). A paper version of the first questionnaire

(Appendix 2.2) was handed to a class of AMET212 (second semester) (65 and 62 students respectively). The questions for all three surveys were almost identical except that SURV2 and SURV3 had two additional questions relating to language. An electronic version of SURV1 was emailed to 30 staff/postgraduates/researchers known to have used or enquired about the system. For SURV1, there were 48 respondents and for the electronic version, there were 15 respondents. In all, there were 63 respondents out of a potential total of 95, representing a return percentage of 68.4 %. The electronic returns were printed and combined with the paper versions for analysis. All questionnaires were archived electronically and are available on request. For SURV2 there were 79 respondents and 55 respondents for SURV3.

The questionnaires were analyzed manually with the assistance of an administrator. For each question of the questionnaire, the number of responses for three to five categories was determined. The categories chosen were dictated by the responses for that question. This meant having to read through all responses to define a category, for a given question, that captured the greatest number of responses. The second category was defined by the remainder of the responses that captured most of the balance of the responses, and so on.

For each question, no more than five categories were used with most (eight out of eighteen) of the questions having three categories. Six of the questions were easy to analyze, requiring only a yes/no response with some respondents giving no response. The results of the questionnaire are shown in Table 2.3 for SURV1 and Table 2.4 for SURV3.

The responses in general were quite good if not very good for different questions. Most of the respondents were undergraduate students (73 %), for whom the system was designed, with 22 % being postgraduates and staff in equal proportion (Table 2.3, Question 1). The vast majority of users – nearly 90 % – found that the system was user-friendly with only 9.5 % of users shown how to use it (Question 2). For SURV3, more than 70 % of the respondents found the system to be user-friendly/easy to use.

In terms of system use (SURV1), 39 % of users accessed it for their projects, 32 % for a specific module, 15 % for study and 9 % for data (Question 3). For SURV3 (Question 1), most users used the system for study (35.7 %), 25.0 % for practicals, 12.5 % for data download, 17.9 % for interest and 8.9 % for projects. Most users accessed it from on-campus (71 %) with 21 % of users accessing it both on- and off-campus. Only 8 % of users accessed it off-campus only (Question 4). For SURV3, most users (87 %) accessed the system on-campus (Question 3).

Table 2.3 Summary results of the open questionnaire SURV1 used to gauge use and feedback to improve the Web-based teaching, learning and research system. The percentage for each category within a given question is shown as well as the total number of responses n¹⁹.

1	Respondent status (e.g., undergraduate student, postgraduate, etc.)	
	Undergrad	73.0
	Postgrad	11.1
	Staff	11.1
	Honours	4.8
	n	63
2	Have you been shown how to use the Web-based data and information system (http://agromet.ukzn.ac.za:5355) and if so by whom and for which module? If you were not shown how to use the system, how user-friendly did you find it?	
	Friendly	87.3
	Shown use	9.5
	Not friendly	3.2
	n	63
3	Please give the reason(s) for your use of the system. If you are a student, please indicate which module(s) you are registered for required your use of the system. Otherwise, where necessary, please elaborate.	
	Project	39.1
	Specific module	31.9
	Study	14.5
	Data	8.7
	Interest	5.8
	n	69
4	Please indicate how you accessed/viewed the system – e.g., on-campus LAN connection, Bluetooth, off-campus, corridor display.	
	On	71.0
	On off	21.0
	Off	8.0
	n	62
5	Were you ever unable to connect to the system? If yes, how many times?	
	Yes	47.2
	No	37.5
	Between 2 and 5	12.5
	> 5	2.8
	n	72

¹⁹ See Appendix 2.2 for questionnaire used

6	What event/screen did you monitor/use and why? Where necessary, please elaborate.
	<div>More than two screens 68.3</div> <div>AWS current 22.2</div> <div>AWS yesterday 9.5</div> <div>n 63</div>
7	What was the purpose for your use of the system – e.g., for interest, personal, study, data download, practical(s), tutorial(s), lecture(s), project? If you used the system for academic work, please indicate the purpose(s) and in each case the corresponding module. Please elaborate.
	<div>Personal interest 31.9</div> <div>Project 29.8</div> <div>Practicals 26.6</div> <div>AMET212 11.7</div> <div>n 94</div>
8	Is the content of the system related to the lecture content of modules you are taking and if so, state which modules and which lecture content? Please elaborate.
	<div>AMET212 49.2</div> <div>Yes 23.8</div> <div>No response 12.7</div> <div>Hydrology 7.9</div> <div>Other modules 6.3</div> <div>n 63</div>
9	Have you used the system for observing any particular near real-time event(s)? If so, please indicate which event(s).
	<div>No 34.7</div> <div>Specific event 30.6</div> <div>Yes 26.4</div> <div>No response 8.3</div> <div>n 72</div>
10	Please describe your frequency of use of the system – e.g., casual, monthly, weekly, regular.
	<div>Casual 52.4</div> <div>Regular 22.2</div> <div>Weekly 14.3</div> <div>Monthly 6.3</div> <div>Daily 3.2</div> <div>n 63</div>
11	Which event/screen did you use the most? If more than one screen, please say which ones. To answer this question you may wish to refer to: http://agromet.ukzn.ac.za:5355
	<div>AWS current/ AWS yesterday 63.0</div> <div>Various 24.7</div> <div>No response 12.3</div> <div>N 73</div>

12	Have you made use of the AWS_today and AWS_yesterday screens? Please elaborate.										
	<table> <tr><td>Yes</td><td>51.6</td></tr> <tr><td>No</td><td>28.1</td></tr> <tr><td>Other screens</td><td>20.3</td></tr> <tr><td>n</td><td>64</td></tr> </table>	Yes	51.6	No	28.1	Other screens	20.3	n	64		
Yes	51.6										
No	28.1										
Other screens	20.3										
n	64										
13	Have you ever downloaded data or graphics from the system? If so, please state the purpose for downloading and the relevant module – e.g., for use for a tutorial, a project, an assignment, a practical, research, personal use. Please elaborate.										
	<table> <tr><td>Yes</td><td>61.9</td></tr> <tr><td>No</td><td>31.7</td></tr> <tr><td>No response</td><td>6.3</td></tr> <tr><td>n</td><td>63</td></tr> </table>	Yes	61.9	No	31.7	No response	6.3	n	63		
Yes	61.9										
No	31.7										
No response	6.3										
n	63										
14	If you did download data or graphics from the system, how easy was it to do? Please elaborate.										
	<table> <tr><td>Easy</td><td>50.8</td></tr> <tr><td>No response</td><td>23.8</td></tr> <tr><td>Not</td><td>19.0</td></tr> <tr><td>Did not download</td><td>6.3</td></tr> <tr><td>n</td><td>63</td></tr> </table>	Easy	50.8	No response	23.8	Not	19.0	Did not download	6.3	n	63
Easy	50.8										
No response	23.8										
Not	19.0										
Did not download	6.3										
n	63										
15	Has the Web-based system improved your appreciation of the ranges of the various weather elements – e.g., range in air temperature, relative humidity, rainfall, wind speed, etc.? Please elaborate.										
	<table> <tr><td>Yes</td><td>80.6</td></tr> <tr><td>No response</td><td>16.1</td></tr> <tr><td>No</td><td>3.2</td></tr> <tr><td>n</td><td>62</td></tr> </table>	Yes	80.6	No response	16.1	No	3.2	n	62		
Yes	80.6										
No response	16.1										
No	3.2										
n	62										
16	Has the Web-based system improved your ability to manipulate data in a spread sheet and/or display data in graphic or table form? Please elaborate.										
	<table> <tr><td>Yes</td><td>65.1</td></tr> <tr><td>No response</td><td>20.6</td></tr> <tr><td>No</td><td>14.3</td></tr> <tr><td>n</td><td>63</td></tr> </table>	Yes	65.1	No response	20.6	No	14.3	n	63		
Yes	65.1										
No response	20.6										
No	14.3										
n	63										
17	Has the Web-based system improved your appreciation/awareness of global climate change and/or global warming aspects? Please elaborate.										
	<table> <tr><td>Yes</td><td>60.3</td></tr> <tr><td>No</td><td>28.6</td></tr> <tr><td>No response</td><td>11.1</td></tr> <tr><td>n</td><td>63</td></tr> </table>	Yes	60.3	No	28.6	No response	11.1	n	63		
Yes	60.3										
No	28.6										
No response	11.1										
n	63										

18	Has the Web-based system improved your appreciation/awareness of the graphical display, and trends, of agro-environmental and environmental data? Please elaborate.								
	<table> <tr> <td>Yes</td><td>66.7</td></tr> <tr> <td>No</td><td>20.6</td></tr> <tr> <td>No response</td><td>12.7</td></tr> <tr> <td>n</td><td>63</td></tr> </table>	Yes	66.7	No	20.6	No response	12.7	n	63
Yes	66.7								
No	20.6								
No response	12.7								
n	63								
19	Are you aware of any similar system(s) used elsewhere? If so, please give details.								
	<table> <tr> <td>No</td><td>76.2</td></tr> <tr> <td>Yes</td><td>15.9</td></tr> <tr> <td>No response</td><td>7.9</td></tr> <tr> <td>n</td><td>63</td></tr> </table>	No	76.2	Yes	15.9	No response	7.9	n	63
No	76.2								
Yes	15.9								
No response	7.9								
n	63								
20	Do you have any suggestions for improvement or specific requirements that could be incorporated as part of the Web-based system? If so, please elaborate.								
	<p>Add dewpoint temperature graph to AWS current screen</p> <p>Advertise</p> <p>Complicated, please simplify</p> <p>Data only on a static background</p> <p>Frontal weather</p> <p>Future weather (x2)</p> <p>Improve visuals</p> <p>Info separate from data; email notifications; mobile app; link to forecasting</p> <p>Make it easier to download data</p> <p>Monthly averages, totals</p> <p>More info needed on use of Website</p> <p>More interactivity</p> <p>Overview screen, better graphics, mobile version</p> <p>Screen should be available all over campus</p> <p>Suggestion box</p> <p>Well demonstrated</p>								
Further general comments/considerations									
Please add further comments relevant to this questionnaire.									
<p>Berg wind forecasting very interesting</p> <p>Demonstration</p> <p>Great tool</p> <p>Helpful, helped with research significantly</p> <p>Impressive, comprehensive</p> <p>More interactivity and flexibility</p> <p>Thanks for service</p> <p>Thanks to MGA, Nico, Steve</p> <p>Try to have further prediction for air temp</p> <p>Useful tool</p> <p>Very useful, enjoyable and interesting resource</p>									

Table 2.4 Summary results of the open questionnaire SURV3 used to gauge use and feedback to improve the Web-based teaching, learning and research system. The percentage for each category within a given question is shown as well as the total number of responses n.

1	What was the purpose for your use of the system – e.g., for interest, personal, study, data download, practical(s), tutorial(s), lecture(s), project? If you used the system for more than one activity, please indicate them.	
	Study	35.7
	Practicals	25.0
	Data download	12.5
	Interest	17.9
	Project	8.9
	n	56
2	How user-friendly did you find the system? Please elaborate.	
	User-friendly	49.0
	Easy	23
	Nil	10.2
	Illegible	2.0
	Difficult initially	8.2
	n	49
3	Please indicate how you accessed/viewed the system – e.g., on-campus LAN connection, Bluetooth, off-campus, corridor display.	
	On campus	87.0
	Off campus	5.6
	Wireless	3.7
	Site	1.9
	Cellphone	1.9
	n	54
4	Were you ever unable to connect to the system? If yes, how many times?	
	Yes	50.9
	No	49.1
	n	53
5	What event/screen did you monitor/use and why? Where necessary, please elaborate.	
	Air temperature	19.2
	AWS screen	17.3
	Greenhouse	9.6
	Rainfall	9.6
	Berg winds	7.7
	Nil	7.7
	Human comfort	7.7
	Sunshine	5.8
	Nothing	3.8
	Radiation	3.8

	Chill units	3.8
	Soil water	1.9
	Frost	1.9
	n	52
6	Is the content of the system related to the lecture content of modules you are taking? If so, state which modules and which lecture content. Please elaborate.	
	Yes	85.2
	No	13.0
	Nil	1.9
	n	54
7	Have you used the system for observing any particular near real-time event(s)? If so, please indicate which event(s).	
	Yes	47.3
	No	47.3
	Nil	5.5
	n	55
8	Please describe your frequency of use of the system – e.g., casual, monthly, weekly, regular.	
	Casual	37.7
	Weekly	34.0
	Regular	28.3
	Monthly	0.0
	n	53
9	Which event/screen did you use the most? If more than one screen, please say which ones. To answer this question you may wish to refer to: http://agromet.ukzn.ac.za:5355	
	Air temperature	17.3
	AWS current	17.3
	Nil	15.4
	Rainfall	9.6
	Human comfort	7.7
	Berg winds	7.7
	Radiation	5.8
	Leaf wetness	5.8
	Chill units	3.8
	Floods	3.8
	Sunshine	1.9
	Greenhouse	1.9
	None	1.9
	n	52
10	Have you made use of the AWS _today and AWS _yesterday screens? Please elaborate.	
	Yes	49.1
	No	49.1
	Nil	1.8
	n	55

11	Have you ever downloaded data or graphics from the system? If so, please state the purpose for downloading and the relevant module – e.g., for use for a tutorial, a project, an assignment, a practical, research, personal use. Please elaborate.
	Yes 85.5
	No 14.5
	n 55
12	If you did download data or graphics from the system, how easy was it to do? Please elaborate.
	Easy 64.8
	Not easy 14.8
	Nil 14.8
	Slow 5.6
	n 54
13	Has the web-based system improved your appreciation of the ranges of the various weather elements – e.g., range in air temperature, relative humidity, rainfall, wind speed, etc.? Please elaborate.
	Yes 85.5
	No 9.1
	Nil 3.6
	Undecided 1.8
	n 55
14	Has the web-based system improved your ability to manipulate data in a spread sheet and/or display data in graphic or table form? Please elaborate.
	Yes 83.6
	No 10.9
	Nil 5.5
	n 55
15	Has the web-based system improved your appreciation/awareness of global climate change and/or global warming aspects? Please elaborate.
	Yes 85.5
	No 5.5
	Nil 9.1
	n 55
16	Has the web-based system improved your appreciation/awareness of the graphical display, and trends, of agro-environmental and environmental data? Please elaborate.
	Yes 79.6
	No 7.4
	Nil 13.0
	n 54
17	Do you think that the graphical display of data has enabled your further understanding of the agro-environmental concepts irrespective of language? Please elaborate.
	Yes 89.3
	Nil 10.7
	n 56

18	What language(s) are you comfortable with?	
	English	78.2
	Zulu	14.5
	Nil	5.5
	French	1.8
	n	55
19	Do you have any suggestions for improvement, specific requirements or simplifications that could be incorporated as part of the web-based system? If so, please elaborate.	
	Yes	4.1
	No	69.4
	Nil	16.3
	More computers	2.0
	More space	2.0
	More historical data	2.0
	Tutorials	2.0
	Publicity	2.0
	n	49
20	Are you aware of any similar system(s) used elsewhere? If so, please give details.	
	Yes	3.9
	No	83
	Nil	13.7
	n	51

Further general comments/considerations	
Please add further comments relevant to this questionnaire.	
<p>The web-based system is easy to use and very helpful</p> <p>Everything is perfect</p> <p>Thanks for a great module, although I found it very challenging, especially the pracs & grasping all the computer stuff</p> <p>Go Prof Savage. Doing an awesome job</p> <p>The system is working perfectly, thanks for providing us with such interesting information!!!</p> <p>Module is good and exciting, but more challenging than the average module</p> <p>Best system I have seen and want to research on more that are similar. Making me decide on my future plans</p> <p>Good system to use for study</p> <p>All good, keep it up :-)</p> <p>Lab should be enlarged for better access of the web-based system</p>	

A high percentage of respondents indicated system connection problems – nearly 50 % (Question 5 – 50.9 % for SURV3, Question 4). This is unfortunate since this may reduce interest in the system. The WebServer software stops for no apparent reason, requiring a manual reset. Towards the end of the reporting period of the project, the frequency of system interruption increased significantly. Whether this was due to interrupts of the UKZN Internet connection or problems with the WebServer software is difficult to know unless the 5355 port is monitored. This monitoring is not within the ambit of this project. The UKZN Information and Communication Services Division (ICS) over a period of more than a year were alerted to the problem. To offset this problem, TimeViewer was used (www.timeviewer.com) . This allowed remote access to the server and therefore it was possible to reset WebServer remotely. This dramatically reduced the system downtime.

Most users accessed more than two of the data/information screens (68 %, Question 6 of SURV1) with 22 % accessing the AWS current screen (17.3 % for SURV3, Question 5). The AWS current screen displays the current air temperature, relative humidity, rainfall total for current day, wind speed, wind direction and sunshine duration total as well as the current minimum and maximum air temperature for the day (Table 2.2, **AWS current row**).

Surprisingly was the high percentage of respondents indicating personal use of the system (32 %, Question 7, SURV1). From a teaching and learning standpoint, this has benefit for the undergraduate student since personal use is the one usage that would probably continue even after the student has completed the current semester.

Almost 25 % of respondents found that the content of the system was related to that of their current modules, with almost 50 % finding that the content was related to AMET212 (Instruments for the Life and Earth Sciences) (Question 8, SURV1). In the case of SURV3, 85.2 % of respondents found that the content was related to their current modules (Question 6).

About 26 % of respondents observed near real-time weather events at some time during the semester (47.3 % for SURV3, Question 7) with 31 % viewing a specific weather event (Question 9, SURV1). Most users (52 %) indicated that they were casual users, 22 % regular, 14 % weekly and 6 % monthly (Question 10, SURV1). Most users (62 %) downloaded data (32 % did not download) from the system (Question 13, SURV1) with 51 % of users indicating that this was easy to do (Question 14, SURV1). For SURV3, 85.5 % of users downloaded data (Question 11) with 64.8 % indicating that this was easy to do (Question 12).

Responses to Questions 15 to 18 were gratifying – more than 60 % (more than 82 % for SURV2 and SURV3) of respondents indicated that they benefited from use of the system

and that their appreciation of the ranges of the various weather elements had improved. They also indicated that system use had improved their ability to manipulate data in a spreadsheet and/or display data in graphic or table form, improved their appreciation/awareness of global climate change and/or global warming aspects (85.5 % for SURV3). They also found that system use had improved their appreciation/awareness of the graphical display, and trends, of agro-environmental and environmental data (79.6 % for SURV3). The increase in the percentage of positive responses for Questions 15 to 18, between the original questionnaire (SURV1) and the second and third questionnaires in 2013 (SURV2 and SURV3), was due to the fact that the respondents in May 2013:

1. were all second year agro-environmental students with little previous exposure to agro-environmental data and information and therefore with much to gain. The respondents of SURV1 were a mixture of second-year students, staff and postgraduates;

2. were all second-year undergraduates and were exposed very early in the semester to the system and with regular, almost weekly, exposure over a four-month period.

What was particularly gratifying about Question 15, however, was the high percentage of 80 % (89 % for SURV2 in May 2013 and 85.5 % for SURV3) of respondents indicating that use of the system had improved their appreciation of the ranges of the various weather elements. It does mean, however, that early exposure to the system could assist in the understanding of physical concepts of the agro-environment.

More than 75 % of respondents of SURV1 (83 % for SURV3) were not aware of a similar system elsewhere (Question 19, SURV1; Question 20, SURV3) with one respondent indicating that the South African Weather Service (SAWS) system was similar and another that the South African Sugarcane Research Institute (SASRI) system was similar. An examination of both systems mentioned showed that they are not similar with the only commonality being that they all display weather data. The SAWS and SASRI systems are regional/national systems but focus on far fewer weather elements with data downloads not available (SAWS) or focus on sugar-growing areas (SASRI). Both SAWS and SASRI staff have requested further information on the Web-based teaching and learning system.

2.4.13 Comments on suggestions for system improvement

Two questions of the questionnaire allowed users to openly comment on the system and to suggest improvements or specific requirements that could be incorporated as part of the system. A total of 27 comments were received. These were divided into positive, negative and potentially actionable comments.

The positive comments included:

Berg wind forecasting very interesting
Great tool
Helpful, helped with research significantly
Impressive, comprehensive
Thanks for service
Thanks to MGA, Nico, Steve
Useful tool
Very useful, enjoyable and interesting resource
Well demonstrated

The negative comments were as follows:

Complicated, please simplify
Improve visuals
Info separate from data; email notifications; mobile app; link to forecasting
Make it easier to download data
More interactivity and flexibility
More info needed on use of Website
More interactivity
Overview screen, better graphics, mobile version

Many of the negative comments arise due to the limitations of the version of the commercial software used. For example, the comments: improve visuals, make it easier to download data, more interactivity and flexibility are challenges presented by the software. The visuals are limited by the resolution the software allows for the uploaded images. This resolution is a compromise between bandwidth and aesthetics. Furthermore, it is not possible with version 3.1 of RTMC Pro for there to be any within text enhancements such as bold, italics, superscripts, subscripts and mathematical symbols. [This is possible with version 4.1.1 of through support for Unicode characters²⁰]. The only interactivity possible is through the use of alarms, hotspots and data tables which may be downloaded as html files for use in Excel. Alarms may be used based on measurements, defined measurement limits (highs or lows, for example), measurement comparisons and/or the rate of change limits being defined for certain measurements. This has already been used in the system through an automated measurement and control application using the automated evaporative cooling system employed in the ICFR forestry nursery (Kaptein and Savage, 2013). In the case of hotspots, these can and have been used to redirect the user to a different Web page constructed to provide more information on particular issues relevant to the visible screen. This aspect needs to be pursued further but requires the "buy-in" by other disciplines willing to make use of the data and information provided for their own teaching, learning and research. There is an

²⁰ The new WebServer software, now part of RTMC Pro 4.1.1, is also more dynamic and interactive, allowing graph zooming and animated graphics. The software takes advantage of resource caching which improves page loads and refreshes significantly.

overview screen that defines the concept of air temperature measurement and some of the other weather elements. There is no mobile application or version necessary since any Web-enabled cell phone can display the data and information system. The procedure is simple and requires two or three key presses, if the URL has been stored previously, to display the information. This procedure has been successfully tested a number of times on a Web-enabled Nokia cell phone.

The potentially actionable comments received were as follows:

2.4.13.1 Advertise

The system has in fact been advertised (The Mercury, Tuesday 27th September 2011; UKZN Online, Volume 5, Issue 35, 16th September 2011; UKZN Teaching and Learning 2010/2011 Annual Report, page 36; UKZN Everyone email to staff and students of 17th August 2011; UKZN Teaching and Learning 2012 Annual Report, page 38). We know by word-of-mouth that lecturers in Agricultural Engineering, Agricultural Plant Sciences, Botany (including Grassland Science), Hydrology, Geography and Soil Science have mentioned the system to their undergraduate and postgraduate students. Two articles on adverse weather phenomenon that were published in The Witness (2nd and 10th January 2013) also served to highlight the system. Two awards, one in 2013 for the Best Paper Presentation at a national conference (Combined Congress 2013: Crops, Soils, Horticulture and Weeds) and a second award in 2014 for the best paper published in the South African Journal of Plant and Soil (Chapter 4), both based on the system, have also assisted in raising the profile of this work nationally. Also, plans are in hand to extend use of the system to students in a large first year UKZN module.

The system was the basis for a published paper based on this chapter, six conference papers and two conference posters and these have assisted in highlighting the system, to the extent that staff at the University of Stellenbosch that have been involved with e-learning have requested that a course be offered there to their staff and postgraduate students.

2.4.13.2 Additions

The system contains many screens, if not too many. The limitation is that only one http port was provided for use. The addition of a dewpoint temperature graph, as suggested, would mean the creation of an additional screen as would adding information on frontal weather. The display of frontal weather is somewhat outside the scope of the Web-based system and is in any case the role of the South African Weather Services.

2.4.13.3 Demonstration

Use of the system has spread by word-of-mouth and personal email contact. There has been no deliberate attempt to demonstrate the system other than through a paper accepted for publication (Savage *et al.*, 2014), in a few practicals of the Agrometeorology modules and during six conference presentations. This decision will soon be reviewed and if there is a need for a demonstration/seminar/Webinar, this will be given.

2.4.13.4 Link to forecasting

This needs to be pursued and is a logical next-step of the system but requires an injection of funding and interested and competent students. Some work on this has already started (Chapter 5) but will not be discussed here.

2.4.13.5 More interactivity

The limitation of RTMCPPro versions 3.1 and 4.0 are that, aside from alarms sent via emails, use of hotspots and display of data tables that may be downloaded, no interactivity is possible. As mentioned previously, interactivity will be possible with version 4.1.

2.4.13.6 Screen all over campus

This is now possible. The late Martin Voges (ICS, UKZN) wrote an html script file (Appendix 2.1) that allows the toggling of the various system screens every 30 s. This then allows the system screens to be displayed on any PC connected to the Internet.

2.4.14 An issue not addressed by the first questionnaire and concluding remarks

With hindsight, a major deficiency with SURV1 was that there was no question that addressed whether graphical and table display of data reduced the role of language, therefore assisting with the cognitive retention of information.

In SURV2 and SURV3 in 2013, in addition to the questions asked previously, the role of language was also surveyed. The SURV2 results showed (Table 2.5) that more than 75 % of the respondents indicated that the graphical display of data had enabled further understanding of the agro-environmental concepts irrespective of language compared to 6 % of the respondents indicating that it had not. Most of the respondents were isiZulu and 72 %

Table 2.5 Results of the second open questionnaire (May 2013) used to gauge the role of the graphical display of data in enabling further understanding of the agro-environmental concepts irrespective of language (79 respondents, SURV2). The percentage for each language and category of answer and the total number of responses n are shown.

17 Do you think that the graphical display of data has enabled your further understanding of the agro-environmental concepts irrespective of language? Please elaborate.						
Home language	Yes	No	No answer	Not really	Neutral	Not absolutely
isiZulu	31 (72 %) ²¹	4 (9 %)	7 (16 %)	1 (2 %)	0	0
English	20 (80) %	1 (4 %)	2 (8 %)	1 (4 %)	0	1 (4 %)
isiXhosa	3 (100 %)	0	0	0	0	0
Other languages ²²	6 (75 %)	0	1 (13 %)	0	1 (13 %)	0
Total (n = 79)	60 (76.0 %)	5 (6.3 %)	10 (12.7 %)	2 (2.5 %)	1 (1.3 %)	1 (1.3 %)

indicated "yes" to this question compared to 80 % for main-language English speakers. A relatively small percentage (13 %) of all respondents did not give an answer to this question. For SURV3, more than 89 % of respondents indicated positively to the identical question.

SURV3 also included a question (Question 18, Table 2.4): What language(s) are you comfortable with? Surprisingly, nearly 78.2 % of the respondents indicated that they were comfortable with English even though the 27 out of 41 that replied to this question are isiZulu mother tongue. This high response may be due to the fact that for many of the technical terms in English for the agro-environmental sciences do not have a corresponding term in isiZulu. There is therefore an urgent need to create a list of isiZulu, and possibly isiXhosa, technical terms specific to Agrometeorology and allied disciplines.

²¹ The percentage in brackets represents the percentage for the particular language (row)

²² Other home languages included Chichowa, French, Setswana, Sotho, Tshivenda, Venda and Xitsonga

In the original project funding proposal the following statement was made: "Students are not adequately exposed to the state of the environment around them and therefore leave with a degree that has not skilled them with a first-hand understanding of the environment and they are therefore unable to easily relate to the problems of our uncertain agricultural and environmental future." It is very pleasing that 80.6 % (SURV1) of respondents indicated that the Web-based system improved their appreciation of the ranges of the various weather elements – e.g., range in air temperature, relative humidity, rainfall, wind speed – and therefore they have improved their first-hand understanding of the environment, irrespective of their home language.

2.5 Conclusions

The Web-based system described was shown to be versatile in terms of allowing the connection of a wide range of sensors and is easily upgradeable in terms of additional dataloggers, sensors and environments. The various graphic screens supported the concept of visual literacy by displaying the graphics and data tables of near real-time Web-based data. There was easy and open access to such data and information through a range of media, including the Internet, FTP, Bluetooth and a Web-enabled cell phone for use in the laboratory, lecture room or off-campus for a wide range of disciplines in the agricultural, earth and environmental sciences, as well as early-warning of a topical event such as Berg winds, flood or frost. Experience showed that students learnt more quickly and had increased interest when using real and very recent data relevant to their chosen discipline. The Web-based system has been used as a tool in teaching and learning. Students were made more aware of the current weather and other environmental conditions via the frequently updated current data. Also through tutorials and projects, they handled large datasets, plotted and interpreted data graphically – thereby enhancing visual literacy. In a questionnaire for which there were 63 respondents out of a potential total of 95, representing a return percentage of 68.4 %, more than 80 % indicated that use of the system had improved their appreciation of the ranges of the various weather elements. More than 60 % of the respondents indicated that they benefited from use of the system, that they had improved their ability to manipulate data in a spreadsheet and/or display data in graphic or table form, improved their appreciation/awareness of global climate change and/or global warming aspects and improved their appreciation/awareness of the graphical display, and trends, of agro-environmental and environmental data. The questionnaire also highlighted some of the weaknesses of the software used for displaying the graphics, in particular text enhancements, resolution and system interactivity. In a subsequent questionnaire (79 respondents), 89 % indicated that the system had improved their appreciation of ranges. More than 75 % of the respondents

indicated that the graphical display of data had enabled further understanding of the agro-environmental concepts irrespective of language. About 78 % of the respondents indicated that they were comfortable with English even though the 27 out of 41 that replied to this question are isiZulu mother tongue. This high response could be due to the fact that many of the technical terms in English for the agro-environmental sciences do not have a corresponding term in isiZulu. There is therefore an urgent need to create a list of isiZulu technical terms specific to Agrometeorology and allied disciplines.

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Appendix 2.1 The html code used (courtesy of the late Martin Voges of UKZN) for automatically toggling static screens of the Web-based data and information system every 30 s.

```

<!DOCTYPE html PUBLIC "-//W3C//DTD HTML 4.01//EN" "http://www.w3.org/TR/html4/strict.dtd">
<html lang="en">
<head>
<title>AgroMet kiosk page display</title>
<!-- Page & script to cycle through a display of all pages at http://agromet.ukzn.ac.za:5355/ for a kiosk. Very
simple client-side requests, no checking for errors, browser peculiarities, undesirable effects, etc. i.e. for use
'voetstoots'.
For customisation etc. see all comments with ">>>AGROMET modifications".
With compliments, Martin Voges, Academic Computing Pmb, March 2012. -->

<style type="text/css">
body, html { margin: 0; padding: 0; width: 100%; height: 100%; overflow: hidden; }
iframe { border: none; }
/* >>>AGROMET modifications: Style(s) below for text, if any, displayed above agromet data (currently an H2
heading) */
h2 {text-align: center;}
</style>
<script type="text/javascript">

/* >>>AGROMET modifications: Adjust the length of time (in seconds) each page is displayed below: */
var displaytime = 30;

/* >>>AGROMET modifications: The common part of each page's URL below should not need to be changed
unless there are changes to the whole site's URLs */
var baseURL = "http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=";

var pgTab = {
  nextIndex: 0,

  scrns: [
/*          eg. as used originally with indiv times for each page:
    {sname: "http://www.google.com", time: 5},
    {sname: "http://www.yahoo.com", time: 10},
    */

/* >>>AGROMET modifications: To add additional screens/tabs to be displayed, add a line with the screen
definition portion of the page's URL below in the format illustrated, eg. for a "New Page" at URL
http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=New%20Page add a line
    {sname: "New%20Page"},
Note all but the last line must terminate with a comma. */

    {sname: "AWS%20current"},
    {sname: "AWS%20yesterday"},
    {sname: "Definition%20of%20terms"},
    {sname: "Human%20comfort"},
    {sname: "AIT"},
    {sname: "AMET%20notices"},
    {sname: "Climate%20change%201"},
    {sname: "Climate%20change%202"},
    {sname: "Global%20warming"},
  ]
}

```

```

    {sname: "Berg%20winds"},
    {sname: "Chill%20units"},
    {sname: "CO2"},
    {sname: "Fire%20danger%20index"},
    {sname: "Flood"},
    {sname: "Fronts"},
    {sname: "Greenhouse%20tunnel%20U"},
    {sname: "Greenhouse%20U%20N-S%20c%20E-W"},
    {sname: "Greenhouse%20tunnel%20U%20Tair%20gradients"},
    {sname: "Leaf%20wetness"},
    {sname: "Temperature"},
    {sname: "Tair%20comparison"},
    {sname: "Tair%20comparison%202"},
    {sname: "Tair%20comparison%20digital"},
    {sname: "Wind%20velocity"},
    {sname: "Energy%20balance"},
    {sname: "ETo"},
    {sname: "Diffuse%20radiation"},
    {sname: "Radiation%20balance"},
    {sname: "Radiation%20calibration"},
    {sname: "Solar%20radiation%20comparison"},
    {sname: "Sunshine"},
    {sname: "Astronomical"},
    {sname: "Infrared%20analyser%20checks"},
    {sname: "Test%20CR1000_AWS%20current"}

    // Note: No comma after last item!
],

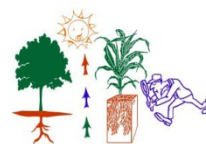
display: function()
{
    var scrn = pgTab.scrns[pgTab.nextIndex];
    frames["displayArea"].location.href = (baseURL + scrn.sname);
    pgTab.nextIndex = (pgTab.nextIndex + 1) % pgTab.scrns.length;
    // setTimeout(pgTab.display, scrn.time * 1000); - if used as originally with indiv times for each page
    setTimeout(pgTab.display, displaytime * 1000);
}
};

window.onload = pgTab.display;

</script>
</head>
<body>
<!-- >>>AGROMET modifications: remove or modify <h2 ... /h2> line below to adapt text displayed above
agmet data, if any. Related CSS style(s) above -->
<h2>http://agromet.ukzn.ac.za:5355/ :-:-:-: AgroMet realtime climate data</h2>
<iframe name="displayArea" width="100%" height="100%"></iframe>
</body>
</html>

```

Appendix 2.2 Open questionnaire used to gauge use and feedback to improve the Web-based teaching, learning and research system.



QUESTIONNAIRE – WEB-BASED TEACHING AND LEARNING DATA AND INFORMATION SYSTEM FOR AGRICULTURAL AND ENVIRONMENTAL SCIENCES
(<http://agromet.ukzn.ac.za:5355>)

BACKGROUND:

1. In July 2011, a multi-disciplinary web-based teaching and learning near real-time data and information system was proposed and a pilot study launched. Subsequently, the UKZN Teaching and Learning Office provided funds for a full system which was launched late last year.
2. The purpose of this open questionnaire for student and staff users is to research, possibly for publication, the value and use of the system and for what purpose and to invite comments on improvements for the future. We appreciate your participation!

INSTRUCTIONS:

1. Please complete and return the questionnaire to the mail box outside Room 120, Rabie Saunders Building, PMB or via Email to savage@ukzn.ac.za by **15 November 2012**. If you wish to remain anonymous please mail the completed questionnaire to Dr MG Abraha, UKZN, Agrometeorology, Room 120, Rabie Saunders Building, PMB 3201.
2. Where relevant, please give additional comments. At the end of the questionnaire, there is a blank area for raising additional points relevant to the topic of the questionnaire.

Date:		
Contact Details:	Name:	
	Email:	
Affiliation:		

1	Please indicate your status, e.g., undergraduate student, postgraduate, academic or support staff member, researcher, etc. If you are a student, please indicate the year of study and degree/programme for which you are registered. If you are a staff member or researcher, please indicate your discipline and/or area(s) of interest.
2	Have you been shown how to use the web-based data and information system (http://agromet.ukzn.ac.za:5355) and if so by whom and for which module? If you were not shown how to use the system, how user-friendly did you find it?
3	Please give the reason(s) for your use of the system. If you are a student, please indicate which module(s) you are registered for required your use of the system. Otherwise, where necessary, please elaborate.
4	Please indicate how you accessed/viewed the system – e.g., on-campus LAN connection, Bluetooth, off-campus, corridor display.

5	Were you ever unable to connect to the system? If yes, how many times?
6	What event/screen did you monitor/use and why? Where necessary, please elaborate.
7	What was the purpose for your use of the system – e.g., for interest, personal, study, data download, practical(s), tutorial(s), lecture(s), project? If you used the system for academic work, please indicate the purpose(s) and in each case the corresponding module. Please elaborate.
8	Is the content of the system related to the lecture content of modules you are taking and if so, state which modules and which lecture content? Please elaborate.
9	Have you used the system for observing any particular near real-time event(s)? If so, please indicate which event(s).
10	Please describe your frequency of use of the system – e.g., casual, monthly, weekly, regular.
11	Which event/screen did you use the most? If more than one screen, please say which ones. To answer this question you may wish to refer to: http://agromet.ukzn.ac.za:5355
12	Have you made use of the AWS_today and AWS_yesterday screens? Please elaborate.
13	Have you ever downloaded data or graphics from the system? If so, please state the purpose for downloading and the relevant module – e.g., for use for a tutorial, a project, an assignment, a practical, research, personal use. Please elaborate.
14	If you did download data or graphics from the system, how easy was it to do? Please elaborate.

15	Has the web-based system improved your appreciation of the ranges of the various weather elements – e.g., range in air temperature, relative humidity, rainfall, wind speed, etc.? Please elaborate.
16	Has the web-based system improved your ability to manipulate data in a spread sheet and/or display data in graphic or table form? Please elaborate.
17	Has the web-based system improved your appreciation/awareness of global climate change and/or global warming aspects? Please elaborate.
18	Has the web-based system improved your appreciation/awareness of the graphical display, and trends, of agro-environmental and environmental data? Please elaborate.
19	Are you aware of any similar system(s) used elsewhere? If so, please give details.
20	Do you have any suggestions for improvement or specific requirements that could be incorporated as part of the web-based system? If so, please elaborate.

Further general comments/considerations
Please add further comments relevant to this questionnaire.

Thank you for your participation – should you wish to receive a copy of the results of the questionnaire, please email savage@ukzn.ac.za

22 October 2012 mjs

Appendix 2.3 Examples of information, based on the Web-based system, supplied to the lay public.²³

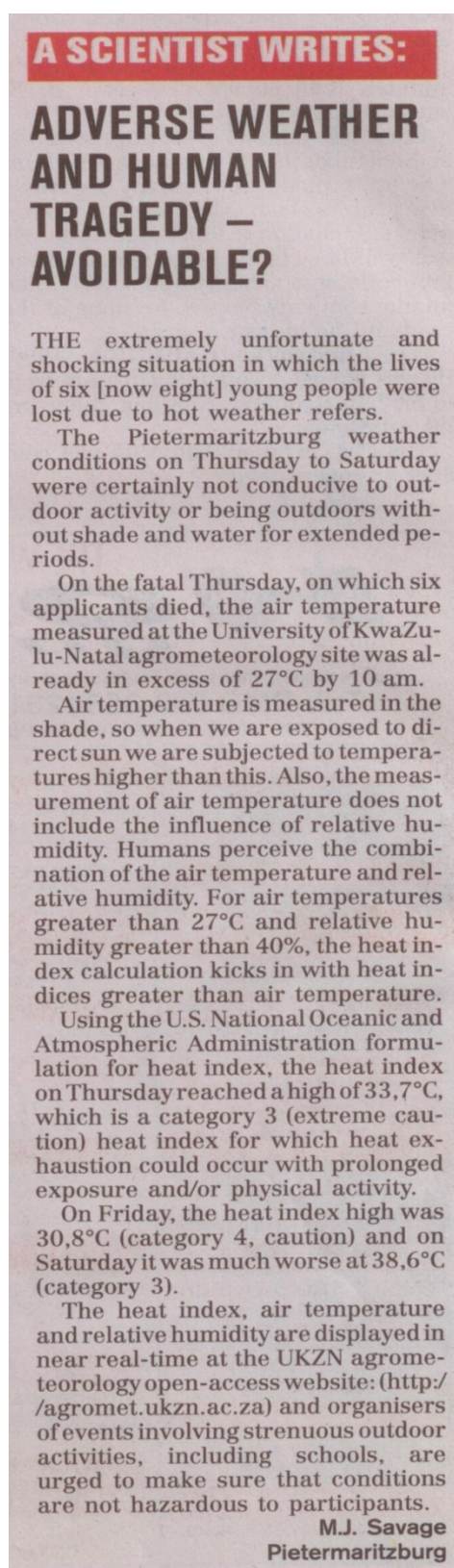


Figure A2.1 An article, published on page 3 of The Witness on 2nd January 2013, regarding the death of eight young people that died due to a high heat index, lack of shade, lack of water and physical activity.

²³ See Supplementary Materials, items 12 and 13 (pages SM42 and SM43 respectively)

Wind speed reached 57 km/h in Sunday's storm

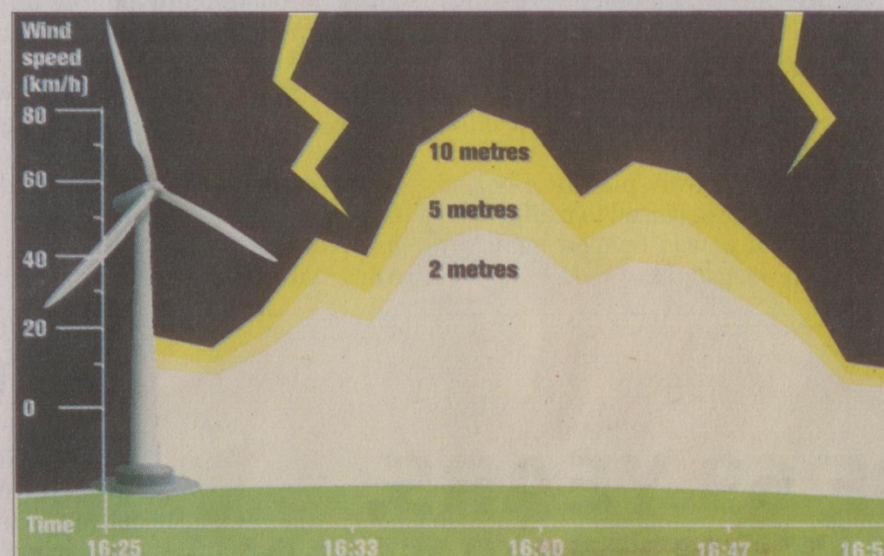
THE highest recorded wind speed at the height of Sunday's storm was 57 km/h, said Michael Savage, a senior professor at the University of KwaZulu-Natal.

Savage has given a breakdown of the storm, which lasted from about 4.30 pm to 4.54 pm. He said the air temperature high in the shade was 32,4°C, resulting in a thunderstorm developing in the late afternoon.

"The wind gust at two metres, the highest recorded wind speed for the day, was 57 km/h at 4.37 pm at the agrometeorology main tower of the University of KwaZulu-Natal," Savage told *The Witness*.

"This corresponds to a Beaufort [scale] wind number of seven [high wind, moderate gale, near gale]. In high winds, it is the wind gust that does the damage, even though the gust may be for a very short period."

The wind speed measurements for the thunderstorm are shown by the solid line curve in the graph.



GRAPHIC: THE WITNESS

Sunday's storm saw wind speeds of 57 km/h just two metres above the ground.

The wind speed high was 47 km/h from almost north. At heights of five metres (dashed line of the chart) and ten metres (dashed-dotted curve)

wind speed increases.

So in open areas, a 10-metre-high tree could experience winds of in excess of 80 km/h as shown.

Michael Savage, a senior professor at the UKZN

IN HIGH WINDS, IT IS THE WIND GUST THAT DOES THE DAMAGE.

This would explain the extensive damage caused to trees in open areas, with damage to power lines in some areas. Savage said knowing the wind speed for the tenth storey of a building is almost an impossible calculation.

"Not only does wind speed change with height above ground in a complex way, but it varies a lot from place to place and is reduced significantly in urban areas due to protection provided by walls, buildings, etc. In more open areas, more damage may occur," he said. — WR.

Figure A2.2 An article, published on page 3 of *The Witness* on 10th January 2013, regarding a storm in Pietermaritzburg that caused extensive damage.

3 Estimation of leaf wetness duration for a short-grass surface²⁴

3.1 Abstract

The measurement of leaf wetness duration (LWD) was investigated using sub-hourly dielectric, infrared thermometer grass-surface temperature, dewpoint temperature, grass temperature using a freely exposed thermometer just above the soil surface and relative humidity (RH) measurements. Near real-time LWD data and information displays and alerts were made available timeously via a Web-based system. The data and information leaf wetness display was also used by undergraduate students, registered for second-year Agrometeorology modules, as part of their lecture, practical and project material. LWD was estimated above a short-grass surface using five methods: dielectric leaf wetness sensors (LWS); a constant RH for which wetness events were registered for RH greater than 87 %; RH between 70 and 87 % if RH increased by more than 3 % in 30 min; and two dewpoint depression based methods for which surface-measured temperature, using an infrared thermometer (IRT), and grass temperature, were compared with the dewpoint at either 0.1 or 2 m. The RH methods generally overestimated LWD compared to the other methods. There was reasonable agreement between IRT- and grass-temperature methods if rain days were excluded but these methods showed poor agreement with LWS measurements of LWD. Microclimatic and radiative conditions, during nocturnal condensing events, are reported. Automatic weather station data would have more value if grass temperature was included for determination of LWD by comparison of grass temperature with a measured dewpoint, with timeous alerts and Web-based display of near real-time LWD data and graphics. The use of the Web-based data and information system for use by students in understanding the measurement of leaf wetness is described.

Keywords: *dielectric leaf wetness sensor; grass-surface temperature; nocturnal grass temperature*

3.2 Introduction

The first agrometeorological application of the Web-based data and information system involved the estimation of leaf wetness duration, using various methods, for a short-grass surface with the results displayed and updated automatically in near real-time.

²⁴ Based on Savage (2012b)

About 14.1 % of crops are lost because of plant diseases annually. This loss corresponds to an annual cost of about US\$220 billion (Agrios, 2005). Early prediction of disease and timeous dissemination of data and information relating to leaf wetness measurement or estimation is one attempt to lower this cost. The estimation of surface wetness on plants and the role and importance of leaf wetness by rain, dew, guttation from leaves and irrigation, for the prediction of leaf diseases, has been reviewed by Magarey *et al.* (2005). As has been mentioned by Savage (2012a) with respect to the rare reporting of conditions relevant to a weather hazard such as frost occurrence, the near real-time reporting of leaf wetness and leaf wetness duration is also rare.

Various methods have been used for determining dew duration or dew events. Direct measurements of dew and rates of dew accumulation have been reported (Monteith, 1957, Wilson *et al.*, 1999). Dew drops forming on wood blocks (Duvdevani, 1947), electrical resistance grids (Gillespie and Kidd, 1978), and dielectric sensors (Decagon Devices, 2010) have been used as leaf proxies. A remote optical wetness sensor has been used for sand-crusted and desert shrub surfaces (Heusinkveld *et al.*, 2008). Kruit *et al.* (2004) used four methods for estimating grassland leaf wetness duration (LWD). They found that although none perfectly predicted LWD, an extended threshold RH method worked best. They used a relative humidity (RH) threshold value of 87% for leaf wetness, but extended this to 70-87% for RH increases of more than 3% in 30 min, as leaves were assumed to be wet under these conditions. A Penman–Monteith model has been used as a "reference" index to estimate crop LWD using automatic weather station (AWS) and net irradiance measurements (Sentelhas *et al.*, 2006).

Empirical methods for estimating LWD have also been used, usually based on AWS data (Kim *et al.*, 2005). Their measurements of wind speed were adjusted to the height of leaf wetness measurements but there is currently no simple method known for adjusting air temperature and RH measurements at a standard height to that of leaf wetness measurements. Sentelhas *et al.* (2004) found that LWD measured by sensors near the standard screen height over turfgrass differed considerably from LWD measured by sensors in a maize canopy, especially during periods with LWD less than 15 h. They found that sensors at 300 mm above turfgrass, at angles between 15 and 45° to the horizontal, provided much more accurate estimates of crop LWD and potential for use in operational plant disease management.

A dielectric (capacitance) leaf wetness sensor (LWS) measures the ability of material on and near its surface to store electrical charge, giving important information about surface and near-surface conditions if the LWS is positioned close to a grass surface. Since the dielectric constant for air is 1 and 80 for liquid water, it is possible to determine whether there is liquid water (dew) on the surface or if the LWS is dry. For the LWS to mimic a leaf, it needs to have similar optical properties – reflection coefficient and emissivity – and similar

physical properties – specific heat capacity, density, length, breadth and thickness – of a typical leaf. The sensor surface also needs to be hydrophobic. More importantly, however, the ideal LWS should require no individual calibration.

The Internet provided a mechanism for the instant placement of data and information. Near real-time field-based measurement systems, such as described in Chapter 2 (Savage *et al.*, 2014), allowed AWS and other data to be collected, displayed in the form of graphs/tables and data and updated automatically and frequently using the Internet. Furthermore, advances in telecommunications allow automatic email and SMS alerts and early warning (nowcasting) of agricultural and environmental events based on near real-time measurements. The telecommunication can be initiated directly using a datalogger programme with a connected GSM modem, or equivalent, or initiated using base-station computer software that has telecommunication capability.

The Internet is a convenient tool for the placement of near real-time data for teaching and learning purposes. Instead of the instructor having to provide data to every student, each student is empowered to extract the data that they need whether it be for lectures, practicals or a project. With instruction the relevant data, such as in this case LWS and LWD data, can be used by students to plot graphs of various types.

In this study, the measurement of LWD is investigated using dielectric, infrared surface temperature, dewpoint temperature, grass temperature and RH measurements with near real-time data and information and alerts made available timeously via a Web-based system. Also, the use of the Web-based teaching and learning data and information system as part of an undergraduate student practical focused on the LWS and LWD is described.

3.3 Materials and methods

Measurements were obtained for the winters of 2011 and 2012 from 19th April 2011 to 15th June 2012, at Pietermaritzburg, KwaZulu-Natal, South Africa (altitude 684 m, latitude 29.628° S, longitude 30.403° E). The long-term average annual rainfall total is 839 mm with relatively mild rainless winters and long-term average of 13 frost days per annum and mean daily minimum air temperatures for April to October of 13.3, 9.4, 5.8, 6.0, 8.6, 11.0 and 13.2 °C respectively.

An AWS system was attached to a 3-m instrumentation mast with additional air temperature sensors extending to 8 m (Table 3.1). Based on World Meteorological Organisation (2008) recommendations, the mast AWS measurements satisfied the requirements for the minimum distance-away from obstacles. A single thermocouple was used to measure grass temperature at a height-above-canopy between 25 and 50 mm (World

Table 3.1 Field-station measurement and base-station system details.

Station details	Field-station mast details
Sensor	Type-E thermocouples for grass temperature, air temperature in seven-plate Gill radiation shields at heights of 0.1, 1, 2,, 8 m; at 0.1 m: leaf wetness sensors ²⁵ , RH and air temperature (CS215 ²⁶); raingauge ²⁷ - rim at 1 m; at 2 m: solar irradiance (CM3 ²⁸), CS500 RH and air temperature ²⁹ , wind speed and direction ³⁰ model 03001 and IRT ³¹ at 2.6 m; four-component net radiometer (CNR1 ²⁸) at 3 m
Field dataloggers	CR1000 ²⁶ datalogger, AM16/32A multiplexer ²⁶
Field-to-base station communication	Datalogger-attached RF416 ²⁶ in turn connected to a panel antenna ³² in line-of-sight with the base station
Grounding at field station	Field station antenna connected to an arrestor, in turn connected to the radio. The datalogger was earthed
Base station for connecting to field station	A RF416 radio connected to an 8-m antennae and surge-protector
Software	Base station software included LoggerNet ²⁶ for data downloads. RTMC Pro version 3.0 ²⁶ (and subsequently 4.0 and 4.1) was used to create a Web-based display of data, graphics and alerts of daily, weekly and monthly LWD totals

²⁵ Model LWS, Decagon Devices Inc., Pullman, Washington State, USA²⁶ Campbell Scientific Inc., Logan, Utah, USA²⁷ Pronamic RAIN-O-MATIC (0.254-mm resolution) (Pronamic ApS, Ringkøbing, Denmark)²⁸ Kipp & Zonen B.V., Delft, The Netherlands²⁹ Vaisala Oyj, Helsinki, Finland³⁰ RM Young Company, Traverse City, Michigan, USA³¹ Apogee IRT model IRR-P (half angle of 22°): Apogee Instruments Inc., Logan, Utah, USA³² Poynting antenna POY-A-PANL-0005: Poynting Direct (Pty), Johannesburg, Gauteng, South Africa

Meteorological Organisation, 2008). In addition, a single infrared thermometer (IRT) was used to measure the grass surface temperature. The instrument (Table 3.1) was attached to the mast and positioned at 45° to the horizontal, facing south and at a height of 2.5 m, sensing a target diameter of 1.9 m. Cost limitations and insufficient datalogger channels prevented replication of the grass and IRT measurements. To avoid nighttime condensation on net radiometer sensors, a four-component net radiometer (Table 3.1) was heated, under datalogger control, during nighttime whenever the RH at 2 m exceeded 95 %. Increased net irradiance measurement errors would result without the heating. Solar irradiance (I_s) measurements were used to indicate sunrise and outgoing (L_u) and incoming (L_d) infrared irradiances used for determining nocturnal radiative conditions.

Dielectric LWS units (Table 3.1) were co-located, 45° to the horizontal with their centre position 100 mm above the soil surface. Following a 2500-mV excitation, the measured LWS voltage depends on the dielectric constant of a zone 10 mm from the upper sensor surface (Decagon Devices, 2010). The average LWS voltage was determined, from ten 12-s measurements, every 2 min because 60-min data were inadequate for LWD determination. The manufacturer recommends that a LWS voltage less than 274 mV corresponds to a dry LWS (dielectric constant of 1) and that greater than or equal to 284 mV corresponds to a wet LWS (dielectric constant of 80). Field calibration for the individual LWS used here was not required – in contrast to the electrical impedance grid units used by Gillespie and Kidd (1978) which required field determination of the wet-to-dry resistance transition point. For timeous early warning of LWD, near real-time data and graphics were displayed on the Internet using a Web-based data and information system:

<http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Leaf%20wetness>

(Table 2.2, **Leaf wetness row**) using commercially-available software (Table 3.1). Daily email and SMS alerts were easy to implement using the base station computer software, allowing automatic alerts and early warning and reporting of daily, weekly and monthly LWD totals for the different methods. The LWD totals were determined using the datalogger programme and stored in the datalogger memory every 2 min. The leaf wetness display served not only to display data and information but was also used as a teaching and learning resource for undergraduate and postgraduate students, providing up-to-date and relevant data for their needs at any time.

Various micrometeorological measurements (19th April to 20th September 2011) were examined, selected from the full dataset for 2011 and 2012, and the dielectric LWS measurements. Leaf wetness was also inferred by comparing surface and grass temperatures with the dewpoint measured at 0.1 or 2 m and by using the two RH methods (Kruit *et al.*, 2004).

For use by students, a practical exercise on leaf wetness was based on the Web-based system. Students were given background information and then were required to download data by following a set of instructions.

The background information given to students concerned details of dielectric sensors: "Extended periods of leaf wetness may result in plant disease and/or encourage its spread. A sensor, known as a leaf wetness sensor mimics a leaf as far as leaf wetness is concerned. A pair of an array of interlocking copper fingers is used. When dry, the pair of fingers is not in electrical contact. So when the sensor is dry, no electrical current can pass through from the one set of fingers to the other since the resistance R is infinite, Using Ohm's Law, $R = V/I$ where V is the voltage, when $I = 0$ mA then R is infinity. However, when the sensor is wet, the film of water conducts electrons and the electrical resistance is finite. The trick though is to define the electrical resistance at which point the sensor may be described as mostly wet. Capacitance is the measure of the electric charge that can be stored in a media such as soil. The dielectric constant (– it is not a constant!) is directly related to capacitance. All media has a dielectric constant. As the media dielectric constant increases, the capacitance of the media increases."

For use by students, a practical exercise required students to download data by following a set of instructions:

"In Internet Explorer, use the URL <http://agromet.ukzn.ac.za:5355>. Navigate to the AWS yesterday tab, right click on the table of data in the bottom right. [The data has the html (hypertext mark-up language) format.] Press CTRL+a (CTRL followed by simultaneously pressing a to select all data) and then press CTRL+c (to copy all data to computer memory). In a blank Excel worksheet, with the cursor at cell A1, press CTRL+v to paste the memory-stored daily AWS data. Delete the repeated header rows so that there remains a header row area and then the data beneath that with no repeated headers. Plot a temporal graph with four series of: the daily-averaged leaf wetness sensor millivoltage for each of the two leaf wetness sensors (left-hand y axis) and daily total wetness for each of the two leaf wetness sensors (right-hand y axis). Discuss, in a couple of sentences, your results. Include discussion on a comparison of the results for the two leaf wetness sensors mounted at about 100 mm above the soil surface."

3.4 Results and discussion

Output voltage for three LWS units, for a six-day period, is shown (Figure 3.1). Changes in upper-surface LWS conditions from dry-to-wet, which corresponds to voltages increasing from about 265 mV to more than 300 mV, are clear (Figure 3.1, with the maximum LWS

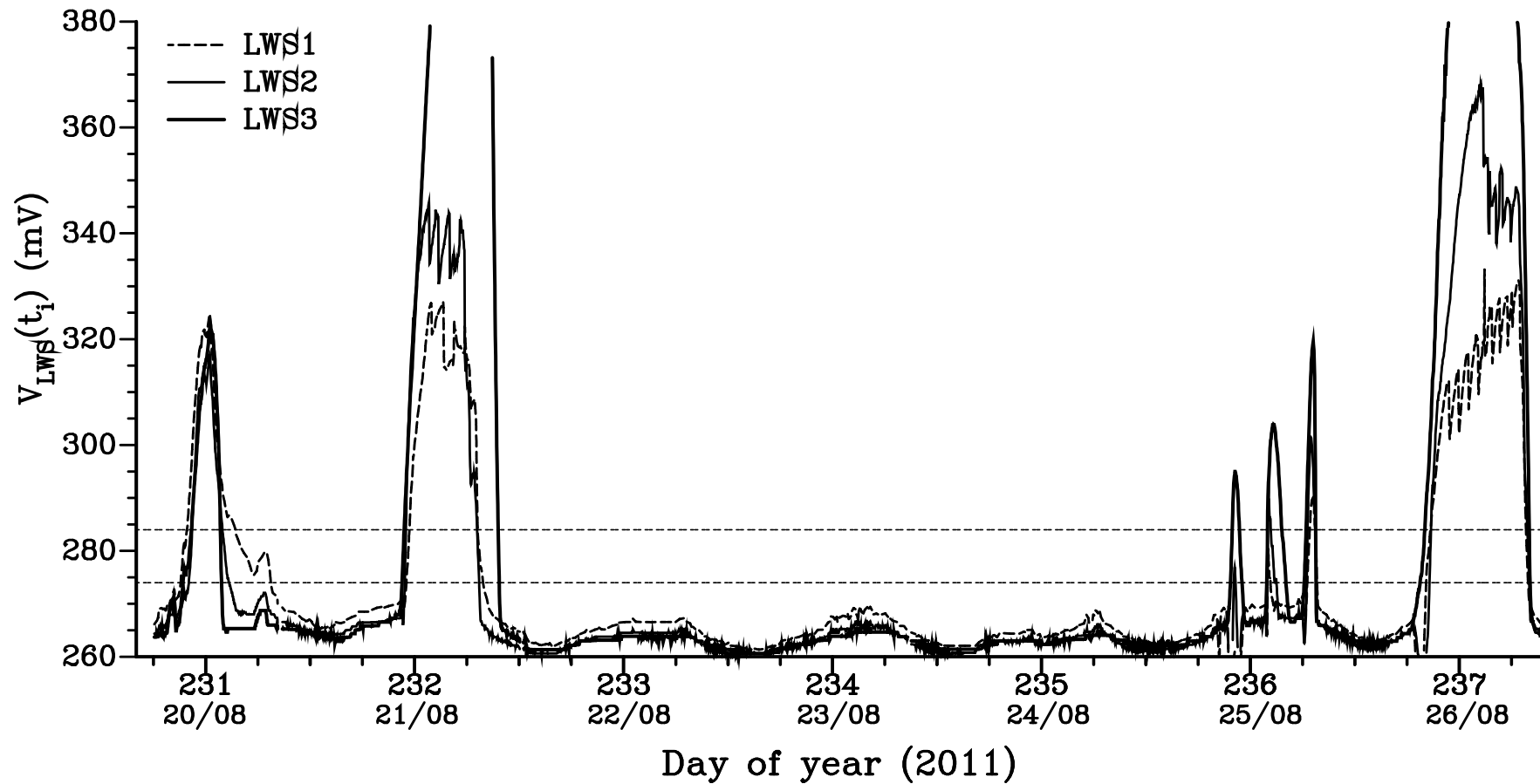


Figure 3.1 Two-min voltage traces for three LWS units for 20th to 26th August, 2011 with significant leaf wetness on three mornings. The two dotted lines correspond to 274 mV below which the sensor is dry, and 284 mV, above which the sensor is wet. LWS3, when dry, yielded voltages which exceeded 380 mV for some of the time – the y-axis scale has therefore been limited to 380 mV for clarity of the events between 274 and 284 mV.

voltage limited to 380 mV for clarity of the events between 274 and 284 mV). The oscillatory nature of the voltage for a wetted LWS, on 21st August 2011 (day 232) and 26th August, could be caused by droplets dripping off the upper surface of the angled-LWS followed by more wetting given further decreases in temperature, and so on. Once the LWS units are wet, the voltages are different. However, the large and abrupt changes, corresponding to dry-to-wet and wet-to-dry transitions, occur at almost the same time for the different units (Figure 3.1). For LWS measurements, RH and air temperatures in the 0 to 0.1-m region are important.

Night-time grass temperatures were field-checked by comparison with IRT surface temperature for wetness and frost conditions (Figure 3.2, with both restricted to less than 7.5 °C to encompass most nights). There are very few grass temperatures less than surface temperature with agreement improving for lower (negative) temperatures, consistent with stable conditions. The difference in height between grass and surface temperatures is therefore

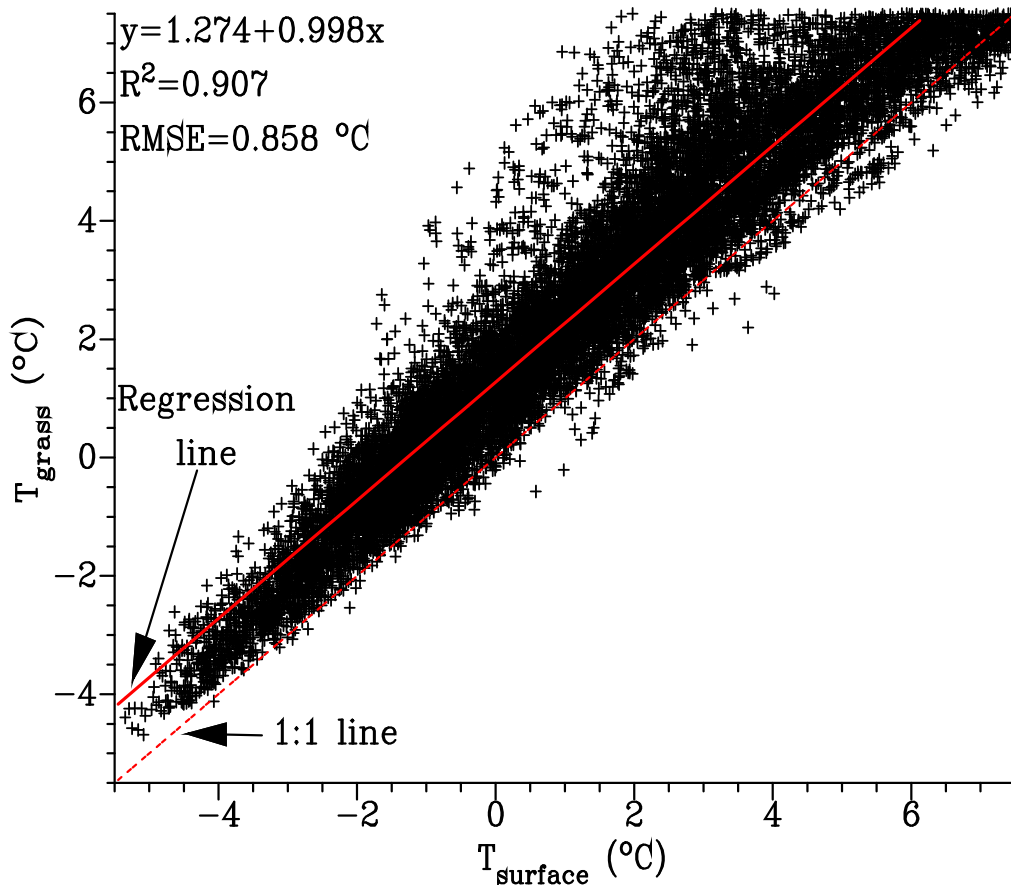


Figure 3.2 Field measurements (2-min) and statistics for IRT surface vs grass temperature for nocturnal conditions (midnight to 06h30) for 22th April to 20th September 2011. Both axes have been restricted to less than 7.5 °C to encompass most nights with frost.

critical, resulting in many cases with $T_{grass} > T_{surface}$. In addition, since leaf wetness is a surface phenomenon, surface temperature in relation to atmospheric dewpoint (condensation) is critical.

Five methods were used for determining LWD: (1) dielectric LWS, (2) grass temperature in comparison with the dewpoint (either at 0.1 or 2 m), (3) surface temperature in comparison to the dewpoint at 0.1 m, (4) the constant RH method and (5) the extended threshold RH method (Kruit *et al.*, 2004; Sentelhas *et al.*, 2008).

The microclimatic conditions (Figures 3.3a and 3.4a) and the voltage traces for three LWS units on winter mornings with surface wetness are shown (Figures 3.3d and 3.4d). The microclimatic conditions for condensing events are fairly similar to those for frost occurrence (Savage, 2012a) except that for these condensing events, afternoon temperatures are usually greater and there is often an increased wind speed at night. LWD for LWS units are fairly similar in spite of very different voltages during wetness periods – they showed the same time for transitions from dry-to-wet and wet-to-dry on both nights (Figures 3.3c and 3.4c). The LWD estimate using surface temperature in comparison to the dewpoint (Figures 3.3d and 3.4d) was in reasonable agreement with that using the LWS units. The estimate of LWD using grass temperature in comparison to dewpoint was in reasonable agreement with the surface temperature method in Figure 3.3d but not so in Figure 3.4d – probably because of the increased wind speeds near sunset and increased nocturnal cloud (Figure 3.3a compared to 3.4a and 3.3b compared to 3.4b).

Daily LWD totals for the five methods for a 31-day period are shown (Table 3.2). The agreement in daily LWD for three collocated LWS units is very good (Table 3.2, first five columns). Agreement between the IRT- and grass-temperature methods is reasonable apart from when one method indicated almost no LWD, corresponding to rain days (underlined in Table 3.2). The statistics for these comparisons, with rain days excluded, are shown (Table 3.3). The two RH methods (Sentelhas *et al.*, 2008) generally yielded larger LWD estimates compared to others (Tables 3.2 and 3.3). For daily LWD < 5.5 h, the IRT estimates of LWD were less than those using the LWS method and *vice versa* for LWD > 5.5 h because of the fact that there were days for which LWS units registered no LWD with the IRT temperature method indicating surface wetness and *vice versa*. In addition, the IRT method, based on surface conditions, generally yielded larger estimates than the grass-temperature method. This result would explain the height differences noted by Sentelhas *et al.* (2004), and mentioned previously, that LWD measured closer to the surface than at screen height gave better estimates of LWD for use in operational plant disease management.

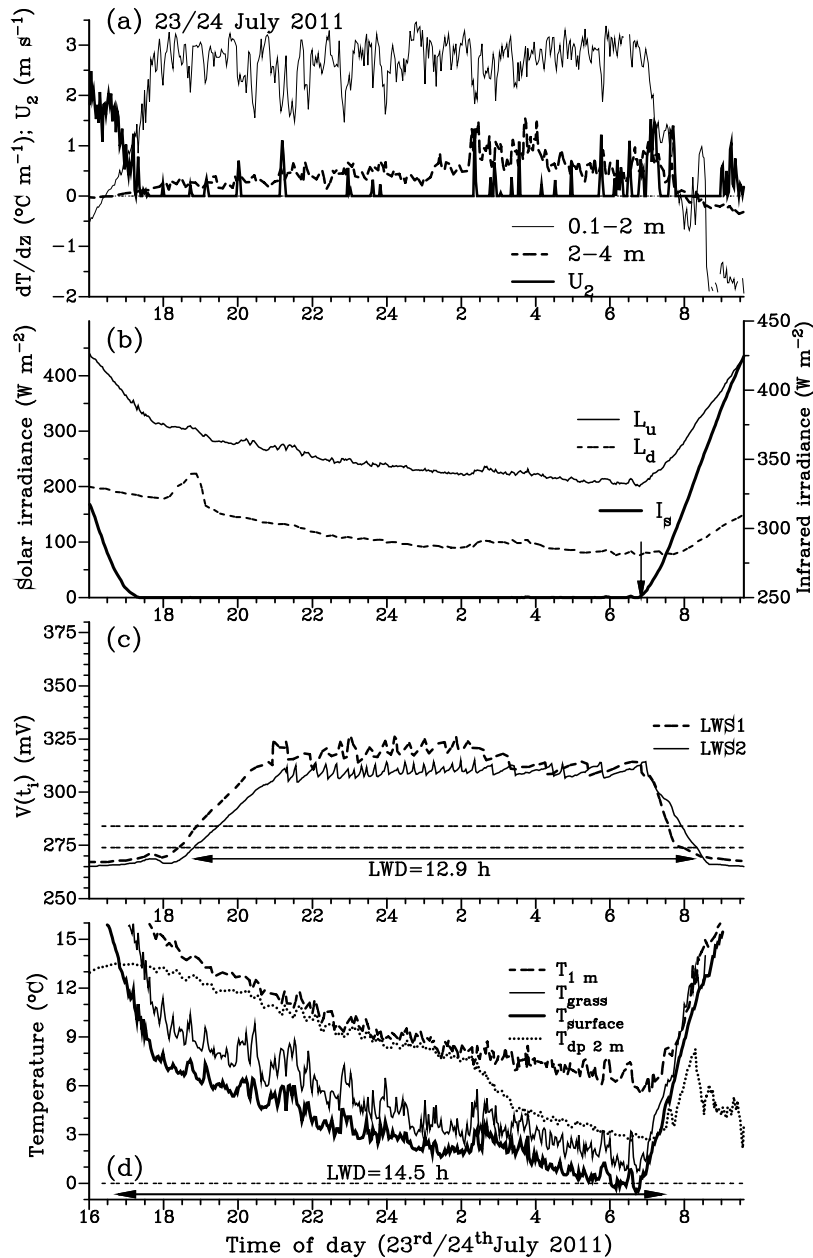


Figure 3.3 Conditions for a night/day early in winter (23rd/24th July 2011) with significant leaf wetness. (a) Air temperature profile gradient between 0.1 and 2 m and between 2 and 4 m and wind speed at 2 m; (b) outgoing (L_u) and downward (L_d) infrared and solar (I_s) irradiances – sunrise is shown by the arrow; (c) LWS voltage $V_{LWS}(t_i)$ traces for two units including the 274 and 284 mV limits shown by the dotted horizontal line; (d) air temperature at 1 m ($T_{1\text{ m}}$), grass temperature (T_{grass}), IRT-measured surface temperature (T_{surface}) and the dewpoint at 2 m ($T_{dp\ 2\text{ m}}$).

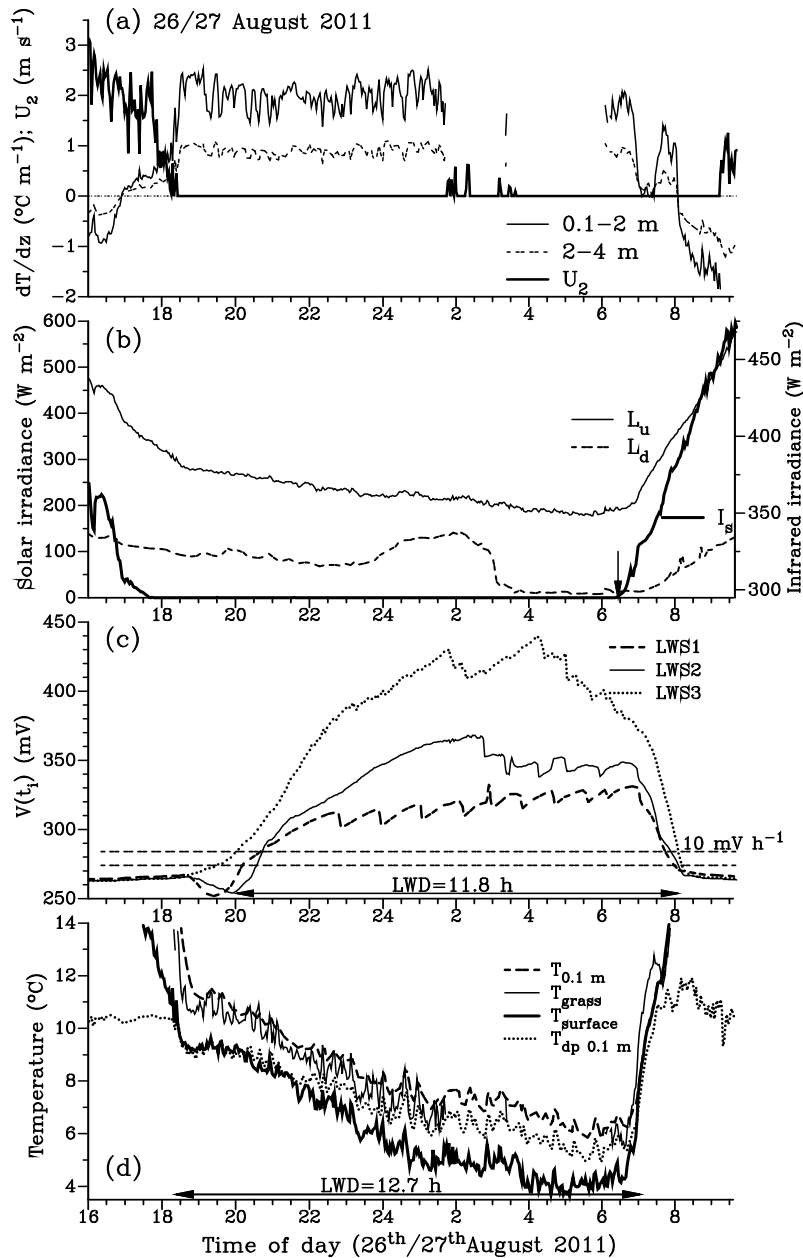


Figure 3.4 Conditions for a night/day in late winter (26th/27th August 2011) with significant leaf wetness. (a) Air temperature profile gradient and wind speed; (b) outgoing and downward infrared and solar irradiances; (c) LWS voltage traces for three units; (d) air temperature at 0.1 m ($T_{0.1 m}$), grass temperature, IRT-measured surface temperature and dewpoint at 0.1 m ($T_{dp 0.1 m}$).

Table 3.2 Daily LWD (h) (starting 20th August (day 231) and ending on 20th September (day 262) 2011) for three LWS units, the IRT-temperature, grass-temperature and the two RH methods and the daily total rainfall (mm).[†] The mean and standard deviation for LWD is also included.

Day	LWD LWS1	LWD LWS2	LWD LWS3	LWD mean	LWD SD	LWD IRT	LWD grass temp- erature	LWD RH	LWD RH (ext- ended)	Rain- fall
231	4.0	2.9	2.9	3.3	0.6	0	0	10.6	13.1	0.3
232	7.2	7.1	9.6	8.0	1.4	1.6	0.0	9.3	10.9	0.0
233	0.0	0.0	0.0	0.0	0.0	7.7	0.0	6.6	7.5	0.0
234	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	1.2	0.0
235	0.0	0.0	0.8	0.3	0.5	5.8	0.0	0.0	1.7	0.0
236	4.0	4.6	6.7	5.1	1.4	3.6	0.5	2.2	5.6	0.0
237	7.6	7.8	8.0	7.8	0.2	7.0	5.0	11.9	13.4	0.0
238	8.4	9.8	10.4	9.6	1.0	8.6	2.7	8.4	9.5	0.0
239	7.5	8.3	9.7	8.5	1.1	0.0	0.0	8.8	11.2	0.8
240	11.5	10.9	10.7	11.0	0.4	0.2	0.0	18.0	18.1	0.8
241	6.9	7.3	7.9	7.4	0.5	8.6	4.2	14.3	15.7	0.0
242	0.0	1.8	1.4	1.1	0.9	6.9	3.8	5.9	6.7	0.0
243	0.2	0.9	1.4	0.8	0.6	2.0	0.0	5.2	7.0	0.0
244	0.0	0.0	0.0	0.0	0.0	0.3	0.0	7.8	7.8	0.0
245	0.0	0.0	0.0	0.0	0.0	1.8	0.0	0.0	0.0	0.0
246	4.5	5.8	9.1	6.5	2.4	0.0	0.0	6.3	7.1	0.0
247	10.1	10.6	12.3	11.0	1.2	5.9	5.1	10.5	12.7	0.0
248	10.1	10.3	10.8	10.4	0.3	12.4	10.7	12.0	13.5	0.0
249	9.7	10.1	10.0	9.9	0.2	11.7	9.2	10.6	12.3	0.0
250	9.8	12.2	13.8	11.9	2.0	6.8	6.9	14.6	15.7	0.0
251	9.9	10.5	8.2	9.5	1.2	6.2	5.6	13.0	14.7	0.0
252	6.1	6.2	6.3	6.2	0.1	3.5	3.3	10.7	12.2	0.3
253	5.5	5.7	6.7	6.0	0.6	6.4	4.1	11.3	12.7	0.0
254	1.9	1.9	2.3	2.0	0.2	5.5	3.1	4.6	4.6	0.0
255	5.0	5.3	5.9	5.4	0.5	2.0	0.0	6.2	8.2	0.0
256	7.0	8.8	5.9	7.2	1.4	3.0	2.5	6.0	7.7	0.0
257	6.4	7.0	7.3	6.9	0.5	0.0	0.0	17.6	19.4	18.3
258	4.5	4.9	5.4	4.9	0.4	4.7	2.0	7.3	8.4	0.0
259	4.1	3.7	4.7	4.2	0.5	4.3	3.9	5.2	6.4	0.0
260	5.1	5.5	6.4	5.7	0.7	5.8	4.2	7.8	9.1	0.0
261	4.0	3.0	4.2	3.7	0.6	4.6	3.5	4.2	6.5	0.0
262	4.0	3.0	4.2	3.7	0.6	4.6	1.1	2.2	4.9	0.0
Total	165.1	175.9	193.0	178.0		143.6	81.3	258.9	305.2	20.3
Total ^{††}	129.6	140.5	156.1	142.1		139.9	78.0	193.3	231.3	

[†] Underlining indicates days with rain; ^{††} Excludes days with rain

Table 3.3 Comparison between daily LWD measured using the IRT method (x) against the LWS sensor, grass temperature and RH and RH extended methods for 20th August to 20th September 2011 excluding rain days.

	LWD LWS (y) vs LWD IRT (x)	LWD Tgrass (y) vs LWD IRT (x)	LWD RH (y) vs LWD IRT (x)	LWD RH extended (y) vs LWD IRT (x)
Slope	0.583	0.763	0.710	0.734
Intercept (h)	2.243	-1.065	3.481	4.764
Coefficient of determination (R ²)	0.228 (NS)	0.654 (S)	0.273 (NS)	0.287 (NS)
Root mean square error (h)	3.406	1.761	3.674	3.672

NS: not significant at 95 %; S: significant at 99 %

All three of the LWS units, after more than a year of field use, showed signs of the paint degrading to powder because of high ultraviolet (UV) exposure. Under accelerated exposure, equivalent to five years of high UV exposure, there was no change in sensor function (unpublished Campbell Scientific LWS manual, 2008). The manufacturer of the LWS recommends treating the surface of the sensor with a UV blocker every 45 days (Decagon Devices, 2010).

Based on the results of this study, the LWS method appears to be accurate and consistent in determining LWD, compared to grass- and IRT-temperature methods. However, according to Savage (2012a), the use of the LWS method for determining frost is problematic, with the grass- and/or IRT-temperature methods more desirable for determination of frost duration.

The Web-based data and information system displayed for leaf wetness was used to assist students in understanding the measurement of leaf wetness (Figure 3.5). The leaf wetness application, used by a total of 69 students in 2011 and 66 students in 2012, was specifically designed for students to download a large dataset (daily data) from the Web-based system as an html file and use the data in Excel. The exercise also required the students to edit the dataset so that only relevant information related to LWS and LWD was included. After editing the large file, the students received instruction on plotting different types of graphs – e.g., temporal and scatter graphs. Using the LWS data and the instruction on graph plotting, they were then able to plot their own double y-axis graph with the daily-averaged leaf wetness sensor millivoltage for each of the two leaf wetness sensors on the left-hand y-axis and daily total wetness for each of the two leaf wetness sensors on the right-hand y-axis. Many of the students had not plotted graphs of this nature before using Excel. As a result,

Leaf wetness

Worldwide, about 14.1 % of crops are lost due to plant diseases annually. This loss corresponds to an annual cost of about US\$220 billion (Plant Pathology, 5 th edition by G.N. Agrios published by Academic Press in 2005). Early prediction of disease is one attempt to lower this cost. Extended periods of leaf wetness may result in plant disease and/or encourage its spread. A sensor, known as a leaf wetness sensor mimics a leaf as far as leaf wetness is concerned. A pair of an array of interlocking copper fingers is used.

A dielectric (capacitance) leaf wetness sensor (LWS), shown in the photograph, measures the ability of material on and near its surface to store electrical charge, giving important information about surface and near-surface conditions if the LWS is positioned 100 mm above a grass surface at 45 degrees. Since the dielectric constant for air is 1 and 80 for liquid water, it is possible to determine whether there is liquid water (dew) on the surface or if the LWS is dry. For the LWS to mimic a leaf, it needs to have the same optical properties – reflection coefficient and emissivity – and the same physical properties – specific heat capacity, length, breadth and thickness – of a typical leaf.

The measurement of leaf wetness duration (LWD) is possible using dielectric, infrared surface temperature, dewpoint temperature, grass temperature and relative humidity (RH) measurements. The manufacturer recommends that a LWS voltage less than 274 mV corresponds to a dry LWS and that greater than 284 mV corresponds to a wet LWS. If the infrared surface temperature or the grass temperature is less than or equal to the dewpoint, then surface wetness has occurred. RH methods have also been used for LWD but these methods are not as good as the other methods mentioned.

Average LWS mV now 261.4 mV

Theoretically, the IRT temperature method should yield the correct estimate of LWD but the method is more expensive and requires dewpoint – it has the advantage of a greater surface-area representation. To increase the value of AWS measurements, AWS systems should also include grass temperature that could be used to estimate LWD if RH measurements are available. Furthermore, timeous email alerts with near real-time data and graphics of LWD displayed on the Internet would considerably enhance the data product.

Icons below indicate the daily, weekly and monthly accumulation of LWD using the LWS method, the IRT method (Target less than or equal to the dewpoint at 100 mm) and the grass temperature method (Tgrass less than or equal to the dewpoint at 100 mm).

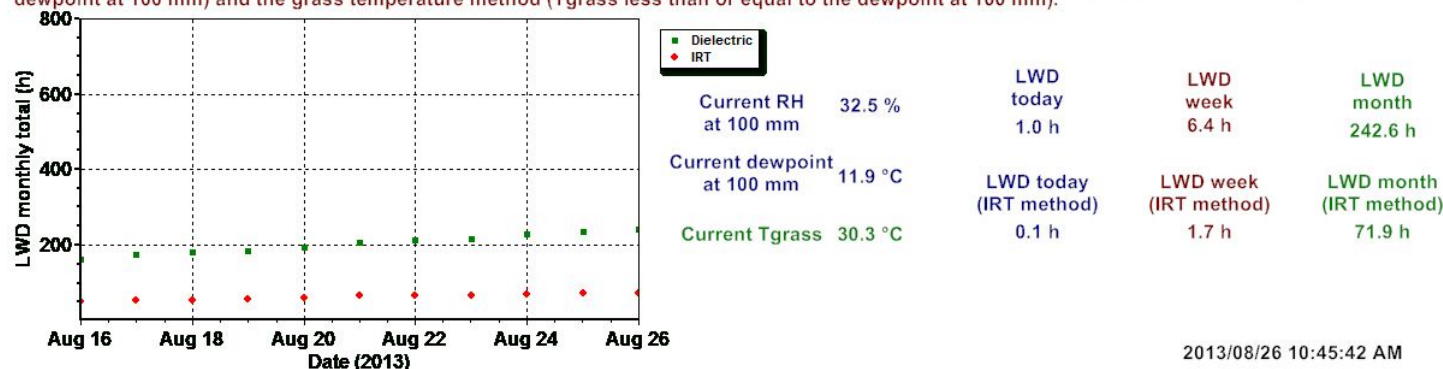


Figure 3.5 The leaf wetness screen for accumulated monthly LWD. Also shown are the average LWS voltage (left of the photograph) and the LWD for today, for the week and current RH and dewpoint at 100 mm and the current grass temperature.

students were given open access to the computers in the laboratory as well as extra staff and demonstrator time, receiving maximum attention so as to be comfortable with graph-plotting. The LWS exercise was held early in the semester so that students were able to use the skills of graph plotting and apply these skills not only in the other practicals but also for their other modules. Their skill in graph-plotting was reinforced since many of the other practicals, and their project, required further graph-plotting.

3.5 Conclusions

Sub-hourly leaf wetness duration measurements using collocated LWS units were consistent. The RH and extended RH methods for estimating LWD yielded the largest LWD estimate for the five methods used. The IRT- and grass-temperature methods for estimating LWD involved comparing these temperatures with the dewpoint at 0.1- or 2-m heights. These two methods showed reasonable agreement with the latter underestimating compared to the LWS estimates. The IRT-temperature method showed reasonable agreement of daily LWD with the grass-temperature method. There was poor agreement between the IRT-temperature LWD estimates and the LWS estimates even if rain days were excluded, underestimating for $LWD < 5.5$ h, although there were days for which LWS units registered no LWD with the IRT-temperature method indicating surface wetness and *vice versa*. Theoretically, the IRT-temperature method should yield the correct estimate of LWD and has the advantage of a greater surface-area representation, but the method is more expensive and requires RH data for a sensor adjacent to the surface. To increase the value of AWS measurements, AWS systems should also include grass temperature that could possibly be used to estimate LWD if RH measurements are also available. Furthermore, timeous email and SMS alerts with near real-time data and graphics of LWD for the current day, week and month displayed on the Internet, as used in this investigation, would considerably enhance the data product. The inclusion of a screen on leaf wetness provided significant benefit to the Web-based system, was relevant to the agricultural plant and biological sciences students and intermeshed the role of the environment in biological systems.

3.6 Acknowledgements

Funding from University of KwaZulu-Natal (UKZN; Teaching and Learning Office, College of Agriculture, Engineering and Science and Research Office) and South African National Research Foundation is gratefully acknowledged. The Water Research Commission is also acknowledged for previously funding equipment used. Administrative and technical support of Jothi Manickum and technical support of Michael Abraha, Nicholas Moyo and Nile Babikir (Agrometeorology Discipline, UKZN), electronic support of Guy Dewar (Electronics

Centre, UKZN) and the support of the UKZN AMET212 students of 2011 is also acknowledged.

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4 Estimation of frost duration for a short-grass surface³³

4.1 Abstract

The estimation of frost duration (FD) is investigated using dielectric, infrared surface temperature and grass temperature sub-hourly measurements. Near real-time FD data and information displays and alerts were also made available via a Web-based system. FD was estimated using a dielectric leaf wetness sensor (LWS) method, for which the sensor voltage was between 274 and 284 mV with a voltage rate of change less than 10 mV h⁻¹ for a 4-min period, and two temperature methods for which infrared thermometer (IRT) and grass temperatures were compared with 0 °C. FD estimation using the LWS method ensured that most of the transitional dry-to-wet and wet-to-dry events were not included in the FD count. Generally, the IRT method yielded the largest estimate of FD, grass temperature method lower and LWS method lowest. Micrometeorological measurements showed consistent air temperature gradients of 2.25 °C m⁻¹ for cloudless nocturnal frosted conditions with few air temperature measurements at 1 m and none above indicating frost occurrence. At the very least, automatic weather station systems should contain a grass thermometer or preferably an IRT for determination of FD with near real-time data and graphics displayed, including timeous alerts of frost occurrence and FD, using the Internet. The Web-based system data and information system consisted of a frost screen for which FD for the different methods, and data tables for student projects, was displayed.

Keywords: *dielectric constant; grass-surface temperature; ice*

4.2 Introduction

The second agrometeorological application of the Web-based data and information system involved the estimation of frost duration, using various methods, for a short-grass surface with the results displayed and updated automatically in near real-time.

"Frost damage is the leading weather hazard, on a planetary scale, as far as agricultural and forest economic losses are concerned" (Garcia *et al.*, 2010). Past and future estimates of frost occurrence are useful in crop production agroecological zoning systems for which data and models may be used to construct crop production suitability maps (Garcia *et al.*, 2010). In

³³ Based on Savage (2012a). Judged the best published paper in the South African Journal of Plant and Soil. The award was by the Board of the South African Society of Crop Production at the 2014 Combined Congress of the South African Soil Science, Crop Science, Horticultural Science and Weed Science Societies

spite of the importance of frost as a weather hazard, near real-time reports of conditions relevant to its occurrence are rare.

Definitions of frost in the published literature vary. Some reports define frost as the occurrence of a temperature at or less than 0 °C, measured in a Stevenson screen or equivalent, at a height of between 1.25 and 2 m (Hogg, 1950; Lawrence, 1952; Hogg, 1971; Snyder and de Melo-Abreu, 2005). For the present study, however, the following definition was used: frost is the condition for which the surface and earthbound objects have a temperature at or below 0 °C, often resulting in ice on leaves and soil if the temperature of the surface, or air near the surface, is less than or equal to the dewpoint temperature. This definition recognises that frost is a surface phenomenon with surface conditions, or those just above, having greater relevance than conditions 1 to 2 m above. This definition also recognises the fact that for frost occurrence either latent energy phase change of water vapour to ice (sublimation) or the freezing of dew (hoar frost) or vegetation (black frost) may occur.

Two types of frost are freeze (advection) frosts and radiative frosts. In South Africa, radiative frosts are more common although freeze frosts may occur and then later spurn radiative frosts. There are two types of radiative frosts: hoar and black frost. A white frost is a relatively heavy coating of a hoar frost. In black frosts, there is no surface ice due to very low and negative dewpoints. The very cold conditions result in cell sap freezing and cells rupturing with vegetation appearing black. Surface ice, however, could occur after black frost occurrence if there is further cooling with air temperature approaching the dewpoint. Hoar frosts occur when atmospheric conditions above the surface are cool, calm, clear and dry with an air temperature inversion for many tens of metres above the surface, although these conditions often also apply to black frosts. The slightest breeze can destroy the air temperature inversion that develops on calm nights. Wind results in convective air movement – warmer air from above mixes with cooler air from below, resulting in warmer surface conditions. Virtually cloud-free sky conditions are required for radiation frosts because nocturnal clouds are effective in increasing the returned infrared irradiance resulting in elevated surface temperatures. Dry atmospheric conditions, or more correctly low water vapour pressure conditions, are required since water vapour is a greenhouse gas that effectively returns infrared irradiance to the surface, elevating surface temperatures. The cool, calm, clear, dry and inversion requirements for frost need to occur simultaneously because if any of these are not met, the chance of frost is much reduced. Atmospheric measurements from an automatic weather station (AWS) system, usually at 2 m above the soil surface, may not represent the conditions at and just above the surface and such measurements are therefore not easily applied for determining frost occurrence or for calculating frost duration (FD). However, the inclusion of an inexpensive exposed temperature sensor in contact with blades of grass could yield valuable information on conditions just above the surface and therefore

information on frost occurrence. Negative surface temperatures, measured using an infrared thermometer (IRT), satisfy the definition of frost occurrence. Furthermore, the detection of ice may be possible using dielectric measurements close to the surface because the dielectric constant for air (1), ice (5) and liquid water (80) are different.

The Internet allows for the placement of near real-time data that may be used for timeous alerts but also for teaching and learning purposes. Instead of the instructor having to provide data to students for their undergraduate projects, students can easily extract relevant data (Savage *et al.*, 2014). With limited instruction, the relevant data such as in this case FD data, can be used by students for guided project work (Appendix 4.1).

The main aim of the study was to determine the occurrence of frost and FD for a short-grass surface for a relatively high relative humidity site using various measurement methods, which may be applied at any location, including dielectric, infrared surface temperature and grass temperature methods. The study also aimed to demonstrate the importance of including a grass thermometer with a normal AWS system for determining frost occurrence and FD. For the purpose of timeous email and SMS alerts for early-warning of frost, and for teaching and research purposes, the Web-based display of collected data and graphics (Chapter 2) was developed to enhance the use of the data and their display.

4.3 Materials and methods

Measurements reported on were from 19th April 2011 to 15th June 2012), Pietermaritzburg, KwaZulu-Natal, South Africa (altitude of 684 m, latitude 29.628° S, longitude 30.403° E).

Details of the measurement site and AWS system and sensors are summarised in Table 4.1, adapted from Savage (2012b). Air temperature and relative humidity was measured in a naturally-ventilated 12-plate Gill radiation shield at a height of 100 mm. A profile of naturally-ventilated air temperature thermocouples, each in a seven-plate shield, was used to determine the environmental lapse rate. Grass temperature was measured using a freely exposed thermocouple, 25 to 50 mm above the soil surface, in contact with blades of grass (World Meteorological Organisation, 2008). Grass-canopy surface temperature was measured using an infrared thermometer (IRT) positioned at 45° to the horizontal, facing south and at a height of 2.5 m, sensing a target diameter of 1.9 m corresponding to an area of 2.8 m². The IRT was calibrated in the laboratory using a large radiator (Savage and Heilman, 2009) and the grass-temperature thermocouple calibrated, in a water bath, against a reference PT1000 resistance thermometer (data not shown). Corrections were necessary for the IRT target temperatures but not for the grass temperatures.

Table 4.1 Field-station measurements and relevant base-station system details.

Station details	Field-station mast details
Sensor	IRT ³⁴ at 2.6 m; at 0.1 m: RH and air temperature (CS215 ³⁵); type-E thermocouples for grass temperature, air temperature in seven-plate Gill radiation shields at heights of 0.1, 1, 2, ..., 8 m; at 2 m: solar irradiance (CM3 ³⁶), CS500 RH and air temperature ³⁷ , wind speed and direction ³⁸ model 03001; four-component net radiometer (CNR1 ³⁶)
Field dataloggers	CR1000 ³⁵ datalogger, AM16/32A ³⁵ multiplexer. All measurements were every 12 s and averaged/totalled every 2 min
Field-to-base station communication	Datalogger-attached RF416 ³⁵ radio and antenna

The collocated leaf wetness sensors (LWS) were placed at a height of 100 mm above soil and at an angle of 45° with respect to the horizontal. Using an excitation voltage of 2500 mV, a LWS voltage less than 274 mV corresponds to a dry LWS and a voltage greater than or equal to 284 mV to that of a wet LWS. Voltages between these two limits correspond to that of a contaminated LWS (Decagon Devices, 2010). Voltage values and/or voltage changes could indicate frost on the sensor surface, or a temporary transitional change in surface conditions from dry-to-wet, wet-to-ice, wet-to-dry, ice-to-wet or from dry-to-ice (Figure 4.1). For the particular dielectric LWS used, the sensor radiation balance and thermodynamic properties including specific heat capacity and sensor area, thickness and density is similar to that of leaves and the sensor surface is hydrophobic (Decagon Devices, 2010). Furthermore, since the LWS does not need to be painted, no calibration for individual units was necessary.

Methods for easy and remote detection of frost were investigated. Frost was judged to have occurred based on grass or IRT surface temperature. Frost was assumed to occur for 2 min when a measured average 2-min (IRT or grass) temperature less than or equal to 0 °C occurred, in keeping with the definition of frost. For timeous early warning of frost, email and SMS alerts were issued for the first daily occurrence of a measured grass temperature of 2 °C or less occurring 2 h or more before sunrise. The first daily occurrence was determined and stored in the datalogger memory with the alerts issued using the base station computer software. The near real-time data of daily, weekly and monthly FD for the various methods were also displayed using a Web-based data and information system:

<http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Frost>

(Table 2.2, **Frost row**).

³⁴ Apogee IRT model IRR-P (half angle of 22°): Apogee Instruments Inc., Logan, Utah, USA

³⁵ Campbell Scientific Inc., Logan, Utah, USA

³⁶ Kipp & Zonen B.V., Delft, The Netherlands

³⁷ Vaisala Oyj, Helsinki, Finland

³⁸ RM Young Company, Traverse City, Michigan, USA

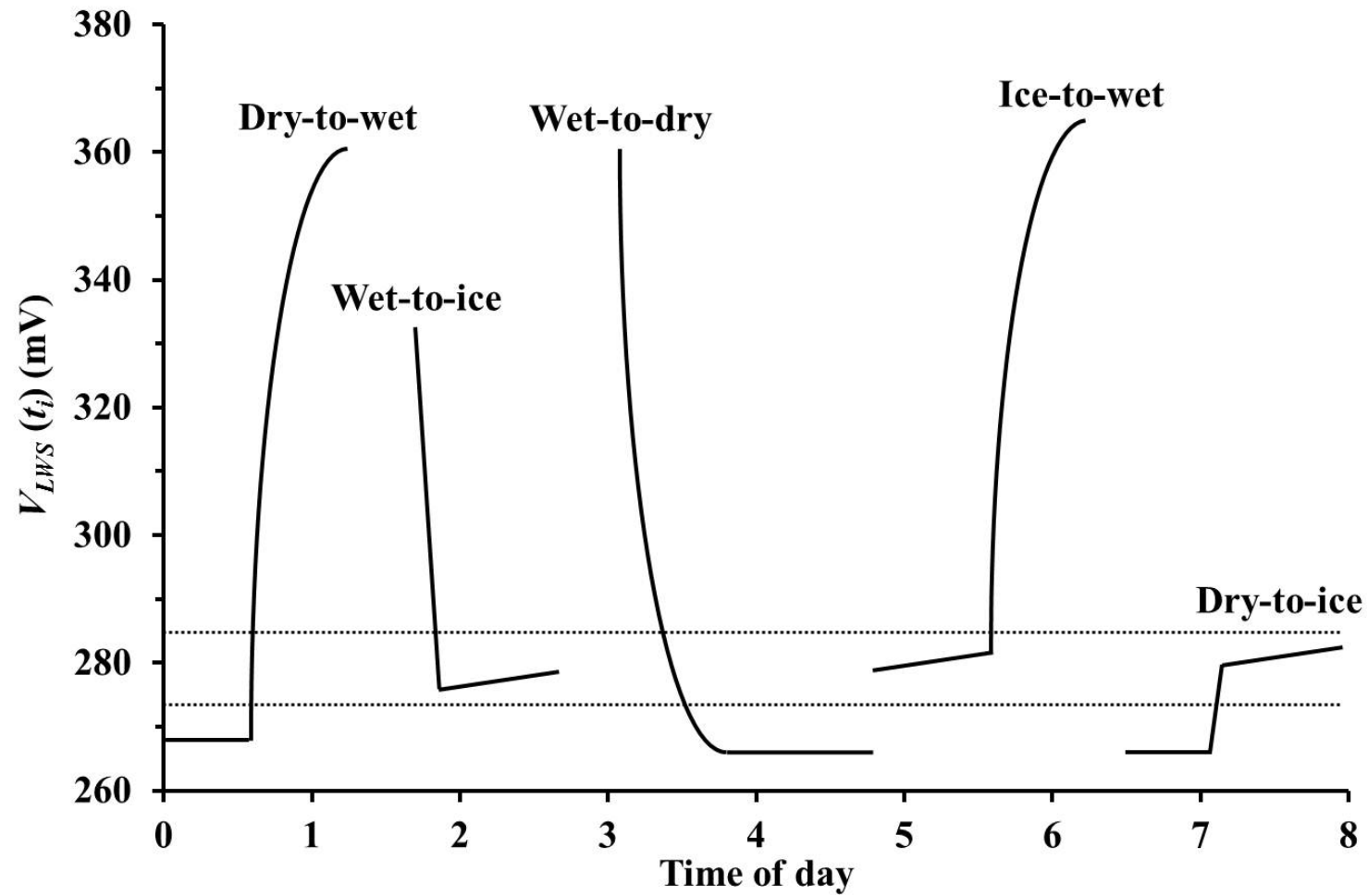


Figure 4.1 Voltage trace for an idealised LWS unit subjected to (left to right) the following near-surface transitions: dry-to-wet, wet-to-ice, wet-to-dry, ice-to-wet and dry-to-ice.

For the dielectric LWS units, frost occurrence was based on:

$$V_L \leq V_{LWS}(t_i) < V_U \quad (4.1)$$

where V_L (mV) is the lower voltage corresponding to the start of contamination, $V_{LWS}(t_i)$ the LWS voltage measured at time t_i (h) and V_U (mV) the upper voltage corresponding to the end of contamination. Leaf wetness occurs when:

$$V_{LWS}(t_i) \geq V_U \quad (4.2)$$

with $V_{LWS}(t_i) < V_L$ for a dry LWS. The manufacturer recommends $V_U = 284$ mV and $V_L = 274$ mV.

The problem with the use of Equation 4.1 for frost is that dry-to-wet and wet-to-dry voltage transitions could also be regarded as frost occurrence (Figure 4.1). Typically, during a condensing event followed by drying, $V_{LWS}(t_i)$ may increase from 265 to 320 mV and later decrease from 320 mV to around 265 mV and therefore satisfy Equation 4.1 for two periods when in fact there was no frost (Figure 4.1, **dry-to-wet and wet-to-dry**).

For use by students for their project (worth eight credits which is equivalent to 26 lectures and six three-hour practicals in a semester), an exercise on measurement of frost duration was based on the Web-based system. A group of four students were given background information on frost and leaf wetness which required them to download data to be used for their project by following a set of instructions (Appendix 4.1). The students were required to meet weekly after the project had been assigned to them and for each meeting, they were required to keep minutes for each meeting, and make a careful note of attendance of each student. Each student was assigned responsibility for one or more tasks – for example, keeping minutes, reading Decagon Devices (2010), data set to be used, photographs of the mast and equipment used for the project, etc. The students were informed that the outcome of the project was a group project which would be marked by an internal and an external examiner but that the marks awarded for each student would be based on the project mark and attendance at meetings.

For the Web-based data and information system for use by undergraduates, the surface, grass, 0.1-m and air temperatures every 1 m up to 8 m and the effective sky temperature were displayed for the most recent five-day period. Effective sky ($CNRI_Tgrass_eff$, °C) and surface ($CNRI_Tsky_eff$, °C) temperatures were estimated from the four-component net radiometer measurements as follows:

$$CNRI_Tgrass_eff = (CG3DnCo / (5.6704 \times 10^{-8}))^{0.25} - 273.15$$

$$CNR1_Tsky_eff = (CG3UpCo / (5.6704 \times 10^{-8}))^{0.25} - 273.15$$

where $CG3DnCo$ ($W\ m^{-2}$) and $CG3UpCo$ ($W\ m^{-2}$) are the infrared irradiance measured using the lower and upper sensors respectively. The net radiometer was operated in the separate component mode for which the net radiometer body temperature was measured. For many winter nights, condensation necessitated use of instrument heating to evaporate the condensed water. Liquid water on both infrared sensors invalidated the infrared irradiance measurements since liquid water is a good absorber of infrared wavelengths. Liquid water on these sensors resulted in a voltage output close to 0 mV. Heater voltage, controlled by the datalogger, was applied during the nighttime only when the measured relative humidity exceeded 95 % (Appendix 4.2). The instrument heater, following application of 12 V, produced about 6 W. The manufacturer recommended instrument heating if a clock and relay are available. In this case, the datalogger supplied both requirements.

For another project, Appendix 4.3, students had been given lectures on the radiation balance, including mention of Brunt's equation for the estimation of downward infrared irradiance for nocturnal conditions using the 2-m air temperature T_z ($^{\circ}C$) and water vapour pressure e_z (kPa) measurements:

$$Ld_Brunt = \sigma(T_z + 273.15)^4(0.44 + 0.08\sqrt{10 \cdot e_z})$$

$\longleftrightarrow \longleftrightarrow$
 Contribution Contribution
 due to $[CO_2]$ due to $[H_2O]$

where $\sigma = 5.6704 \times 10^{-8} W\ m^{-2}\ K^{-4}$ is the Stefan-Boltzmann constant. Through the display of Ld_Brunt and the measured Ld , it is immediately obvious to the students that the Ld_Brunt estimate consistently underestimated measured Ld . Through a guided tutorial, students were asked to explore why this was the case and also could explore the linear relationship that Brunt proposed between $Ld/\sigma(T_z + 273.15)^4$ and $\sqrt{10 \cdot e_z}$ for nighttimes to develop new coefficients that express the significantly increased $[CO_2]$ between 1934 and today. The revised version, Ld_today , was also be added to the system for students to visually compare, in near real-time, with the measured Ld and Ld_Brunt .

4.4 Results and discussion

The 2-min output voltage for two LWS units, for a six-day period of frost (19th to 25th August 2011), is shown (Figure 4.2b) as well as the grass temperature and air temperatures at 1 m for confirmation of frost occurrence (Figure 4.2a). The occurrence of frost on five of the seven night/day periods is clear, because the LWS voltages stabilise between $V_L = 274$ and $V_U =$

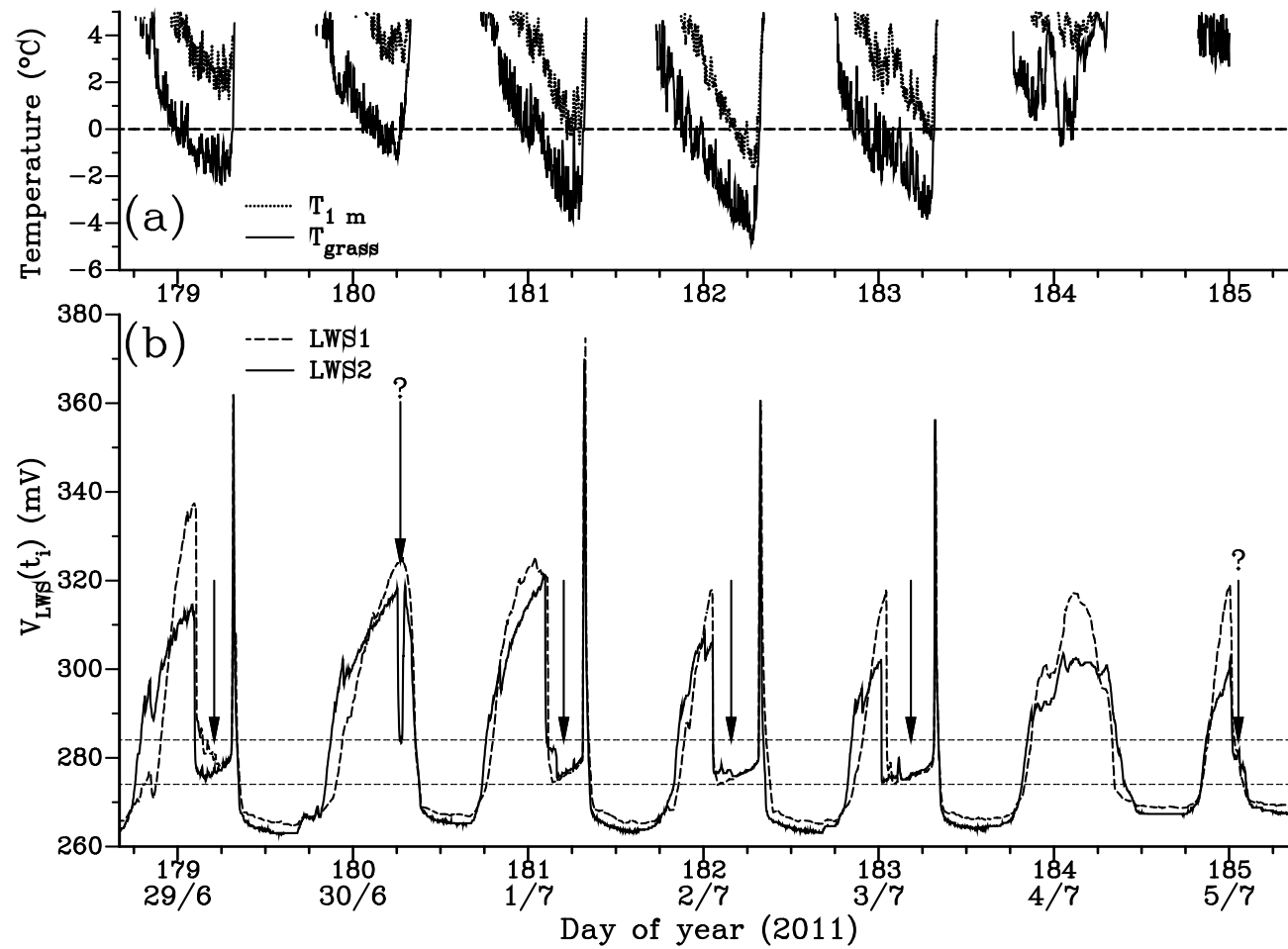


Figure 4.2 (a) Two-min grass temperatures and 1-m air temperatures for a week of frost; (b) two-min voltage traces for two leaf wetness sensors (LWS). Frost is indicated by arrows with the question mark indicating possible frost.

284 mV (Equation 4.1), and is confirmed by the negative grass temperatures. The change in LWS voltage for all units, corresponding to wet-to-ice and ice-to-wet transitions corresponding to the start and end of a hoar frost respectively, generally occur at the same time. For some night/day periods it is not that clear if there was significant frost. Therefore, as previously alluded to, a clearer definition as that provided by Equation 4.1 was required for frost determination. For days with significant frost, after ice has melted from the sensor surface – usually because of increased solar irradiance at sunrise – the LWS voltage increased as ice melts and then rapidly decreases as the melted ice evaporated.

A second criterion, applied to all LWS units, was used to more accurately trap only frost events from LWS voltage measurements. The following criterion, based on consecutive 2-min voltage differences recalled from the datalogger memory every 2 min, was applied in the datalogger programme in conjunction with Equation 4.1:

$$\sum_{i=1}^2 \left| \frac{V_{LWS}(t_{i+1}) - V_{LWS}(t_i)}{2(t_{i+1} - t_i)} \right| < \Delta V_{LWS} \quad (4.3)$$

where ΔV_{LWS} (mV h⁻¹) corresponds to a relatively small average rate of change in voltage, typically 10 mV h⁻¹ which is equal to 0.1666 mV min⁻¹, compared to a much larger rate of increase for a dry LWS that suddenly became wet. Typically, at the start of a wetting event, the rate of change of $V_{LWS}(t_i)$ can be more than twice ΔV_{LWS} although after more of the surface was wetted, the measured voltage may become stable with the rate of voltage change decreasing but with voltages in excess of V_U (Figure 4.1, dry-to-wet). Hence use of $\Delta V_{LWS} = 10$ mV h⁻¹ attempts to remove from the LWS record of frost those events that satisfy Equation 4.1 but not Equation 4.3.

The protocols for determining FD, for a period of five months (from 19th April 2011), using the LWS method were cross-checked against FD determined using IRT surface and grass temperatures less than or equal to 0 °C. To investigate the impact of the constants used in Equations 4.1 and 4.3 on FD estimation, the lower limit V_L of 274 mV in Equation 4.1 was adjusted to 272 mV and the limit of $\Delta V_{LWS} = 10$ mV h⁻¹ in Equation 4.3 was adjusted to 5 and 20 mV h⁻¹ (Figure 4.3). Although the FD totals for the five-month period for the IRT and LWS methods were in reasonable agreement using different constants (Figures 4.3c and d), there was an increased root mean square error (RMSE) and reduced coefficient of determination (R^2). For the constants used in the case of Figures 4.3a and b, the data comparisons for Figure 4.3a had slightly increased RMSE and reduced R^2 but the FD total for the LWS method was more in agreement with the IRT method than that in Figure 4.3b. The limit constants of $V_L = 274$ mV, $V_U = 284$ mV and $\Delta V_{LWS} = 10$ mV h⁻¹ were therefore used routinely for LWS estimation of FD.

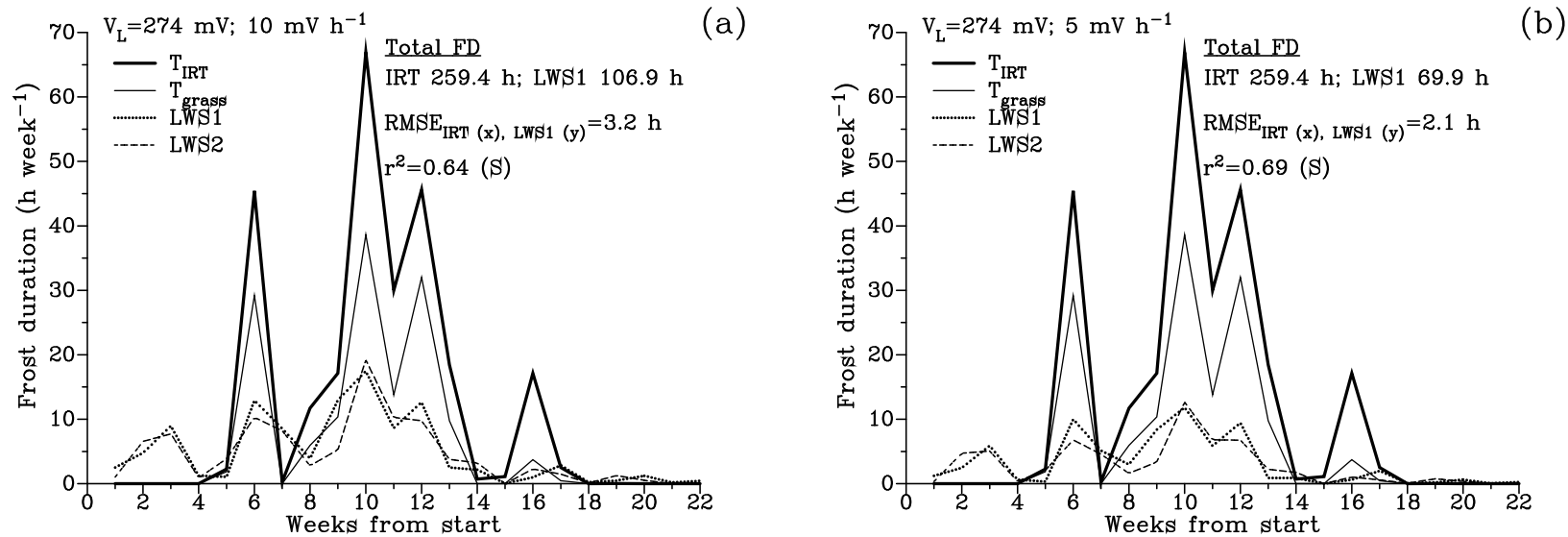


Figure 4.3 (a) and (b) Measured frost duration, from 19th April 2011, using infrared thermometer (IRT) and grass temperature methods for which either is less than or equal to 0 °C and leaf wetness sensors (LWS1 and LWS2) using Equations (4.1) and (4.3); with $\Delta V_{LWS} = 10 \text{ mV h}^{-1}$ (a); $\Delta V_{LWS} = 5 \text{ mV h}^{-1}$ (b). The root mean square error (RMSE) and coefficient of determination (R^2) of the infrared thermometer (IRT, x) and leaf wetness sensor (LWS1, y) frost duration estimates are shown.

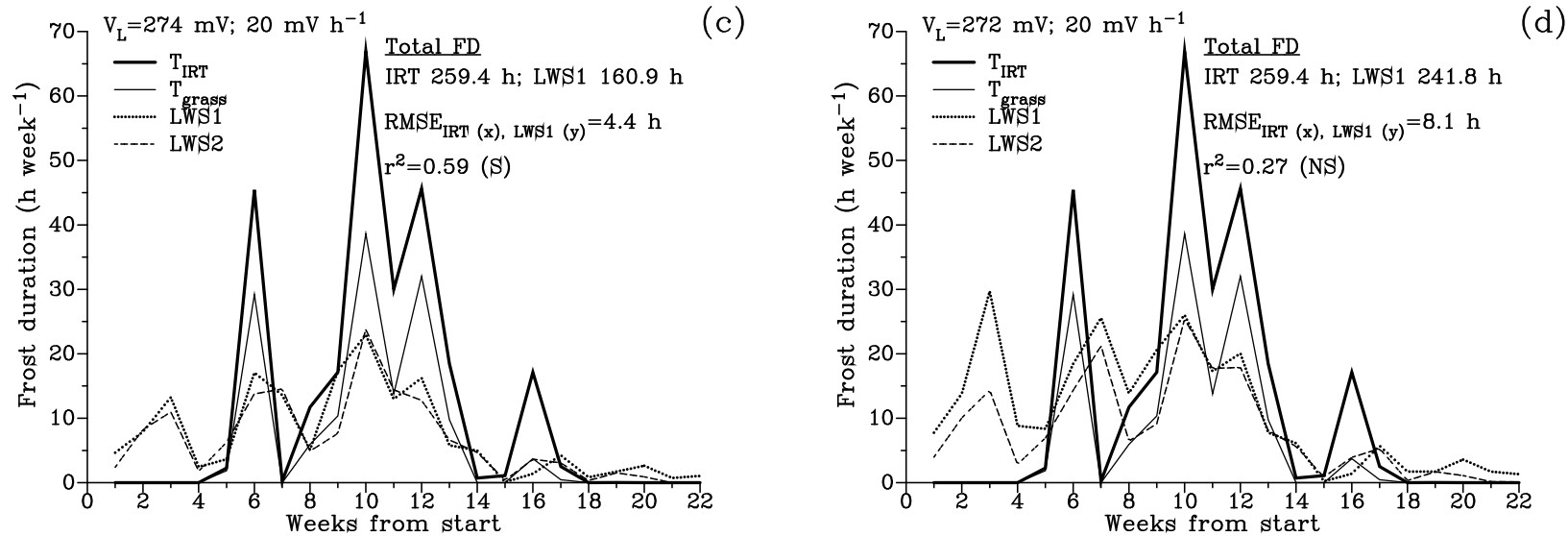


Figure 4.3 (c) and (d) Measured frost duration, from 19th April 2011, using infrared thermometer (IRT) and grass temperature methods for which either is less than or equal to 0 °C and leaf wetness sensors (LWS1 and LWS2) using Equations (4.1) and (4.3): with $\Delta V_{LWS} = 20 \text{ mV h}^{-1}$ (c); with $V_L = 272 \text{ mV}$ in Equation (4.1) and $\Delta V_{LWS} = 20 \text{ mV h}^{-1}$ in Equation (4.3) (d). The root mean square errors (RMSE) and coefficient of determination (R^2) of the infrared thermometer (IRT, x) and leaf wetness sensor (LWS1, y) frost duration estimates are shown.

Estimates of FD were usually greatest for the IRT method, next for grass-temperature method and least for the LWS method. This is expected since the IRT surface measurements are the coldest during non-advective nocturnal air temperature inversion conditions. The grass temperatures, about 25 to 50 mm away, were generally slightly greater by about 1.27 °C – the y intercept of the regression of the grass vs surface temperature relationship for the winter of 2011 for temperatures between midnight and 06h30 was 1.27 °C with a slope of almost 1 (Chapter 3, Figure 3.2). The LWS sensors were positioned further away from the surface at a mid-position height of about 100 mm.

Leaf wetness sensor voltage measurements represent conditions on the LWS upper surface as well as those 10 mm above (Decagon Devices, 2010). Thus if there is a thin layer of ice on the LWS surface, the measured dielectric constant would be between that of ice and air. This could result in a dielectric constant (measured voltage) between 1 (air, typically 265 mV) and 5 (ice, typically 280 mV) (Figure 4.1). Given the high nocturnal relative humidity of the study site for the duration of the experiment, black frost did not occur. LWS units do not detect black frost – unless with further temperature decreases after the occurrence of black frost, sublimation occurs. Both the grass- and IRT-temperature methods would, however, record temperatures below 0 °C in the case of a black frost but these methods cannot indicate if and when the vegetation freezes unless the freezing point of the vegetation is known.

In order to examine the correspondence in FD for the different methods, three night/day periods for which frost occurred, as judged by surface temperature at or below 0 °C, were examined (Figures 4.4–4.6). The environmental lapse rate (ELR = dT/dz , °C m⁻¹) between 0.1 and 2 m was surprisingly constant for cloudless and relatively windless nights for this site at around 2.25 °C m⁻¹ (stable) with that between 2 and 4 m less than 1 °C m⁻¹ (Figures 4.4a, 4.5a and 4.6a). The inference is that air temperature at 0.1 and 2 m were decreasing at similar rates for such nights for this site. Between 2 and 4 m, there was probably more atmospheric mixing with the air temperature difference being smaller. Sunrise, indicated by an arrow in Figures 4.4b, 4.5b and 4.6b, resulted in an increase in solar irradiance and a slight and slow increase in the downward (L_d) and upward (L_u) infrared irradiances. Following sunrise, both ELRs changed sign, corresponding to a change to unstable conditions. As expected, the 2- to 4-m ELR changed sign slightly later than that for the 0.1- to 2-m layer,

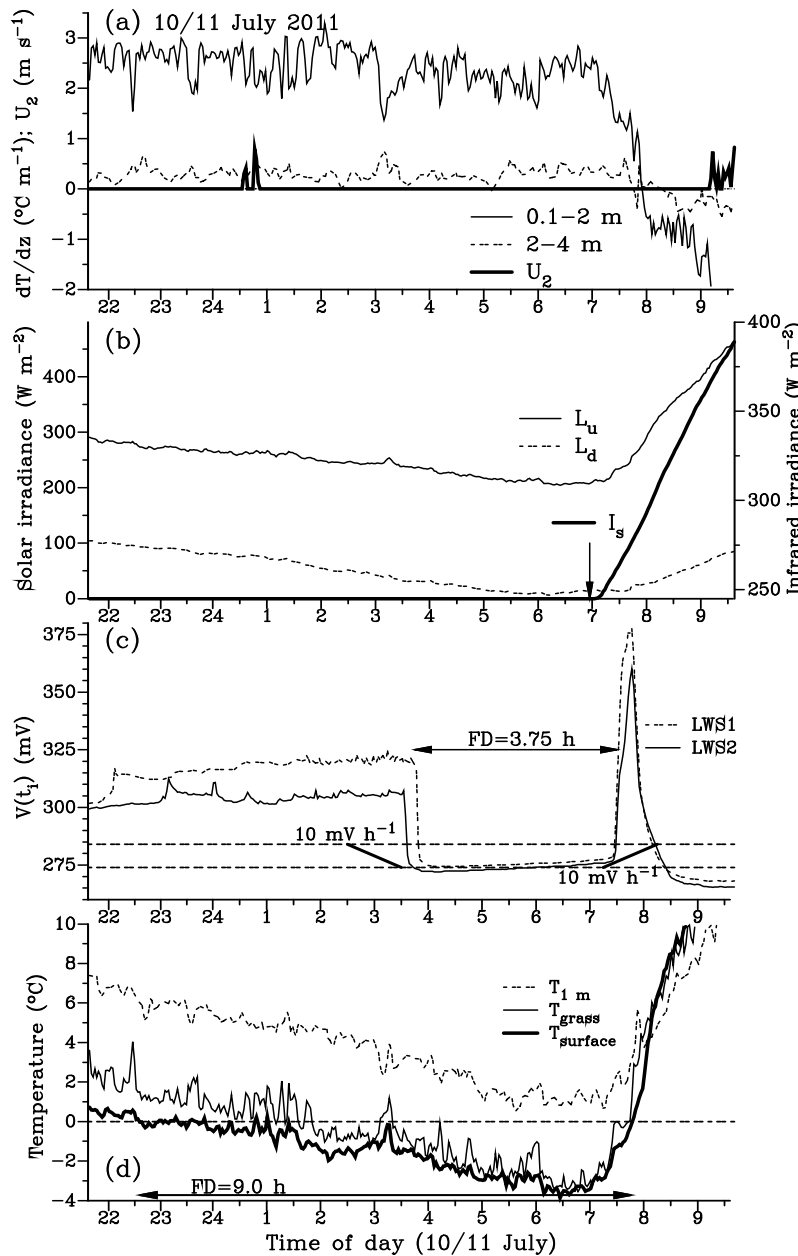


Figure 4.4 Conditions for a night/day in winter (10/11th July 2011) with significant frost. (a) The environmental lapse rate and wind speed; (b) the outgoing and downward infrared and solar irradiances; (c) the LWS voltage traces for two units for which the average frost duration (FD) is 3.75 h. The ΔV_{LWS} value, used to exclude the wet-to-ice and ice-to-wet transitions, is shown by the line segments marked 10 mV h⁻¹; (d) the air temperature at 1 m, grass temperature, and infrared thermometer (IRT)-measured surface temperature. The frost duration (FD) is 9.0 h based on the duration for which surface temperature is less than or equal to 0 °C.

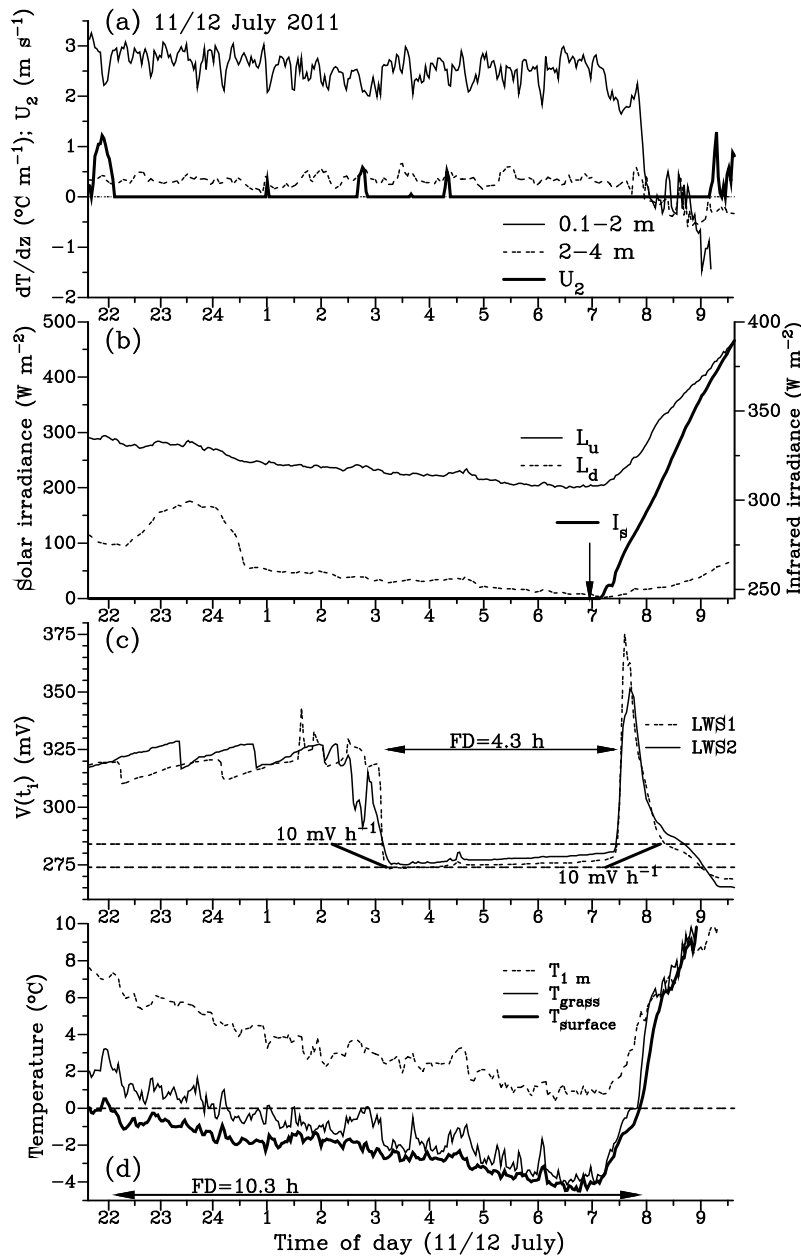


Figure 4.5 Conditions for a night/day in winter (11/12th July 2011) with significant frost. (a) The ELR and wind speed; (b) the outgoing and downward infrared and solar irradiances; (c) the leaf wetness sensor (LWS) voltage traces for two units for which the average frost duration (FD) is 4.3 h; (d) the air temperature at 1 m, grass temperature, and infrared thermometer (IRT)-measured surface temperature. The frost duration (FD) for the IRT method is 10.3 h.

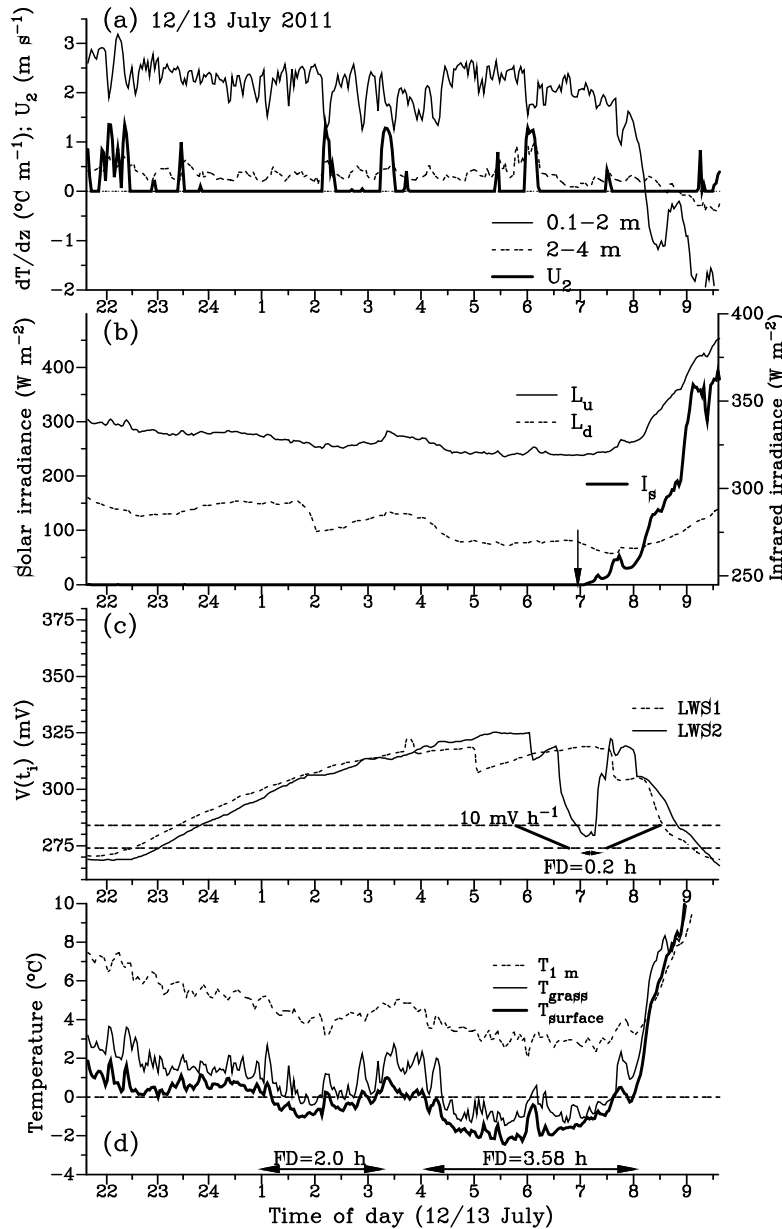


Figure 4.6 Conditions for a night/day in winter (12/13th July 2011) with slight frost and windier conditions. (a) The ELR and wind speed; (b) the outgoing and downward infrared and solar irradiances; (c) the leaf wetness sensor (LWS) voltage traces for two units for which the average frost duration (FD) is 0.2 h for the one LWS with none recorded for the other; (d) the air temperature at 1 m, grass temperature, and infrared thermometer (IRT)-measured surface temperature. The total FD for the IRT method is 5.58 h.

with the surface warming more rapidly than air at higher heights.

The other factor affecting the ELR is wind speed. For windier nights (Figure 4.6a), the ELR was reduced with wind speeds in excess of 1 m s^{-1} decreasing the 0.1- to 2-m ELR to less than $1.5 \text{ }^{\circ}\text{C m}^{-1}$ compared to in excess of $2.5 \text{ }^{\circ}\text{C m}^{-1}$ for other nights (Figures 4.4a and 4.5a). Of particular importance with respect to the ELR on cloudless and windless nights and the definition of frost was that for an ELR in excess of $2.5 \text{ }^{\circ}\text{C m}^{-1}$ and a measured air temperature at 2 m of around $5 \text{ }^{\circ}\text{C}$, for example, the surface temperature could be less than $0 \text{ }^{\circ}\text{C}$ and hence frost could occur. Hence, air temperatures measured at 1 m or higher by themselves are not good indicators of frost occurrence. This justifies the inclusion of grass temperature at AWS systems for determination of frost occurrence and FD. Air temperatures at 1 m or higher may be good indicators of frost occurrence on cloudless and windless nights if the ELR is known or can be predicted accurately. In the former case, ELR measurements are unfortunately rare. In the latter case, the accurate prediction of surface temperature from air temperature at a standard height above the surface would require inputs not commonly available.

The voltage output for the LWS units for three frost mornings is shown (Figures 4.4c, 4.5c and 4.6c). Of the three, the morning depicted in Figure 4.6c had the least frost because of increased wind speed (Figure 4.6a) and a greater downward infrared irradiance (L_d , Figure 4.6b), the latter probably because of transient clouds. There was agreement between the LWS units apart from the morning with the lowest FD. This disagreement was presumably because of LWS exposure differences. For the mornings depicted in Figures 4.4c and 4.5c, LWS voltages are initially greater than 284 mV (leaf wetness) and then their decrease following the onset of frost (Equation 4.1) is abrupt. The slope of the voltage during the transitional change from the larger voltage to between $V_L = 274$ and $V_U = 284 \text{ mV}$ is greater than $\Delta V_{LWS} = 10 \text{ mV h}^{-1}$ (Equation 4.2) and depicted by small line segments labelled "**10 mV h⁻¹**" (Figures 4.4c and 4.5c). Although it is difficult to determine whether the LWS had mostly ice or liquid water on its surface, these transitional changes in voltage and the voltage change when the ice melts were short in duration with occasional transitions from wet-to-dry after all the frost had melted being indicated as frost. For both mornings, the frost melted after sunrise (arrows in Figures 4.4b and 4.5b) and after positive solar irradiance values.

The various temperatures above and at the grass surface for three frost mornings are depicted in Figures 4.4a, 4.5a and 4.6a. Of particular note was that above-surface temperatures, apart from those within 100 mm of the surface, rarely recorded less than $0 \text{ }^{\circ}\text{C}$. For nocturnal conditions, grass temperatures were almost always greater than IRT surface temperatures. The duration of frost, as recorded by surface temperatures at or below $0 \text{ }^{\circ}\text{C}$, is indicated (Figures 4.4d, 4.5d and 4.6d). These durations are more than double those recorded by LWS units positioned at a mid-position height of 100 mm above the surface.

These results would be applicable to turf-grass and similar grassed surfaces. Further research would be required to assess applicability of these results to, for example, a tree crop with a canopy height exceeding 3 m with bare soil between the trees. In such a case, it may be that more than one temperature measurement is required – for example, a "grass" minimum thermometer above the soil surface and a "grass" minimum thermometer at tree-height.

The Web-based data and information system displayed was used to assist students in understanding the occurrence and requirements of frost (Figure 4.7). Since the emphasis of the Web-based system is on near real-time events and data, no project on frost occurrence was assigned to students in 2012 – the semesterised system with modules ending in June or starting in August, result in frost events occurring after the module ended or before it started.

Many students do not understand the concept and consequence of atmospheric stability – for example, that during stable conditions, the lowest temperatures are at the surface with air temperature increase with increase in height away from the surface and the reverse for unstable conditions. To improve this situation, profile air temperature measurements, from 1 to 8 m together with the surface temperature measured using an infrared thermometer and the grass temperature at 0.1 m were displayed in the Temperature screen (Figure 4.8).

The Radiation balance screen displayed the radiation balance components. For the frost occurrence application, only the L_d and L_u infrared components of the radiation balance are of importance. The measured L_u component could be checked but it was not possible to check the measured L_d . The outward infrared irradiance was estimated using:

$$L_u = \sigma(T_{surface} + 273.15)^4$$

where $T_{surface}$ is the measured IRT temperature of the grass surface. For hourly data for the period 19th August 2011 to 7th November 2012, the agreement between the outgoing infrared irradiance estimated from the measured IRT surface temperature ($L_u(IRT)$) and the measured outgoing infrared irradiance ($L_u(CNR1)$) was reasonable: $L_u(IRT) = 0.972 L_u(CNR1) + 11.57$ ($R^2 = 0.9084$, $RMSE = 15.97 \text{ W m}^{-2}$).

For the Brunt's Law project, students were supplied with radiation balance components as well as the 2-m air temperature and water vapour pressure measurements. They were asked to consider how the constants (a and b) used in Brunt's equation may have been altered by climate change. Applying Brunt's equation and rearranging so as to have $\sqrt{10 \cdot e_z}$ as an independent variable:

Frost is a condition for which the surface and earthbound objects have a temperature below 0 °C resulting in ice on or within leaves and soil.

The two main types of frost are freeze frosts (also referred to as advection frosts) and radiative frosts. In South Africa, radiative frosts are more common. There are two types of radiative frosts: hoar frost and black frost. A white frost is a relatively heavy coating of a hoar frost. In the case of a black frost, there is no ice on the soil or plant surfaces due to the very low dewpoint temperature - the dewpoint is negative. The conditions are however very cold, resulting in freezing of cell sap in vegetation and rupture of cells. Hence vegetation appears black in colour.

Hoar frosts occur when atmospheric conditions above the surface are cool, calm, clear and dry (CCCD). Calm conditions are required since even the slightest breeze can destroy the air temperature inversion that develops on calm nights - resulting in cooler conditions near the surface and warmer above the surface. Wind would result in warmer air from above mixing with the cooler air from below, resulting in warmer conditions at the surface. Clear conditions are required since any cloud would very effectively return infrared irradiance to the surface resulting in elevated surface temperatures. Dry conditions are required since water vapour is a greenhouse gas that effectively returns infrared irradiance to the surface, elevating surface temperature.

The cool, calm, clear and dry atmospheric requirement for frost all act simultaneously in that if any one of these atmospheric conditions are not met, the chance of frost is much reduced. It therefore becomes possible to predict the occurrence of frost by measurement of atmospheric conditions such as air temperature, wind speed, water vapour pressure (or relative humidity), for example, a few hours before frost occurrence. The problem however is that these AWS measurements are usually at a height of 2 m above the surface and therefore do not represent the conditions just above the surface.

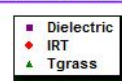
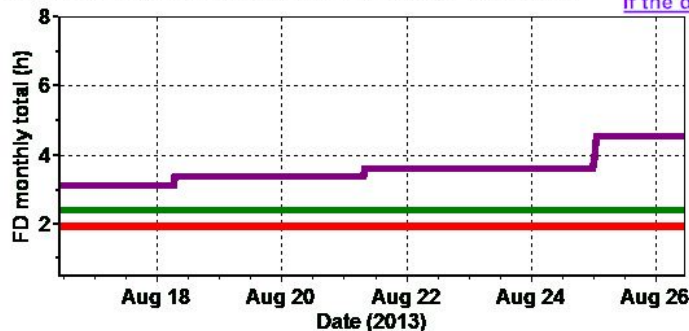
This problem can be overcome by having sensors near the surface. One such sensor is an unshielded temperature sensor in contact with blades of grass. The daily minimum of this temperature is referred to as the grass minimum temperature. Another difficulty in determining the possibility of frost is that it is very difficult to determine the occurrence of clouds at night. The occurrence of an isolated nocturnal cloud may temporarily increase the measured air temperature, especially air temperature near the surface. Therefore observation of the rate of decrease of the nighttime air temperature may give important clues about frost. In particular, if the air temperature during the night happens to increase, this could be an indication of cloud (or a warm front passing) and therefore reduced chance of frost.

A dielectric sensor, which measures the ability of material on its surface to store electrical charge, can also give important information about the surface conditions if the sensor is positioned near the surface of the earth. The dielectric constant for air (1), liquid water (80) and ice (5) are different. Using such a dielectric sensor, it is easy to determine the difference between liquid water (dew) on the surface of the sensor compared to a dry sensor with surrounding air in contact with the surface. If ice has formed, the dielectric constant will be between that of liquid water and air but closer to that of air. If careful measurements are made, it may be possible to determine if the dielectric sensor has a deposit of ice.

Current dielectric condition for three sensors: 261.74 mV

If the dielectric mV is between 274 and 284 mV then it is likely that there is surface frost

If the dielectric mV is greater than 284 mV then it is likely that there is dew (leaf wetness)



Current	Grass min	Tair min	Min Tsurface	Grass min
wind speed	yesterday	(at 2 m)	(IRT) today	today
0.15 m/s	5.0 °C	12.3 °C	8.7 °C	10.5 °C

Current air temperature gradient between 0.1 m to 8 m: -0.41 °C/m

Positive: inversion/stable.
Negative: unstable

Frost duration today based on dielectric condition: 0.00 h

Leaf wetness/dew duration today: 0.95 h



2013/08/26 10:50:30 AM

Figure 4.7 The frost screen containing relevant background information on frost and FD estimation as well as graphical and digital display of the conditions related to frost occurrence.

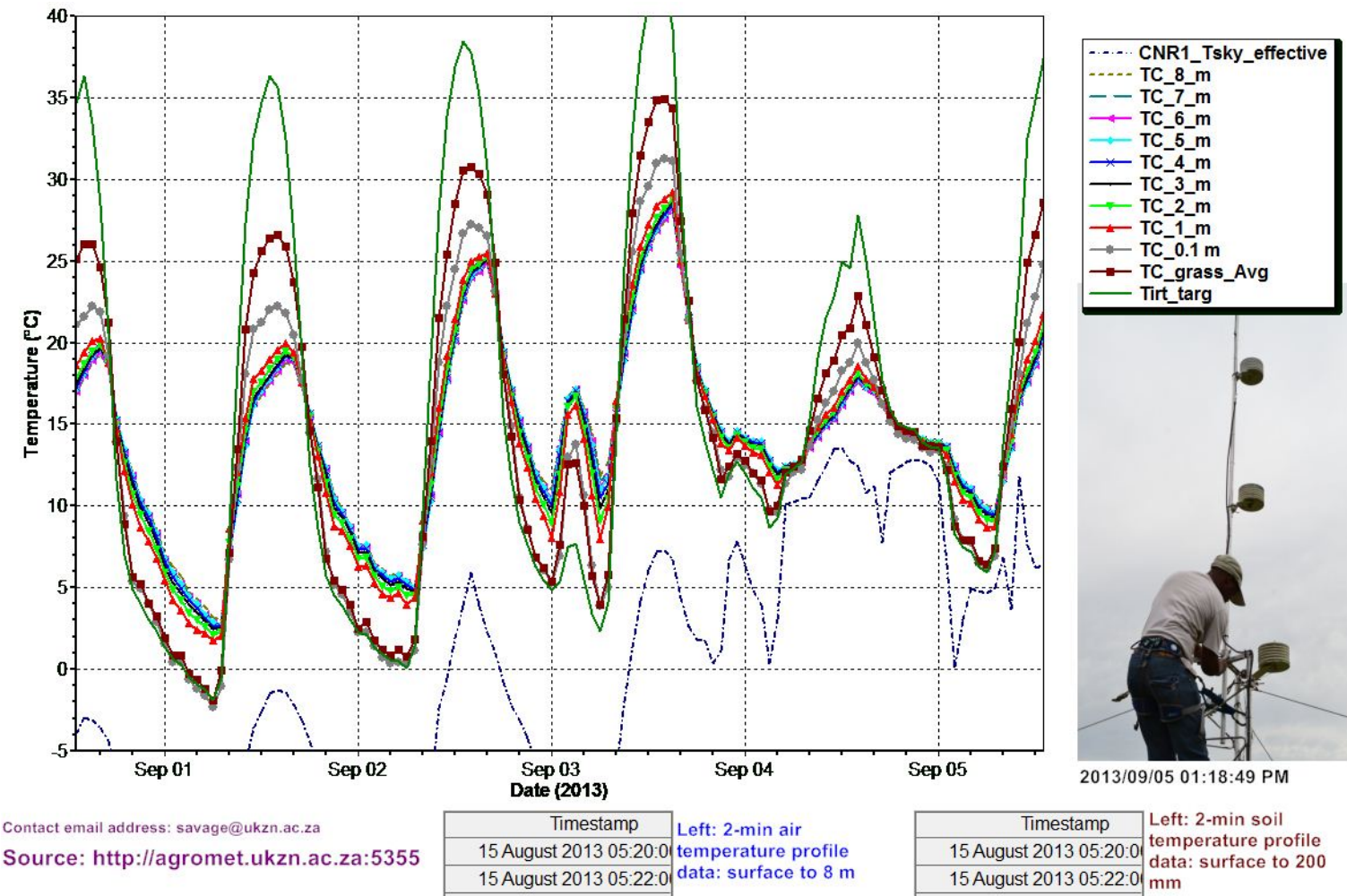


Figure 4.8 The temperature screen containing temporal variation in hourly surface, grass, air temperatures every 1 m to a height of 8 m and the effective sky temperature for a five-day period. At the base of the display are the 2-min profile air and soil temperature data for students to download for creating their own temporal graphs.

$$L_d/\sigma(T_z + 273.15)^4 = a' + b'\sqrt{10 \cdot e_z}$$

where a' and b' are the modified coefficients for current conditions. A scatter plot of $L_d/\sigma(T_z + 273.15)^4$ as a function of $\sqrt{10 \cdot e_z}$, using nighttime measurements of L_d , T_z and e_z , yielded an intercept $a' = 0.4188$ and slope $b' = 0.1232$. The new coefficients were then used in the datalogger programme to calculate Ld_today in near real-time using:

$$Ld_today = \sigma(T_z + 273.15)^4 \times (0.4188 + 0.1232\sqrt{10 \cdot e_z})$$

and plotted using the Web-based system (Figure 4.9). Students were therefore able to visually see the result of Brunt's Law using the original and the modified coefficients.

4.5 Conclusions

Dielectric leaf wetness sensor measurement of frost duration (FD) was problematic. Dry-to-wet and wet-to-dry transitional condensing events without freezing followed by drying typically corresponding to LWS voltage increases from around 260 mV (dry) to in excess of 320 mV (wetness), and *vice versa*, had to be identified and excluded. These transitional events were identified using sub-hourly measurements by excluding LWS voltage rates of change that were greater than or equal to 10 mV h⁻¹ for 4 min but at the same time including events for which the LWS voltage was between the 274 and 284 mV lower and upper limits respectively. The FD estimated using dielectric LWS units at 100 mm tended to underestimate FD compared to that estimated using the infrared (IRT) surface- and grass- (25 to 50 mm) temperature methods, presumably because of the fact that the LWS sensors are at a greater distance (100 mm) from the surface compared to IRT sensors that measure surface temperature. The air temperature measurements at 1 m, or higher, were rarely less than 0 °C and should not be used to define grass-surface frost events without adjustment for the 1-m or higher temperature for the measurement height difference. None of the methods used could detect black frost events, which did not occur for the high nocturnal relative humidity experienced at the study site. The grass- and IRT-temperature methods would indicate less than 0 °C for black frosts with the LWS method yielding no indication of black frost unless further temperature decreases caused sublimation. Air temperature gradients between the surface and 2 m for cloudless nocturnal frosted and windless conditions were about 2.25 °C m⁻¹, typically resulting in the 2-m air temperature measurements more than 4 °C greater than those at the grass surface. The Web-based system used allowed for timeous email and SMS alerts of frost with near real-time data and graphics of FD displayed for the current day, week and month for the various methods. To increase the value of AWS measurements, it is recommended that AWS systems should also include grass temperature that could be

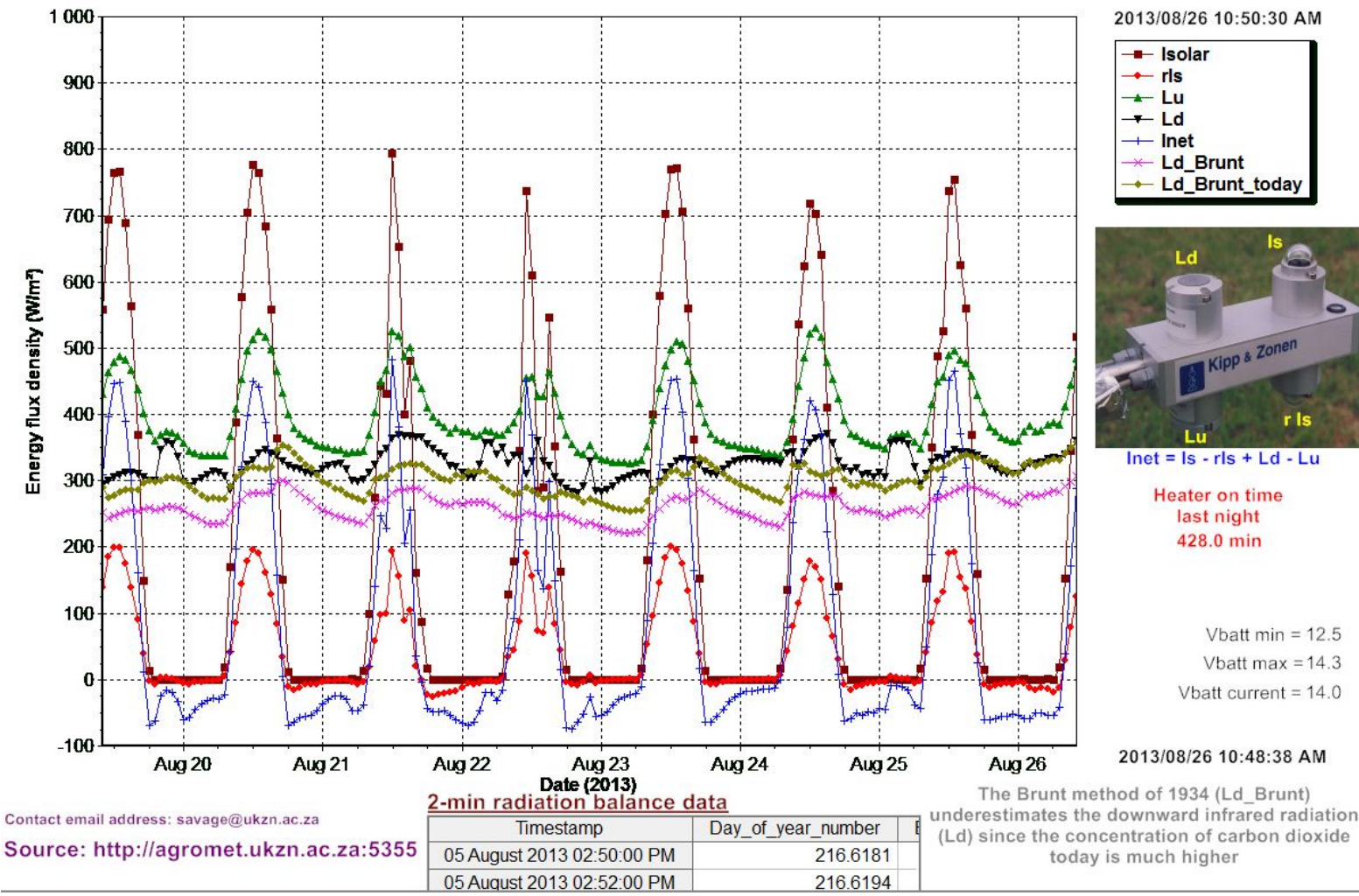


Figure 4.9 The Radiation balance screen showing the temporal variation in hourly radiation balance components for a five-day period. At the base of the display are the 2-min radiation balance component data for students to download for creating their own temporal graphs.

used to estimate FD. The Web-based system was used to assist undergraduate students in understanding the causes and characteristics of frost as well as the importance of the downward infrared irradiance in influencing the daily minimum surface temperature. Through project work, the students revised the coefficients of Brunt's equation and were able to assess, in near real-time, the suitability of the revised coefficients.

4.6 Acknowledgements

Funding from University of KwaZulu-Natal (UKZN; Teaching and Learning Office, College of Agriculture, Engineering and Science and Research Office) and South African National Research Foundation is gratefully acknowledged. The Water Research Commission is also acknowledged for previously funding equipment used. Administrative and technical support of Jothi Manickum and technical support of Michael Abraha, Nicholas Moyo and Nile Babikir (Agrometeorology Discipline, UKZN), electronic support of Guy Dewar (Electronics Centre, UKZN) and the support of the UKZN AMET212 students of 2011 is also acknowledged.

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Appendix 4.1 E-mail to second-year undergraduate students giving the background to their project on leaf wetness and grass minimum temperature and frost occurrence.

From: Michael Savage
To: Ayanda Kunene; Jitesh Ramphal; Ntobeko Mchunu; Thembisile Zaca
Date: 2011/09/21 06:55 PM
Subject: AMET212 Group 11: The role of leaf wetness and grass minimum temperature in determining frost condition
Attachments: LWSmanual.pdf; Duration of frost and dew above short grass mjs.pdf; measurement of temperature wmo Chapter 2.pdf

You are contracted to determine frost conditions. This includes normal measurements found at an AWS: solar radiation (CMP3 sensor), air temperature and relative humidity using a CS500 combination sensor and air temperature, 03001 RMY wind speed and direction sensor, a generic raingauge, an infrared thermometer, a type-E thermocouple (chromel- constantan) thermocouples and three leaf wetness sensors. Since a CR800 datalogger (has three differential channels) is to be used the thermocouple sensors are to be connected to a AM16/32A multiplexer. Use ShortCut to develop a program for a CR800 datalogger with an AM16/32A multiplexer using the 2x32 mode of the multiplexer (- which allows a total of 32 differential measurements).

- (a) What is an essential requirement for temperature measurement using thermocouples?
- (b) While the CR800 has a temperature reference – the CR800 internal panel temperature, this cannot be used as the reference temperature for thermocouples connected to the multiplexer. Why not?
- (c) Use ShortCut to write your datalogger program. Specify a CR800 datalogger, a 12-s scan interval and if asked a 50-Hz voltage rejection. Then connect the AM16/32A multiplexer to the CR800. A thermistor (a type of temperature sensor – model T107) wired to the datalogger, but physically attached to the panel of the multiplexer, may be used as a temperature reference for thermocouples connected to the multiplexer. Use ShortCut to connect to the datalogger the T107 probe.
- (d) Add the raingauge to the datalogger – generic with a multiplier of 1.
- (e) Add the 03001 RMY Young wind speed and wind direction sensor to the datalogger.
- (f) Attach the CMP3 solar radiation sensor to the multiplexer.
- (g) In order to attach CS500 RH/Tair sensor to the multiplexer, two differential voltage measurements are added to the multiplexer – one for AirTC and one for RH. For these measurements, name the measurement result CS500 and use the following voltage specifications: 250 mV voltage range and a 250-micro second measurement integration but do not specify that the voltage input be reversed to cancel offsets. Use a multiplier of 1 and an offset of 0. Use two calculations in the datalogger to calculate AirTC and RH:

$$\text{AirTC} = \text{CS500}(1) * 0.1 - 40$$

$$\text{RH} = \text{CS500}(2) * 0.1$$
 Calculations cannot be done on the multiplexer – they are done in the datalogger.
 Add the following calculations: dewpoint (Tdp); water vapour pressure (kPa) using the label e_kPa, water as the reference surface and by specifying the temperature Tdp; water vapour pressure (kPa) above ice using the label ei_kPa, ice as the reference surface and by specifying the temperature Tdp.
- (h) Add the three leaf wetness sensors to the multiplexer - model LWS. Specify the default threshold values.
- (i) Add the precision infrared thermometer (model SI-111) to the multiplexer. Use 1 for all of the coefficients indicated.
- (j) Add to the datalogger, the CS215 SDI RH/Tair sensor which will be housed in a radiation shield at a height of 100 mm above the grass.

Create two data output tables – one for 2 min and one for 60 min. In each table, store the average of all measurements except for RH which should be sampled and for wind speed and wind direction use wind vector. You may need to include minutes dry, minutes contaminated and minutes wet.

For your report, print your datalogger program (*.cr8 file) and the wiring definition file (*.def) as two separate appendices.

If necessary, add further explanation to each of these appendices.

(k) All of the equipment used in your project is currently installed to the Agrometeorology instrument mast (AIM). At some stage, you would need to take photographs of the relevant equipment to include in your report.

Appendix 4.2 CRBasic datalogger code for four-component net radiometer heater control.

```
'CNR1 four-component net radiometer heat control
RealTime(RTime(1))
Dim Heaterontime, Heaterstatus_sum
Units Heaterontime=min
If TimeIntoInterval(0,24,Hr) Then Heaterstatus_sum=0
NowMin=RTime(4)*60+RTime(5)
If (NowMin>=(SunsetUTC+120-45) OR NowMin<(SunriseUTC+120+45)) AND RH>95 Then
  Heaterstatus=1
  Heaterstatus_sum=Heaterstatus+Heaterstatus_sum
  Heaterontime=SCAN_INTERVAL*Heaterstatus_sum/60
Else
  Heaterstatus=0
EndIf
If BattV<11.5 Then
  Heaterstatus=0
EndIf
PortSet(4,Heaterstatus)
NowMinutes = (Hour*60)+Minute+(Second/60)
```

Appendix 4.3 E-mail to second-year undergraduate students giving the background to their project on the application of Brunt's law equation of yesteryear for estimating returned infrared irradiance.

From: Michael Savage
To: Salona Reddy; 210523131@ukzn.ac.za; Andile Thabethe; Samiksha Singh
Date: 2011/08/31 01:47 PM
Subject: AMET212 Group 4: Application of Brunt equation of yesteryear for estimating returned infrared irradiance
Attachments: amet210 chapter 3 summary 2011.pdf; cnr1_8-09.pdf

Dear All

I will guide you on this project - a nice one. You will be testing the Brunt equation developed in 1934. This equation estimates the returned infrared under cloudless conditions from: air temperature and water vapour pressure. However, there is a problem in applying this equation today. What is the problem? Your main resource will be data from the AIM (Agromet instrumentation mast). You would need to visit the mast to take photographs of the equipment.

You will be using the Kipp and Zonen CNR1 four-component net radiometer. It is listed on ShortCut. The manual is attached for REFERENCE only. Do not print it. In addition, you will use air temperature and water vapour pressure data.

All surfaces spontaneously emit infrared irradiance. There are three types: near infrared, middle infrared and far infrared. The amount of infrared is governed by the Stefan-Boltzmann law - see summary of Chapter 3 of AMET210 attached.

In particular, read and understand the following sections of the summary:

- Greenhouse gas
- Clouds
- Infra red radiation
- Important greenhouses gases
- Global warming potential
- Radiation balance
- Greenhouse gases
- Radiation measurement systems
- Infra red radiation
- Water vapour and carbon dioxide absorption
- Shortwave and infra red irradiance
- Global warming
- The atmospheric "window"
- The atmospheric (greenhouse) effect
- Planck's law
- Outgoing radiation and the effect of water vapour (Brunt's equation)

5 Nowcasting grass-surface, grass and air temperature minima based on sub-hourly pre-dawn measurements³⁹

5.1 Abstract

Technological advances over the past several decades now allow automatic weather station (AWS) systems to perform sub-daily, even sub-hourly, temperature measurements including grass-surface, grass and air temperatures. One valuable application of the sub-hourly temperature dataset such as used in this study is in the area of nowcasting the minimum temperature for each day. For this purpose, four temperature models were tested, using 12-months of historic data from four locations varying in altitude, for their ability to nowcast 4-h or 2-h-ahead of sunrise the minimum temperature. The models used employed either the exponential or square root function to describe the rate of nighttime temperature decrease. The models were also applied in real-time using a Web-based system

<http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Daily%20minimum%20temperature%20nowcasting>

(Table 2.2, **Minimum temperature nowcasting row**) for which 4-h and 2-h nowcasts were made for one location with email alerts used for nowcast of temperatures close to 0 °C. For these nowcasts the AWS datalogger used covariance and variance calculations to determine the necessary coefficients for the nowcasted temperature reduction. Using the historic data, model 1 nowcasts vs the measured minimum air temperature yielded root mean square error (RMSE) values less than 1 °C for the 2-h-ahead nowcasts. Model 2 (also exponential) for which a constant model coefficient was used was usually slightly less accurate but the RMSE was also less than 1 °C. For the 4-h-ahead nowcast, the RMSEs increased to less than 2 °C for all locations. Model 3 (square root) yielded good 2-h-ahead comparisons between nowcasted and actual daily minimum air temperature for the Marianna (Florida, USA) and Cedara (KwaZulu-Natal, South Africa) locations with the RMSE less than 1 °C, but for the remaining locations RMSEs for this model increased to around 2 °C in some cases. The 4-h-ahead nowcasts generally yielded increased RMSE. For Pietermaritzburg (KwaZulu-Natal, South Africa), two-min grass-surface, grass and 2-m air temperature data were used. All model nowcasts for the grass-surface and grass daily minimum exhibited increased RMSE compared to those for air temperature at 2 m. Model 1 (exponential) applied to the historic data and data collected using the Web-based real-time system yielded reasonable 2-h-ahead nowcasts with an increase in the variability for the 4-h nowcasts.

³⁹ The contents of this chapter should remain confidential, until further notice, since the University of KwaZulu-Natal has expressed an interest in the intellectual property described

Keywords: *daily minimum temperature; frost; temperature modelling*

5.2 Introduction

The third agrometeorological application of the Web-based data and information system involved the nowcasting of daily minimum temperatures for frost prediction, using various methods, for a short-grass surface with the results displayed and updated automatically in near real-time.

Routine, timely and reasonably accurate nowcast of temperature conditions, particularly on a frost morning for example, is not yet possible in spite of technological advances over several decades that now allow sub-hourly temperature measurements. Early nowcasting and early warning of temperature minima would be of benefit to animal and crop production, as well as to manufacturing enterprises and the lay public for planning purposes. City, district or regional weather predictions are often not sufficiently accurate in nowcasting near-surface temperatures and cannot be used with confidence for specific locations with different topography, altitude, soil-surface cover, etc.

This investigation, similar to complex event processing (CEP) used for the observation and management of business process (Janiesch *et al.*, 2012), proposes a dynamic measurement, Web-based early nowcasting and control system based on sub-hourly temperature measurements. The terminology in relation to the subdivision of very short-range weather forecasts into weather nowcasting and nearcasting is not consistent. Glickman (2000) refers to nowcasting as a short-term weather forecast, generally for the next few hours, also stating that the U.S. National Weather Service specifies zero to three hours, but that up to six hours has also been used. For the purposes of this work, the term nowcasting will be used with the time period being at most six hours ahead.

Nowcasting of the minimum grass-surface, grass, or air temperature is essential if the impacts of frost, for example, are to be minimized and if active methods for combatting frost are to be effective. For grass-surface temperature, it is assumed that the grass fully covers the soil. An important indicator of frost occurrence at a remote/unattended site is the air, grass or grass-surface temperatures. The rate of temperature reduction during the nighttime is influenced by, amongst other factors, wind speed, atmospheric water vapour pressure, atmospheric stability, precipitation, sky temperature and cloud type and amount. During nighttime stable conditions, greatest temperature decreases occur under calm, dry, and cloud-free conditions.

Various models have been used to determine the diurnal variation in temperature (air and soil) given measured daily maximum (T_x) and minimum (T_n) temperatures, day of year, time of day and location. For example, Johnson and Fitzpatrick (1977) proposed, for cloudless days and the absence of frontal weather systems, a method for estimating the diurnal temperatures during the daylight hours based on measurements of T_x and T_n . Based on T_x and T_n , day of year/time of day, location information and three empirical constants, Parton and Logan (1981) used a sine-exponential model for estimating the diurnal variation in air temperature – sinusoidal from sunrise to sunset and exponential from sunset to the next sunrise. This model is physically plausible with the sinusoidal part mimicking the temporal influence of solar irradiance and the exponential part mimicking Newton's law of cooling for a heated surface after sunset and before sunrise. Wann *et al.* (1985) compared a number of models and concluded that the sine-exponential model gave the best accuracy for estimating hourly temperatures from daily maxima and minima. Snyder and de Melo-Abreu (2005) described the use of a square root model to predict the minimum air temperature using measurements from two hours after sunset to sunrise the next morning.

The applicability of both the sunset to sunrise exponential and square root models, the former inverted so as to nowcast the minimum temperature from sub-hourly temperature measurements, was investigated. Their application in real-time so as to allow timely nowcast of the minimum air temperature based on sub-hourly air temperature measurements, and therefore the rate of temperature decrease, several hours before sunrise, was also investigated. The models are also applied to grass temperature and grass-surface temperature, the latter using an infrared thermometer. The relative accuracy of the four model methods tested was investigated using historic data from selected locations at different altitudes and different data frequencies. Furthermore, the implementation of the Web-based system (Chapter 2) employing the various models using real-time temperature measurements is described.

5.3 Theory

During stable nighttime conditions, in the absence of a frontal weather system and with cool, calm, cloud- and mist-free conditions, air temperature decreases continually reaching a minimum at around sunrise. For such conditions, Parton and Logan (1981) used a three-parameter model assuming that the air temperature $T(t)$ (°C) at any time t (h) during the nighttime can be determined from measurements of the daily maximum T_x (°C) and minimum T_n (°C) temperatures and is given by:

$$T(t) = T_n + (T_{ss} - T_n) \exp\left(\frac{-b(t-t_{ss})}{24-D}\right) \quad (5.1)$$

for time t before midnight where T_{ss} ($^{\circ}\text{C}$) is the air temperature at sunset, denoted time t_{ss} (h), $b = 2.2$ is an empirically-determined constant for air temperature measured about 1.5 m above ground and D (h) the daylength and $24 - D$ the nightlength for the location for the current day. For times t after midnight, the period since sunset, $t - t_{ss}$, is replaced by $t + 24 - t_{ss}$. In Equation (5.1), in the case of air temperature, the time lag between the minimum air temperature and that at sunrise has been ignored. Parton and Logan (1981) found this lag to be -0.17 h for air temperatures at a height of 1.5 m and -0.18 h at 0.1 m – that is, the minimum air temperatures occurred about 10 min before sunrise. Their sensitivity analysis showed that changes to this lag time resulted in only small increases in the air temperature estimation error. They further assumed that the daytime variation in air temperature is described by a truncated sine function:

$$T(t) = T_n + (T_x - T_n) \sin\left(\frac{\pi(t - t_{sr})}{D + 2a}\right) \quad (5.2)$$

where t_{sr} is the sunrise time and a (h), approximately 1.86 h, is an empirically-determined constant. The sunset temperature T_{ss} in Equation (5.1) is estimated from T_x , T_n , D and a using:

$$T_{ss} = T_n + (T_x - T_n) \sin\left(\frac{\pi D}{D + 2a}\right). \quad (5.3)$$

For the square root model for nighttime air temperatures two hours after sunset:

$$T(t) = T_{ss+2} - c\sqrt{t - t_{ss+2}} \quad (5.4)$$

for t before midnight where T_{ss+2} is the measured air temperature 2 h after sunset which is referred to as time t_{ss+2} , c ($^{\circ}\text{C h}^{-0.5}$) is an empirical constant and $t - t_{ss+2}$ is the duration between t and 2 h after sunset. For times after midnight, $t - t_{ss+2}$ is replaced by $t + 24 - t_{ss+2}$. By rearrangement of Equation (5.4), the constant c for the period between t_{ss+2} and t_{sr} may be determined from the nowcasted air temperature minimum (T_{pn}) and the measured air temperature T_{ss+2} at time t_{ss+2} :

$$c = \frac{T_{pn} - T_{ss+2}}{\sqrt{t_{sr} + 24 - t_{ss+2}}} \quad (5.5)$$

where $t_{sr} + 24 - t_{ss+2}$ is the period between two hours after sunset and sunrise. The method is restricted to the period between two hours after sunset and sunrise since the net irradiance is relatively constant between these two times (Snyder and de Melo-Abreu, 2005).

Four nowcasting model methods were tested for estimating the minimum air/grass/grass-surface temperature four and two hours before sunrise based on sub-hourly temperature measurements between six and two hours before sunrise:

1. by inverting the exponential decay function (Equation 5.1);
2. by application of model 1 using $b = 2.2$;
3. by application of the square root function based on temperature measurements 4 h before sunrise (Equation 5.4);
4. by application of the square root model based on temperature measurements 2 h before sunrise.

The models proposed for nowcasting of the minimum grass-surface, grass and air temperatures are based on the assumption that two to four hours is a sufficient notice period for active methods for combatting frost such as sprinkler irrigation, heaters, fans, and others, to be in place or for animals to be moved to protected environments or for planning methods/protocols to be implemented by manufacturing enterprises and lay public. These methods, applied in real-time, may allow timely nowcasting of the minimum temperature based on sub-hourly temperature measurements. For this purpose, the nighttime exponential equation (Equation 5.1) was inverted and solved for T_n so as to nowcast the minimum temperature T_{pn} :

$$T_{pn} = \frac{T(t) - T_{ss} \exp\left(\frac{-b(t-t_{ss})}{24-D}\right)}{1 - \exp\left(\frac{-b(t-t_{ss})}{24-D}\right)} \quad (5.6)$$

given the measurement of temperature at time t after midnight where:

$$b = -\left(\frac{24-D}{t-t_{ss}}\right) \ln\left(\frac{T(t)-T_n}{T_{ss}-T_n}\right). \quad (5.7)$$

For sub-hourly diurnal temperature data, which includes the minimum air temperature, regressing $\ln(T(t) - T_n)$ as a function of $(t - t_{ss})/(24 - D)$ was assumed to yield a straight line with a slope of $-b$. For nowcasting, the empirical constant b may be determined, during several calm and cloud-free nights, days preceding the calculation of T_{pn} . Clouds and/or mist or rainfall and/or increased wind speed hours before sunrise could reverse or hinder the nighttime rate of air temperature decrease. A reversal of the expected temperature decrease for some of the time could result in $b < 0$ and possibly an unreliable nowcast. Conversely, more rapid temperature decreases than expected could result, for the assumed b value, in T_{pn} greater than T_n . Changes in atmospheric conditions from one night to another could also result in different b values and therefore reduce the accuracy of the method.

Assuming that the exponential model may be inverted and the square root model applied to the expected nighttime decrease in temperature it is proposed that, given real-time measurements, of grass-surface/grass/air temperature prior to the occurrence of the minimum temperature, the methods are used to routinely nowcast the minimum temperature.

Generalising the exponential model (Equations 5.1 and 5.6) to two measured temperatures $T(t_1)$ and $T(t_2)$ instead of $T(t)$ and T_{ss} , where $T(t_2)$ is a measured temperature at a later time t_2 than temperature $T(t_1)$, with the two times several hours apart:

$$T_{pn} = \frac{T(t_2) - T(t_1) \exp\left(\frac{-b(t_2 - t_1)}{t_{sr} - t_1}\right)}{1 - \exp\left(\frac{-b(t_2 - t_1)}{t_{sr} - t_1}\right)} \quad (5.8)$$

if times t_1 and t_2 are both before midnight or both after midnight. If t_1 is before midnight and t_2 after midnight, then

$$T_{pn} = \frac{T(t_2) - T(t_1) \exp\left(\frac{-b(t_2 + 24 - t_1)}{t_{sr} - t_1}\right)}{1 - \exp\left(\frac{-b(t_2 + 24 - t_1)}{t_{sr} - t_1}\right)}. \quad (5.9)$$

The following four methods are proposed for determining T_{pn} , 4 h or 2 h before sunrise from pre-dawn sub-hourly temperature measurements.

5.3.1 Method 1 Inversion of exponential model

This proposed method yields two model nowcasts using sub-hourly temperature measurements between four to two hours before sunrise for the first nowcast and six to four hours before sunrise for the second to determine the assumed exponential decrease in air temperature and hence determine the exponential decay factors b . These factors together with the measured temperatures before sunrise are then used to obtain T_{pn} four and two hours before sunrise. Modelled on the previous theory for a nighttime period (Equation 5.7) usually after midnight, for the 2-h-ahead nowcast, the temperatures $T(t_{sr-4})$ and $T(t_{sr-2})$ at and between times t for which $t_{sr-4} \leq t \leq t_{sr-2}$ allow the decay factor ($b = b_{sr-4to-2}$) to be determined from the slope of the plot of $\ln(T(t) - \min(T_{sr-4to-2}) + 0.01)$ vs $\frac{t - t_{sr-4}}{t_{sr-2} - t_{sr-4}}$ where $\min(T_{sr-4to-2})$ represents the minimum of the temperatures between the two times and $t_{sr-2} - t_{sr-4} = 2$ h. The constant of 0.01 °C is required to ensure that the argument of the logarithm is always positive and hence defined when $T(t) = \min(T_{sr-4to-2})$. Using this method, unlike the Parton and Logan (1981) method, a different $b = b_{sr-4to-2}$ value from $b = 2.2$ is determined for each early-morning period. Similar procedures were used for the 4-h-ahead nowcasts.

By inversion of Equation 5.1 (Equations 5.8 or 5.9), and application to the period 4 to 2 h before sunrise with a nowcast 2 h before sunrise, T_{pn} was determined assuming a continued and exponential decay after t_{sr-2} , at the same exponential rate:

$$T_{pn} = \frac{T(t_{sr-2}) - T(t_{sr-4}) \exp\left(\frac{-b_{sr-4to-2}(t_{sr-2} - t_{sr-4})}{t_{sr} - t_{sr-4}}\right)}{1 - \exp\left(\frac{-b_{sr-4to-2}(t_{sr-2} - t_{sr-4})}{t_{sr} - t_{sr-4}}\right)} \quad (5.10)$$

which simplifies to:

$$T_{pn} = \frac{T(t_{sr-2}) - T(t_{sr-4}) \exp(-b_{sr-4to-2}/2)}{1 - \exp(-b_{sr-4to-2}/2)} \quad (5.11)$$

For a nowcast 4 h before sunrise:

$$T_{pn} = \frac{T(t_{sr-4}) - T(t_{sr-6}) \exp(-b_{sr-4to-2}/3)}{1 - \exp(-b_{sr-6to-4}/3)} \quad (5.12)$$

The equations and methods used for historic data or nowcasts are shown in Table 5.1. For times when the calculated b value was out of its expected range, typically $|b| < 1$, then Equation 5.11 was applied using $b_{sr-4to-2} = 2.2$ and $T(t_{sr-2})$ replaced by the minimum temperature between 4 to 2 h before sunrise.

5.3.2 Method 2 Application of exponential model with $b = 2.2$

This proposed model, instead of the values for b ($= b_{sr-4to-2}$ and $b = b_{sr-6to-4}$) determined by regression (Table 5.1), uses a fixed value of 2.2 (Parton and Logan, 1981) in Equation (5.11). In the case of real-time analyses, this method is the simplest of all model methods tested since no real-time regression analysis is required. Model 2 is also used as part of model 1 when the absolute value of the calculated b value is less than 1.

5.3.3 Method 3 Application of square root model

This method for determining T_{pn} for times t between 4 and 2 h before sunrise was modelled on the square root model (Equation 5.4) using the relationship:

$$T(t) = T(t_{sr-4}) - c_{sr-4to-2} \sqrt{t - t_{sr-4}} \quad (5.13)$$

Table 5.1 Equations and datalogger methods used for the 2-h nowcasting of the daily minimum temperature.

Model	Determination/value of constant ⁴⁰	Calculation ⁴¹ of T_{pn}	Conditions for trapping nighttime increases in temperature
1	$b_{sr-4to-2} = -[\text{covariance}(\frac{t-t_{sr-4}}{t_{sr-4}-t_{sr-2}}, \ln(T(t) - \min(T_{sr-4to-2})) + 0.01)] / \text{variance}_p(\frac{t-t_{sr-4}}{t_{sr-4}-t_{sr-2}})$	$T_{pn} = \frac{T(t_{sr-2}) - T(t_{sr-4}) \exp(-b_{sr-2to-4}/2)}{1 - \exp(-b_{sr-4to-2}/2)}$	<p>If $(b_{sr-4to-2} < 1)$ then</p> $T_{pn} = (\min(T_{sr-4to-2}) - T_{sr-4} \exp(-\frac{2.2}{2})) / (1 - \exp(-\frac{2.2}{2}))$ <p>else if $(b_{sr-4to-2} < 0)$ or $T_{sr-4} < T_{sr-2}$ then $T_{pn} = \min(T_{sr-4to-2})$</p> <p>else</p> $T_{pn} = (T_{sr-2} - T_{sr-4}) \exp(-\frac{b_{sr-4to-2}}{2}) / (1 - \exp(-\frac{b_{sr-4to-2}}{2}))$
2	$b = 2.2$	$T_{pn} = \frac{T(t_{sr-2}) - T(t_{sr-4}) \exp(-2.2/2)}{1 - \exp(-2.2/2)}$	<p>If $(b_{sr-4to-2} < 1)$ then</p> $T_{pn} = (\min(T_{sr-4to-2}) - T_{sr-4} \exp(-\frac{2.2}{2})) / (1 - \exp(-\frac{2.2}{2}))$ <p>else if $(b_{sr-4to-2} < 0)$ or $T_{sr-4} < T_{sr-2}$ then $T_{pn} = \min(T_{sr-4to-2})$</p> <p>else $T_{pn} = (T_{sr-2} - T_{sr-4}) \exp(-\frac{2.2}{2}) / (1 - \exp(-\frac{2.2}{2}))$</p>

⁴⁰ Covariance, variance and slope, where for example, $b = -\text{slope} = -\text{covariance}(X, Y) / \text{variance}_p(X)$, performed 2 h before sunrise based on 2-min temperature measurements 4 to 2 h before sunrise where variance_p is the population variance

⁴¹ Calculations performed 2 h before sunrise

Model	Determination/value of constant ⁴⁰	Calculation ⁴¹ of T_{pn}	Conditions for trapping nighttime increases in temperature
3	$c_{sr-4to-2} = -[\text{covariance}(T - T_{sr-4}, \sqrt{t - t_{sr-4}})]/\text{variance}_p(\sqrt{t - t_{sr-4}})$ for temperatures 4 to 2 h before sunrise	$T_{pn} = T_{sr-4} - 2c_{sr-4to-2}$	If $c_{sr-4to-2} < 0$ or $T_{sr-4} < T_{sr-2}$ then $T_{pn} = \min(T_{sr-2to-4})$ else $T_{pn} = T_{sr-4} - 2c_{sr-4to-2}$
4	$c_{sr-4to-2} = -[\text{covariance}(T - T_{sr-2}, \sqrt{t - t_{sr-2}})]/\text{variance}_p(\sqrt{t - t_{sr-2}})$ for temperatures 4 to 2 h before sunrise	$T_{pn} = T_{sr-2} - \sqrt{2} c_{sr-4to-2}$	If $(c_{sr-4to-2} < 0$ or $T_{sr-4} < T_{sr-2}$ or $T_{sr-4} - \sqrt{2}c_{sr-4to-2} > T_{sr-2} + 5)$ then $T_{pn} = \min(T_{sr-4to-2})$ else $T_{pn} = T_{sr-4} - \sqrt{2}c_{sr-4to-2}$

Therefore, using temperature measurements between 4 and 2 h before sunrise, a plot of $T(t) - T(t_{sr-4})$ vs $\sqrt{t - t_{sr-4}}$ yields a slope of $-c_{sr-4to-2}$ from which T_{pn} is determined using:

$$T_{pn} = T(t_{sr-4}) - c_{sr-4to-2} \sqrt{t_{sr} - t_{sr-4}} \quad (5.14)$$

which simplifies to

$$T_{pn} = T(t_{sr-4}) - 2c_{sr-4to-2} \quad (5.15)$$

where it is assumed that the same $c_{sr-4to-2}$ can also be used for times 2 h before sunrise and sunrise.

5.3.4 Method 4 Application of modified square root model

This method is the same as model 3 for determining T_{pn} for times t between 4 and 2 h before sunrise but with $T(t_{sr-2})$ replacing $T(t_{sr-4})$:

$$T_{pn} = T(t_{sr-2}) - c_{sr-4to-2} \sqrt{t_{sr} - t_{sr-2}} \quad (5.16)$$

which simplifies to

$$T_{pn} = T(t_{sr-2}) - \sqrt{2} c_{sr-4to-2} \quad (5.17)$$

where again it is assumed that the same $c_{sr-4to-2}$ can be used for times 2 h before sunrise and sunrise.

The various equations and datalogger methods used in the datalogger for the Web-based early-warning system used are outlined in Table 5.1. These protocols were also used for the spreadsheet calculations for the historic air temperature data for all sites.

All model determinations a few hours before sunrise are compromised by events such as transient clouds, increased wind speed, changes in atmospheric stability and precipitation with consequential likely disagreement between model determinations and measurements. Usually, however, these events tend to reduce the chance of freezing conditions.

5.4 Materials and methods

Methods were applied to real-time temperature measurements from Pietermaritzburg and to

historic data from four locations. Sub-hourly temperature data, predominantly air temperature from four locations varying in altitude from 30 to nearly 2000 m, were used. The relevant details of the various weather station systems, sensors, datalogging equipment and data used are shown in Table 5.2. For Pietermaritzburg, which included grass-minimum and grass-surface temperatures, data for 2011 and 2012 were used. The data for part of 2011 were used for model development with 2012 data used for testing goodness of model fit. Grass temperature for this site was measured in accordance with the World Meteorological Organization (2008) guidelines for sensor exposure. A 25-mm length of type-E thermocouple wire was freely exposed 25 to 50 mm above the soil surface so as to be in contact with blades of grass. Grass-canopy surface temperature was measured using an 8 to 14 μm germanium lens infrared thermometer (IRT) positioned at 45° to the horizontal, facing south and at a

Table 5.2 Location, datalogging, sensor and data details.

Station details	Field-station sensor details	Data
(a) Pietermaritzburg, Mast 1, South Africa (altitude 684 m, latitude 29.628° S, longitude 30.403° E)	IRT ⁴² at 2.6 m; unshielded type-E thermocouple (24-gauge) for grass temperature at 25 to 50 mm above soil surface; CR1000 ⁴³ datalogger, multiplexer. Datalogger-attached RF416 ⁴³ broad-spectrum radio, panel antenna in line-of-sight with base station Field station antenna connected to an arrestor, in turn connected to radio. The datalogger was earthed. A RF416 radio connected to an 8-m antennae and surge-protector. Base station software included LoggerNet ⁴³ for data downloads	2-min surface, grass and air temperature measurements for 21 st April to 18 th August 2011
(b) Marianna, Tower 130, Jackson County, Florida, USA (altitude 35 m, latitude 30.850° N, longitude 85.165° W)	CS107 ⁴³ air temperature sensor in 12-plate Gill shield at 0.6-m height; CS215 ⁴³ air temperature and RH instrument in 12-plate Gill shield at 2 m CR10X ⁴³ datalogger with attached RF401 ⁴³ radio and cell modem	15-min air temperature measurements for 2004 for 0.6- and 2-m heights
(c) Cedara, South Africa (altitude 1076 m, latitude 29.5333° S, longitude 30.2833° E)	TR1 ⁴⁴ air temperature and relative humidity sensor ETo ⁴⁴ datalogger station	15-min air temperature measurements for 1 st January 2005 to 17 th April 2006 for 2-m height
(d) Cathedral Peak, South Africa (altitude 1935 m, latitude 29.4833° S, longitude 30.5° E)	Unshielded 75- μm thermocouples and 21X ⁴³ datalogger.	20-min air temperature measurements for 1992 for 0.5- and 1.5-m heights

⁴² Apogee IRT model IRR-P (half angle of 22°): Apogee Instruments Inc., Logan, Utah, USA

⁴³ Campbell Scientific Inc., Logan, Utah, USA

⁴⁴ Adcon Telemetry GmbH, Inkustrasse 24, A-3400 Klosterneuburg, Austria

height of 2.5 m, sensing a grass target diameter of 1.9 m. Air temperature and relative humidity were measured in a naturally-ventilated 6-plate Gill radiation shield at 2 m. The thermocouples for grass temperature were calibrated, in a water bath, against a reference PT1000 resistance thermometer (data not shown) and the IRT calibrated using a large radiator (Savage and Heilman, 2009). No corrections for the thermocouple temperatures were applied. Corrections were applied for surface temperature based on the IRT voltage output and the sensor body temperature. All temperature measurements were performed differentially every 15 s and averaged every 2 min. This allowed a sufficiently large sample number (60) of data pairs for the linear regression statistics for the period 4 to 2 h before sunrise (Table 5.1). The calculations for daylength and sunrise time, required for all four models, were included in the datalogger program using VBA functions provided by the National Oceanic and Atmospheric Administration:

<http://www.srrb.noaa.gov/highlights/sunrise/calcdetails.html>

Use of hourly temperature data, for which only two temperatures would be available 2 h before sunrise, would not allow the necessary slope calculations using the exponential and square root models and would result in a two-point model. Hence more frequent data collection was used. For the nowcasts for the PMB site, once the temperatures for the period 4 to 2 h before sunrise had been stored, they were recalled from datalogger memory, reformulated as necessary for the exponential and square root models for linearization of the model relationships and then a covariance instruction, part of the datalogger instruction set, applied to obtain the slope values ($b_{sr-4to-2}$ and $c_{sr-4to-2}$ for the respective models) from covariance and population variance instructions (Table 5.1). These instructions allowed T_{pn} to be determined four hours and two hours before sunrise.

The historic datasets also contained sub-hourly air temperatures (Table 5.2). The four models (Table 5.1) were applied to 15-min air temperature measurements for 2004 for 0.6- and 2-m heights for Marianna, Jackson County, Florida, USA (Table 5.2). For this dataset (ftp://if-fwn-prdw01.osg.ufl.edu/fawnpub/data/15_minute_obs/), model nowcasts were made 2 h before sunrise using air temperature measurements 4 to 2 h before sunrise as well as nowcasts 4 h before sunrise using measurements 6 to 4 h before sunrise. For Cedara and Cathedral Peak (South Africa), 15- and 20-min air temperature data were used, respectively. In the case of Cathedral Peak, Catchment VI (CVI, Fig. 1.1), air temperature measurements at 0.5- and 1.5-m heights were used (Table 5.2).

In the case of method 1, in an attempt to trap events for which the nighttime temperature increases due to cloud(s), conditions were imposed based on a calculated slope value b or that the temperature at t_{sr-2} exceeds that at t_{sr-4} . For this method, nowcasts with a b value less than 1 resulted in large deviations between T_{pn} and T_n . For $|b| < 1$, T_{pn} was estimated

using Equation (5.11) using $b = 2.2$ and $T(t_{sr-2}) = \min(T_{sr-4to-2})$. The latter ensured that the lowest measured temperature for this time period was used in the computation. If temperatures were increasing with the result that $T(t_{sr-2}) > T(t_{sr-4})$ or the computed b was negative then T_{pn} was assigned the minimum temperature between the two times, or else Equation (5.11) was applied using the computed $b_{sr-2to-4}$. The conditions for method 2 were similar to those from method 1 (Table 5.2).

In the case of Pietermaritzburg, for nowcasting the minimum temperatures (grass-surface, grass, and air), email alerts were used and near real-time data displayed, T_{pn} in particular, on the Internet using an open Web-based data and information system: <http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Daily%20minimum%20temperature%20prediction>

5.5 Results and discussion

Comparisons between the four model determinations of the daily minimum air temperature T_{pn} for the four locations were compared against the actual daily air temperature minimum T_n using statistical analyses and regression scatter plots. Confidence intervals (99 and 95 %) for slopes and intercepts were determined to test for significant differences from 1 and 0 respectively.

5.5.1 Pietermaritzburg 2-min measurements of grass-surface, grass and air temperature

Judging by the increased root mean square error (RMSE), the T_{pn} vs T_n air temperature comparisons for the nowcasts 2 h before sunrise were less variable than for the grass-surface and grass temperatures (Table 5.3a, Figure 5.1). For model 1 (exponential, Equation 5.11) T_{pn} comparisons with T_n , the RMSE values are 0.870, 1.349 and 1.329 °C for air, grass and grass-surface temperatures respectively. For the 2- and 4-h nowcasts, the differences between the grass-surface, grass and air temperature regression slopes and intercepts from 1 and 0 °C respectively for models 1 and 2 were small (Tables 5.3 and 5.4). The model method 3 and 4 comparisons were more variable than those for models 1 and 2 (Figure 5.2 compared to 5.1a) and characterised by increased RMSE and decreased coefficient of determination (R^2). Furthermore, model 1 comparisons were characterised by a smaller (positive) intercept (Table 5.3a, Figures 5.1a and 5.2). The slope value for model 3 was large and statistically different from models 1, 2 and 4.

For model 1 (exponential), the average b value for air temperature ($b = 2.131$) was less than 2.2 and even less for the grass (1.470) and surface (1.600) temperatures. Only positive b

Table 5.3 Model[†] statistics for comparisons of T_n with T_{pn} , the latter 2 h before sunrise: (a) Pietermaritzburg 2-min air (2 m), grass (25 to 50 mm) and surface temperature minimum temperature determinations for the 2011 data set. The most accurate determinations – for model 1 – are shaded; (b) Marianna 15-min air (0.6 and 2 m) temperature minimum temperature nowcasts for the 2004 data set; (c) Cedara 15-min air (2 m) temperature for the 2005-6 data set (1st January 2005 to 17th April 2006); (d) Cathedral Peak 20-min air (0.5 and 1.5 m) temperature for the 1992 data set.

Measure- ment	Model	Slope	Intercept (°C)	R ²	RMSE (°C)	MBE (°C)	n ††	Average b or c /fixed b = 2.2 used	f †††
(a) Pietermaritzburg, 2011									
Air temper- ature (2 m)	1	1.018	0.352d	0.961	0.870	0.484	158	2.131	26
	2	1.013	0.353cd	0.963	0.841	0.369	158	2.2	
	3	0.930ab	2.426cd	0.891	1.374	1.920	159	0.908	23
	4	0.994	1.084cd	0.957	0.884	1.080	159	0.908	
Grass temper- ature (25 to 50 mm)	1	1.020	0.203	0.937	1.349	0.297	160	1.470	29
	2	0.998	0.440cd	0.939	1.298	0.438	160	2.2	
	3	0.934b	2.584cd	0.870	1.851	2.280	158	1.208	27
	4	0.979	1.336cd	0.940	1.268	1.324	158	1.208	
Grass-surface temper- ature	1	1.014	0.237	0.939	1.329	0.289	158	1.600	26
	2	1.009	0.283d	0.932	1.398	0.291	158	2.2	
	3	0.990	2.150cd	0.859	2.056	2.111	159	1.160	29
	4	1.005	1.090cd	0.937	1.337	1.093	159	1.160	
(b) Marianna, Jackson County, 2004									
Air temper- ature (0.6 m)	1	0.991b	0.344cd	0.994	0.621	0.222	351	2.591	21
	2	0.995	0.174d	0.993	0.650	0.164	361	2.2	
	3	1.000	-0.161	0.990	0.785	-0.158	351	0.395	
	4	0.996	0.074	0.992	0.691	0.074	360	0.395	
Air temper- ature (2 m)	1	0.992	0.367cd	0.994	0.620	0.252	361	2.681	19
	2	0.996	0.167d	0.993	0.643	0.160	361	2.2	
	3	1.003	-0.173d	0.990	0.773	-0.156	360	0.401	
	4	0.997	0.066	0.992	0.686	0.066	360	0.401	
(c) Cedara, 2005-6									
Air temper- ature (2 m)	1	0.988	0.529cd	0.973	0.710	0.388	465	2.172	38
	2	0.989	0.441cd	0.970	0.753	0.432	465	2.2	
	3	0.989	0.317cd	0.961	0.857	0.190	464	0.432	34

Measure- ment	Model	Slope	Intercept (°C)	R ²	RMSE (°C)	MBE (°C)	<i>n</i> ††	Average <i>b</i> or <i>c</i> /fixed <i>b</i> = 2.2 used	<i>f</i> †††
	4	0.987	0.501cd	0.969	0.758	0.499	464		
(d) Cathedral Peak, 2002									
Air temper- ature (0.5 m)	1	1.008	0.293cd	0.960	0.957	0.358	351	2.318	37
	2	1.019	0.107	0.959	0.987	0.038	358	2.2	
	3	1.014	-0.022	0.938	1.217	0.163	350	0.539	36
	4	1.018	0.071	0.962	0.950	0.060	357	0.539	
Air temper- ature (1.5 m)	1	0.998	0.388cd	0.964	0.910	0.373	358	2.316	
	2	1.010	0.191	0.962	0.950	-0.111	358	2.2	
	3	1.012	0.014	0.941	1.198	0.115	357	0.526	
	4	1.005	0.273cd	0.954	1.038	0.273	357	0.526	

a and/or b denotes significantly different from a slope of 1 at 99 and 95 % levels respectively;
c and/or d denotes significantly different from an intercept of 0 °C at 99 and 95 % levels
respectively

† Model 1: application of exponential model; model 2: inversion of exponential model to
sunrise; model 3: application of square root model

†† *n* is the number of data pairs. Days for the T_n , T_{pn} regression comparisons

††† *f* is the percentage of values replaced using the conditional statements of Table 5.1

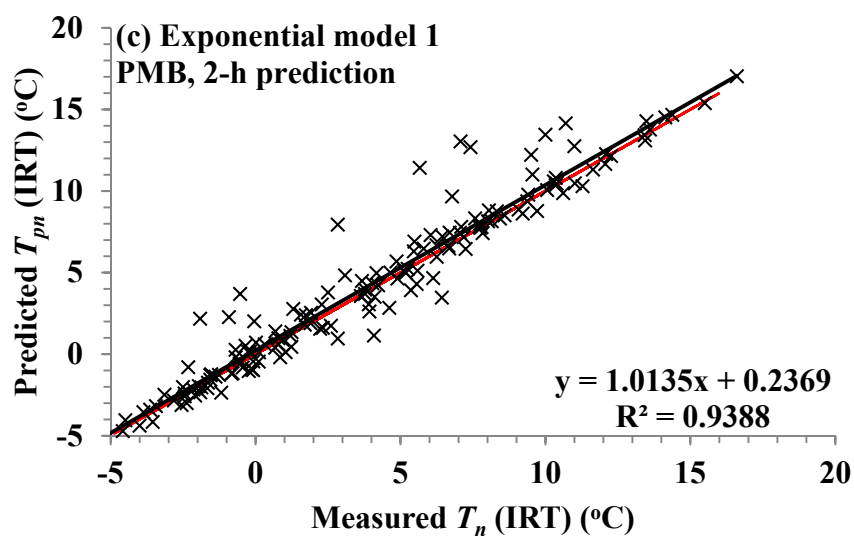
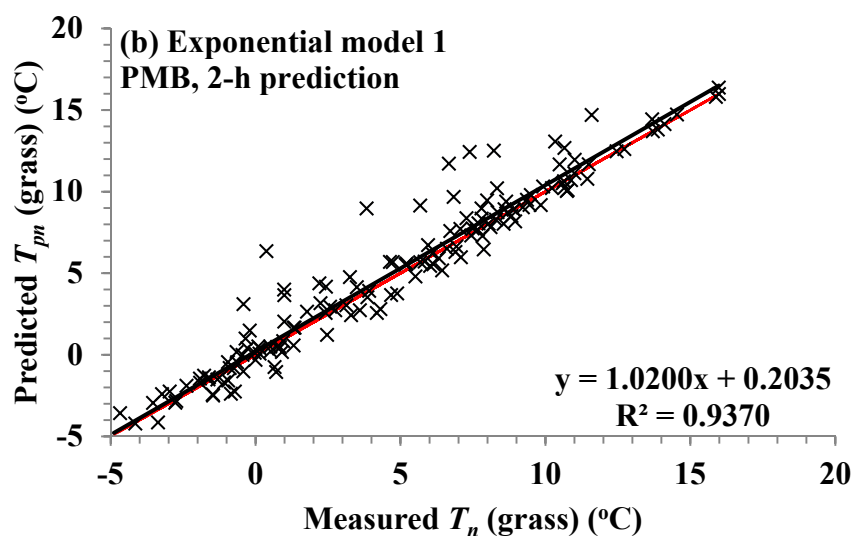
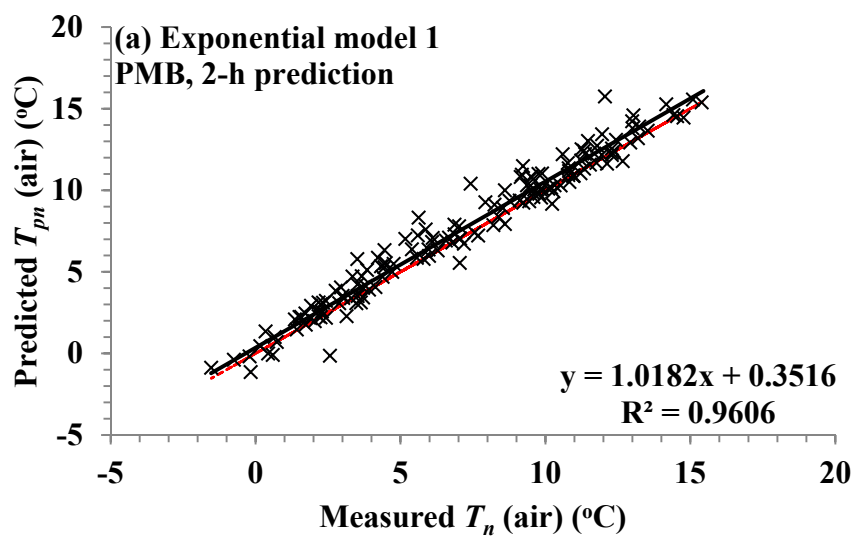


Figure 5.1 Regression plots for the experimental exponential model 1 for the 2-h-ahead nowcasted for hourly Pietermaritzburg data (a) for model-predicted minimum air temperature (T_{pn}) vs measured minimum air temperature (T_n); (b) for model-predicted T_{pn} (grass) vs T_n (grass); (c) for model-predicted T_{pn} (IRT) vs T_n (IRT). The regression line (solid) and 1:1 lines (dotted) are shown.

values were included in the averaging. A decreased b value implies a reduced rate of reduction in the nighttime temperatures. For the 159-day period, about 25 % of the nights contained negative b values or nights for which $T_{sr-2} > T_{sr-4}$ (Table 5.1, last column).

In general, models 1, 2 and 4 fared well in determining T_{pn} for the 2-h nowcast with model 1 usually the best. For the 4-h nowcasts, the RMSE increased by between about 15 % and 100 % for the different temperatures (air, grass, grass-surface) for the different models (Table 5.3a cf 5.4a) and R^2 decreased, particularly for the grass and grass-surface temperatures. As was the case for the 2-h nowcasts, use of model 3 yielded less accurate determinations.

5.5.2 15- or 20-min measurements of air temperature for all other locations

The 15- or 20-min T_{pn} vs T_n air temperature comparisons for the 2-h nowcasts for all other locations and for all heights and models were not statistically different with slopes not different from 1 and intercept from 0 °C. As was the case for the Pietermaritzburg comparisons, model 1 was marginally better than the other models for all locations. For models 1 and 2, for Cathedral Peak, a high-altitude site, exhibited the largest RMSE for both measurement heights. This is probably due to the more frequent precipitation events, compared to the other locations, affecting the nowcast accuracy.

Model 3 nowcasts had the greatest RMSE for all locations apart for the 2-m air temperatures at Marianna (Table 5.3b, c, d). For Cedara for which the 2-h nowcast comparisons were for more than 15 months, the slopes were significantly less than 1 for all models (Table 5.3c). This location, situated in a first-order catchment also had an increased percentage of the number of days with b or c values less than 0 or T_{sr-2} greater than T_{sr-4} . The same applied to the 4-h nowcasts for models 3 and 4 (Table 5.4c).

The 4-h model nowcast comparisons also exhibited increased RMSE for all models – between about 15 and 80 % (Tables 5.3b, c, d compared to Table 5.4b, c, d) and Figures 5.3a vs 5.3b and 5.4a vs 5.4b).

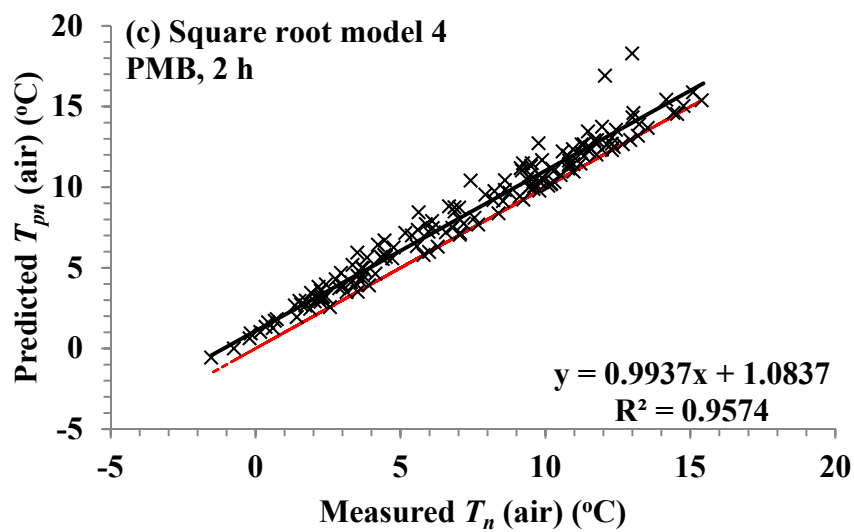
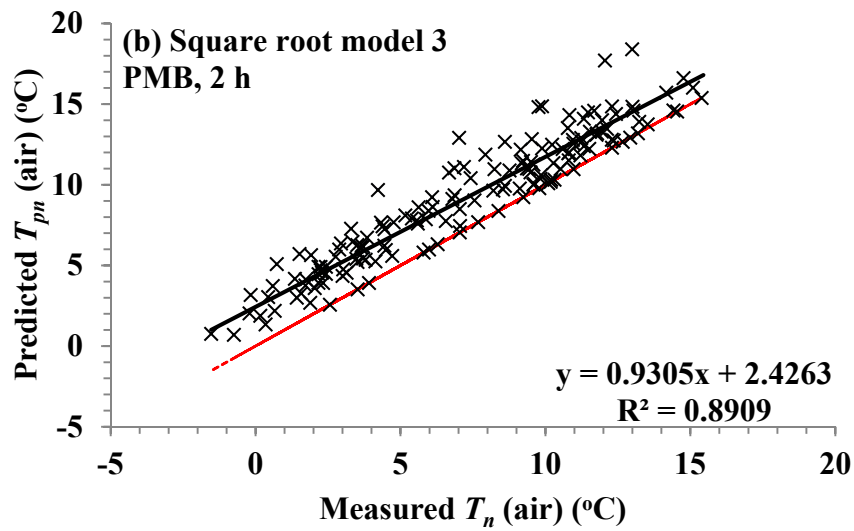
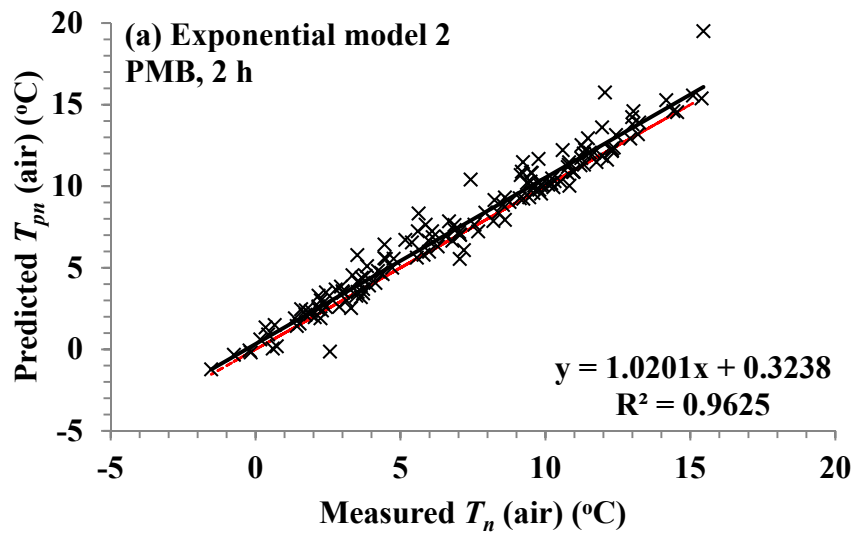


Figure 5.2 Regression plots for the exponential model 2 for which $b = 2.2$ for the 2-h-ahead nowcasted for hourly Pietermaritzburg data (a) for model-predicted minimum air temperature (T_{pn}) vs measured minimum air temperature (T_n); (b) for model-predicted T_{pn} (grass) vs T_n (grass).

Table 5.4 Model statistics for 4-h nowcasts: (a) Pietermaritzburg; (b) Marianna; (c) Cedara; (d) Cathedral Peak.

Measure- ment	Model	Slope	Intercept (°C)	R ²	RMSE (°C)	MBE (°C)	<i>n</i>	Average <i>b</i> or <i>c</i> /fixed <i>b</i> = 2.2 used	<i>f</i>
(a) Pietermaritzburg, 2011									
Air tempera- ture (2 m)	1	0.982	1.307cd	0.911	1.266	1.177	163	1.908	24
	2	0.977	1.359cd	0.911	1.260	1.331	163	2.2	
	3	1.015	0.152	0.867	1.653	0.261	157	1.024	
	4	0.978	0.880cd	0.896	1.391	0.866	157	1.024	
Grass tempera- ture (25 to 50 mm)	1	0.992	1.114cd	0.910	1.560	1.079	161	1.491	26
	2	0.988	1.242cd	0.909	1.565	1.232	161	2.2	
	3	1.012	0.014	0.709	3.214	0.067	0	1.443	
	4	0.998	0.632d	0.800	2.477	0.630	0	1.443	
Grass- surface tempera- ture	1	1.020	0.881cd	0.892	1.804	0.955	163	1.631	29
	2	1.024	0.919cd	0.892	1.808	0.940	163	2.2	
	3	1.058	-0.315	0.756	3.045	-0.101	157	1.348	
	4	1.042	0.342	0.831	2.381	0.373	157	1.348	
(b) Marianna, Jackson County, 2004									
Air tempera- ture (0.6 m)	1	0.984ab	0.967cd	0.988	0.872	0.743	351	2.743	18
	2	0.994	0.627cd	0.989	0.820	0.619	361	2.2	
	3	1.004	0.148	0.988	0.882	0.209	352	0.490	
	4	0.996	0.501cd	0.989	0.823	0.499	352	0.490	
Air tempera- ture (2 m)	1	0.981ab	0.895cd	0.988	0.845	0.691	362	2.399	58
	2	0.991	0.664cd	0.989	0.816	0.658	362	2.2	
	3	1.004	0.135	0.989	0.796	0.193	352	0.509	
	4	0.996	0.509cd	0.989	0.818	0.507	352	0.509	
(c) Cedara, 2005-6									
Air tempera- ture (2 m)	1	0.992	0.955cd	0.947	0.999	0.865	471	2.185	33
	2	1.000	0.781cd	0.945	1.026	0.781	471	2.2	
	3	1.018	0.402cd	0.937	1.130	0.608	464	3	20
	4	1.006	0.711cd	0.944	1.048	0.712	464	4	

Measure- ment	Model	Slope	Intercept (°C)	R ²	RMSE (°C)	MBE (°C)	<i>n</i>	Average <i>b</i> or <i>c</i> /fixed <i>b</i> = 2.2 used	<i>f</i>
(d) Cathedral Peak, 2002									
Air tempera- ture (0.5 m)	1	0.980	0.973cd	0.935	1.198	0.823	351	2.387	29
	2	0.989	0.720cd	0.922	1.332	0.709	362	2.2	28
	3	0.998	0.394d	0.886	1.657	0.378	362	0.627	
	4	0.988	0.719cd	0.911	1.433	0.716	362	0.627	
Air tempera- ture (1.5 m)	1	0.976	0.963cd	0.939	1.167	0.772	362	2.347	
	2	1.021	0.976cd	0.877	1.784	0.999	362	2.2	
	3	0.993	0.428d	0.894	1.600	0.370	362	0.603	
	4	0.983	0.748cd	0.917	1.388	0.774	362	0.603	

Overall, the exponential model 1, for which the *b* coefficient determined 2- or 4-h ahead of time was used to determine T_{pn} , yielded the best statistical comparisons with T_n . The RMSEs for both models 1 and 2 were consistently less than 1 °C. Models 3 and 4 based on the square root model were not as good, often exhibiting RMSE greater than 1 °C.

5.5.3 Implementation of the minimum temperature nowcast methodology into a near real-time web-based system

The model 1 (exponential) equations, for using $b = 2.2$, were added to the datalogger programme for calculating the nowcasted 2-h and 4-h ahead air, grass and grass-surface temperatures. The results are displayed in the screen:

[http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Daily
%20minimum%20temperature%20nowcasting](http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Daily%20minimum%20temperature%20nowcasting)

Additional information about the various models is included in this screen. A challenge in the implementation was due to the fact that datalogger programme changes resulted in a reset of the graphics.

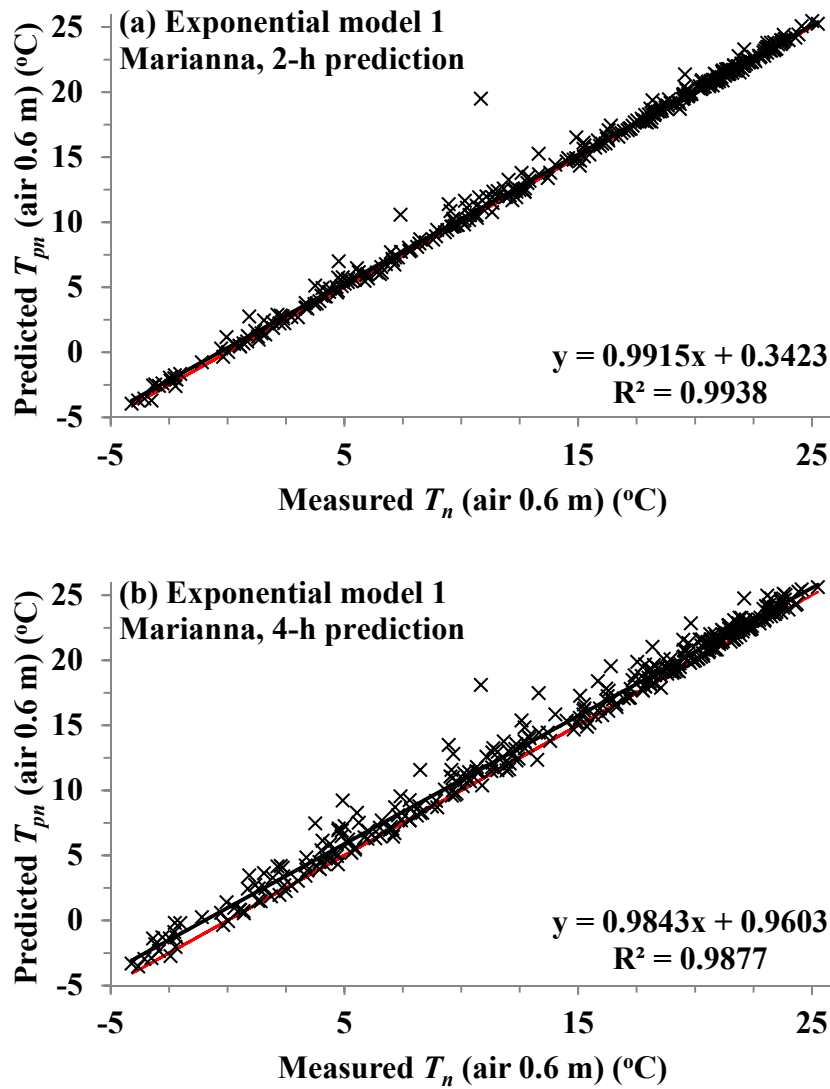


Figure 5.3 Regression plots for the experimental exponential model 1 for hourly Marianna data (a) for model-predicted minimum air temperature at 0.6-m (T_{pn}) for the 4-h-ahead nowcasted vs measured minimum air temperature (T_n) at 0.6 m; (b) for model-predicted T_{pn} for the 2-h-ahead nowcast (grass) vs T_n (grass).

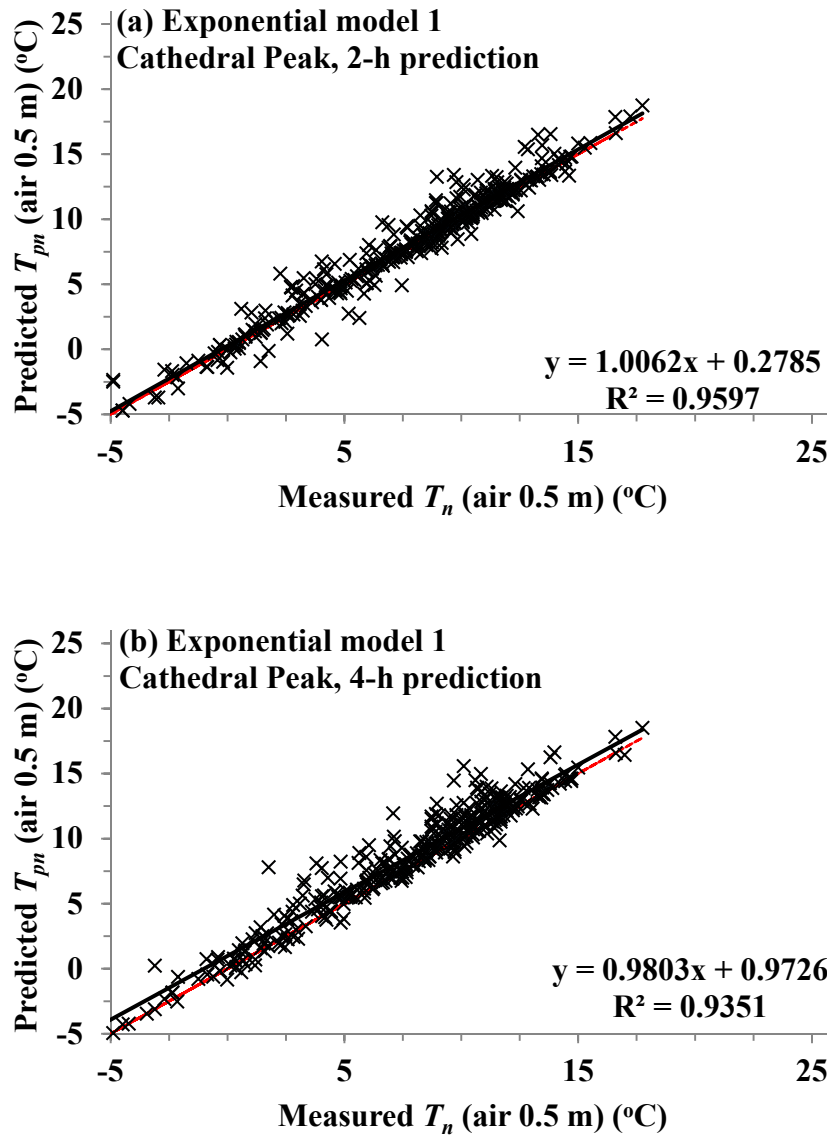


Figure 5.4 Regression plots for the experimental exponential model 1 for hourly Cathedral Peak data (a) for model-predicted minimum air temperature at 0.5-m (T_{pn}) for the 4-h-ahead nowcasted vs measured minimum air temperature (T_n) at 0.5 m; (b) for model-predicted T_{pn} for the 2-h-ahead nowcast (grass) vs T_n (grass).

5.6 Conclusions

Exponential and square root models for nowcasting the daily minimum air temperature for grass-surface, grass and air temperature 2 h and 4 h ahead of sunrise were successfully applied using sub-hourly temperatures for four locations with very different altitudes. Using the historical data, for both the 2-h ahead and the 4-h-ahead nowcasts, model 1 (exponential) usually yielded the lowest RMSE – less than 1.0 °C for the former and 1.3 °C for the latter. For the 4-h nowcasts, the intercept of the comparison of T_{pn} with T_n was much larger, sometimes as large as 1.4 °C, compared to 0.5 °C for the 2-h nowcasts. Except for Marianna (Florida, USA), all T_{pn} with T_n comparisons yielded slope values not statistically different from unity. Model 3 (square root) 2-h-ahead nowcasts usually had an increased RMSE for the T_{pn} with T_n comparison and even more so for the 4-h-ahead nowcasts, The T_{pn} vs T_n comparisons for grass-surface and grass temperatures were more variable with a significant increase in RMSEs. For the nowcasts, in general, model 1, for which the rate of reduction in nighttime temperatures was determined by covariance and variance instructions in the datalogger, yielded the best statistical comparisons for which the RMSE were less than 1 °C. The display of near real-time data provided a convenient method for the display of the nowcasted minimum grass, grass-surface and air temperatures.

5.7 Acknowledgements

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6 Web-based near real-time surface energy balance for short grass using surface renewal, temperature variance and dissipation theory⁴⁵

6.1 Abstract

Increasingly, near real-time evaporation and surface energy fluxes are required, for example, for comparison with satellite flux estimates or for use when remotely-sensed estimates are compromised either by the lack of data or the occurrence of cloud particularly for summer-rainfall areas. Net irradiance and soil heat flux components of the shortened surface energy balance for short grass were measured with the sensible heat flux (H) determined in near real-time using surface renewal (SR) and temperature variance (TV) methods and using a surface renewal-dissipation theory (SRDT) method. Measurements of air temperature from an unshielded fine-wire thermocouple placed at heights of 0.275 and 0.465 m above the soil surface were obtained at 10 Hz. From these measurements, the following air temperature statistics were determined every 30 min: mean, variance, skewness, and air temperature structure functions of order 2, 3 and 5 for lag times of 0.4 and 0.8 s. For cloudless conditions, the 0.4-s lag corresponded to the maximum of the negative of the structure function of order 3 divided by the time lag and was therefore used for the calculation of H using the SR and SRDT methods. The SR method requires calculation of the air temperature ramp amplitude and the quiescent and ramping periods for a 30-min period. For the air temperature ramp amplitude, the roots of a cubic polynomial were obtained in real-time using a datalogger program employing an iterative procedure for which the ramp amplitude was determined to within 0.005 °C from which H was determined using a SR weighting factor of 1. For the TV method, the direction of H was determined from the sign of the third-order air temperature structure function and the magnitude of H determined from the mean, variance and skewness of air temperature with adjustments for skewness applied for positive skewness and unstable events. The SRDT method, which uses the square of the SR ramp amplitude, the ramp period and the variance of air temperature, tended to underestimate H compared to SR and TV methods (for the SRDT vs SR method: slope = 0.771, coefficient of determination (R^2) = 0.990, root mean square error (RMSE) = 3.1 W m⁻²) using data from 1 June to 28 July 2012. With adjustment for skewness, the TV method showed good agreement with the SR method (slope = 1.035, R^2 = 0.905, RMSE = 13.2 W m⁻²). A shortened surface energy balance was used to determine the latent energy flux and hence evaporation from measured net irradiance from two- and four-component net radiometers, the measured soil heat flux and H , the latter using SR, TV and SRDT methods. The real-time iterative procedure allowed the fluxes, updated half-hourly, to be displayed using a Web-based data and information system:

⁴⁵ Based on Savage (2012)

<http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Energy%20balance>

(Table 2.2, **Energy balance row**). Half-hourly energy balance components are tabulated.

Keywords: *high frequency thermocouple measurements; skewness of air temperature; temperature structure functions*

6.2 Introduction

The fourth and final agrometeorological application of the Web-based data and information system involved the estimation of the surface energy balance components, using various methods, for a short-grass surface with the results displayed and updated automatically in near real-time.

The surface energy balance is often shortened as

$$R_{net} = LE + H + S \quad (6.1)$$

where R_{net} is the net irradiance, LE the latent energy flux from the surface, H the sensible heat flux and S the soil heat flux. All terms are in W m^{-2} . A number of simplifications have been made in using this form of the surface energy balance – for example, that there is no advection of sensible or latent energy flux and that the stored energy and biochemical energy fluxes are negligible.

Increasingly, near real-time evaporation and surface energy flux data and micrometeorological data are required, for example, for validation and/or calibration with satellite flux model estimates or for use when remotely-sensed model estimates are compromised by the occurrence of cloud, particularly for summer-rainfall areas. In this work, the methodology and results are reported for near real-time estimation of evaporation through using relatively inexpensive temperature-based methods for obtaining sensible heat flux H with display of evaporation ET (mm), H and other energy balance components in graphical and table form using the data and information Web-based system.

If all terms of the shortened energy balance are independently measured, then a test of the equality of the available energy flux density $R_{net} - S$ with $LE + H$ can be performed. If there is equality, then the energy balance is said to be closed. Many methods for estimating LE , such as the Penman-Monteith method, Bowen ratio, Priestley-Taylor, ETo and other evaporation estimation methods, assume that the energy balance is closed and hence LE is calculated as a residual using $LE = R_{net} - H - S$. This approach is also adopted here. In the case of the eddy covariance method, LE and H can be measured separately, allowing closure

to be checked. Usually for the eddy covariance method, the energy balance is not closed with $H + LE < R_{net} - S$. Some researchers have recommended forcing closure by assuming that the Bowen ratio (H/LE) remains the same before and after adjustment for non-closure (Twine *et al.*, 2000).

Temperature-based methods may be used for determining H – methods such as those based on surface renewal (reviewed by Mengistu and Savage, 2010), temperature variance (reviewed by Abraha and Savage, 2012) and dissipation theory (Castellví and Snyder, 2009). These methods require high frequency measurements of air temperature and have been reviewed in part by Savage (2010) and in the above-mentioned references.

For all three methods used in this study for determining sensible heat fluxes, there has been no simple methodology published in the literature or no near real-time methodology published for obtaining and public-displaying estimates of sensible heat flux using only high frequency air temperature measurements. The aim of this work was to obtain sensible heat flux estimates, using surface renewal, temperature variance and dissipation theory methods, in near real-time and then to implement the use of such estimates in the Web-based data and information system (Chapter 2) together with measurements of net irradiance and soil heat flux so as to then estimate latent energy flux and evaporation in near real-time.

6.3 Theory

Various (air) temperature methods, involving high frequency measurements and statistics, have been used to estimate sensible heat flux H . These methods include surface renewal (SR), temperature variance (TV) and combination surface renewal-dissipation theory (SRDT) for which statistics for n temperature measurements for a typical averaging period of 30 min, such as the mean (\bar{T} , °C), variance (σ_T^2 , °C²), skewness (S_T , no units), are required:

$$\bar{T} = \sum_{i=1}^n T_i / n \quad (6.2)$$

$$\sigma_T^2 = \sum_{i=1}^n (T_i - \bar{T})^2 / (n - 1) \quad (6.3)$$

$$S_T = (1/\sigma_T^3) \sum_{i=1}^n (T_i - \bar{T})^3 / (n - 1) \quad (6.4)$$

and, in addition, the air temperature structure functions S_r^k of order $k = 2, 3$ or 5 (°C², °C³ and °C⁵ respectively) with sample time lag r (s) where:

$$S_r^k = \frac{1}{n-j} \sum_{i=1+j}^n (T_i - \bar{T}_{i-j})^k \quad (6.5)$$

for which the number of temperature measurements is $n - j$ with the measurement frequency f (Hz) is given by

$$j = f \times r. \quad (6.6)$$

In the case of the SR method, array-based dataloggers such as the older CR10X, 21X and 23X dataloggers (Campbell Scientific, Logan, Utah, USA) allow scan rates of 0.125 s with typical temperature lags of 0.25 and 0.5 s used – corresponding to 2 and 4 lags respectively. The newer and faster table-based dataloggers (CR1000, CR3000 and CR5000) allow scan rates of 10 Hz and greater. Typical lags of 0.2 and 0.4 s or 0.4 and 0.8 s are employed. The newer loggers also allow storage of the high frequency air temperature data from which any desired time lag can then be used post-data collection for calculating S_r^2 , S_r^3 and S_r^5 .

In the case of the TV method, the relationship between the skewness and statistical moment of order 3 (M_3 , °C³) is given by:

$$S_T = (1/\sigma_T^3) M_3 / (n - 1) \quad (6.7)$$

where

$$M_3 = \sum_{i=1}^n (T_i - \bar{T})^3. \quad (6.8)$$

Various definitions of skewness can be found in the literature. In the Excel 2010 help, the following definition is used:

$$S_T = \left(\frac{n}{n-1} \right) (1/\sigma_T^3) M_3 / (n - 2) \quad (6.9)$$

where $n = 18000$ for half-hourly 10-Hz data. For large sample sizes, $n/(n - 2) \rightarrow 1$ and therefore the result of Equation 6.9 approaches that of Equation 6.7. Note that the possibility of $n = 2$ in Equation 6.9 for skewness is excluded just as $n = 1$ is excluded in Equation 6.3 for variance.

6.3.1 Surface renewal (SR)

Snyder *et al.* (1996) used air temperature structure functions and the procedure of van Atta (1977) to calculate the amplitude a (°C) and the ramp period τ (s) of high frequency air temperature measurements, above a canopy, over an averaging period. The ramp period τ is also referred to as the inverse ramp frequency corresponding to the sum of the quiescent and ramping periods. The surface renewal (SR) sensible heat flux $H = H_{SR}$ is then calculated using:

$$H_{SR} = \alpha z \rho_a c_p a / \tau. \quad (6.10)$$

The term α is a correction or weighting factor, z the measurement height above the soil surface, ρ_a the density of air (kg m^{-3}) and c_p the specific heat capacity of air at constant pressure ($\text{J kg}^{-1} \text{K}^{-1}$). The variable $a z$ represents the volume of air per unit ground area exchanged on average for each ramp in the sample period for height z (Paw U *et al.*, 1995). Castellví *et al.* (2002) interpreted $a z$ as the mean eddy size responsible for the renewal process. The weighting factor α is usually determined empirically from the slope of the linear regression of eddy covariance estimates of $H = H_{EC}$ (y) against $H = H_{SR}$ (x) using $\alpha = 1$. For the SR method the second, third and fifth air temperature structure functions are calculated in near real-time from the high frequency air temperature measurements. Typically, lag times r of 0.4 and 0.8 s are applied to the high frequency air temperature measurements used. The air temperature amplitude a (°C) and inverse ramp frequency τ (s) for the SR method can be determined from S_r^2 , S_r^3 and S_r^5 for air temperature (van Atta, 1977). An estimate of the ramp amplitude a for the averaging time interval is determined by solving for the real roots of

$$a^3 + pa + q = 0 \quad (6.11)$$

where

$$p = 10 S_r^2 - S_r^5 / S_r^3 \quad (6.12)$$

(van Atta, 1977). The ramping period τ is then calculated using

$$\tau = -a^3 r / S_r^3. \quad (6.13)$$

By definition, τ is always positive. By definition for unstable conditions, $a > 0$ °C and therefore $a^3 r > 0$ °C³ s with the result that $S_r^3 < 0$ °C³ from Equation 6.13 since $\tau > 0$ s (Savage, 2010). Similarly, for stable conditions, $a < 0$ °C forces $S_r^3 > 0$. The key to the SR approach is the solution of the real roots of the cubic equation and that the direction of H_{SR} is

indicated by the sign of a .

For the SR theory to be valid, τ should be much greater than the time lag r , typically

$$\tau > 10 r. \quad (6.14)$$

Snyder *et al.* (2007) also imposed an upper condition that

$$\tau < 600 \text{ s}. \quad (6.15)$$

To date, there has been no simple methodology nor no near real-time methodology proposed for the solution of the real roots of the van Atta (1977) cubic equation.

Castellví *et al.* (2012) have questioned the SR method for which α is obtained by calibration using simultaneous EC and SR measurements of H . For their measurements in a mature orange orchard, Castellví *et al.* (2012) found that EC-SR calibration method for determining α was dependent on weather conditions and daily and seasonal weather patterns. They suggested an SR method for which α is obtained from horizontal wind speed measurements, leaf area index, canopy height and the vertical extent of the foliage. Whichever method(s) for determining α are used, the air temperature ramp amplitude a and ramp period τ are still required.

The aim of this work was to obtain in near real-time the real roots (a) to the van Atta (1997) cubic polynomial and hence calculate τ and $H = H_{SR}$, for both stable and unstable conditions, using the Web-based data and information system (Chapter 2).

6.3.2 Temperature variance (TV)

The sensible heat flux using temperature variance $H = H_{TV}$ (Tillman, 1972) is determined for unstable conditions using

$$H_{TV} = \rho_a c_p (\sigma_T^3 k g z / \bar{T})^{0.5} \quad (6.16)$$

where k is the von Kármán constant, g the acceleration of gravity (m s^{-2}), σ_T^2 is the air temperature variance and \bar{T} the average air temperature for the output time interval. The TV method also often referred to as flux variance has received much attention (Savage, 2010; Abraha and Savage, 2012), particularly for strongly unstable conditions. The method, however, applies no correction for stability. For stability correction, the Tillman (1972) method involves the use of air temperature skewness S_T through use of a skewness factor

$f(S_T)$, applied in this study only for $S_T > 0$ for which $f(S_T) < 2.238$ (Figure 6.1):

$$H_{TVST} = \rho_a c_p (\sigma_T^3 k g z / \bar{T})^{0.5} \times f(S_T) \quad (6.17)$$

where

$$f(S_T) = \frac{(0.0549 + 0.0137 \exp(4.39 S_T))^{0.5}}{(0.0137 \exp(4.39 S_T))^{0.5}} \quad (6.18)$$

where the flux direction is given by S_r^3 :

$$H_{TVST} = \frac{-S_r^3}{|S_r^3|} \rho_a c_p (\sigma_T^3 k g z / \bar{T})^{0.5} \times f(S_T) \quad (6.19)$$

(Savage, 2010). For skewness values $S_T > 0.83$, the correction for stability is less than 5 % – i.e., $f(S_T) < 1.05$ (Figure 6.1).

As far as is known, much of the research using flux variance has either not involved stability correction, or is applied offline using Monin-Obukhov Similarity Theory (MOST)

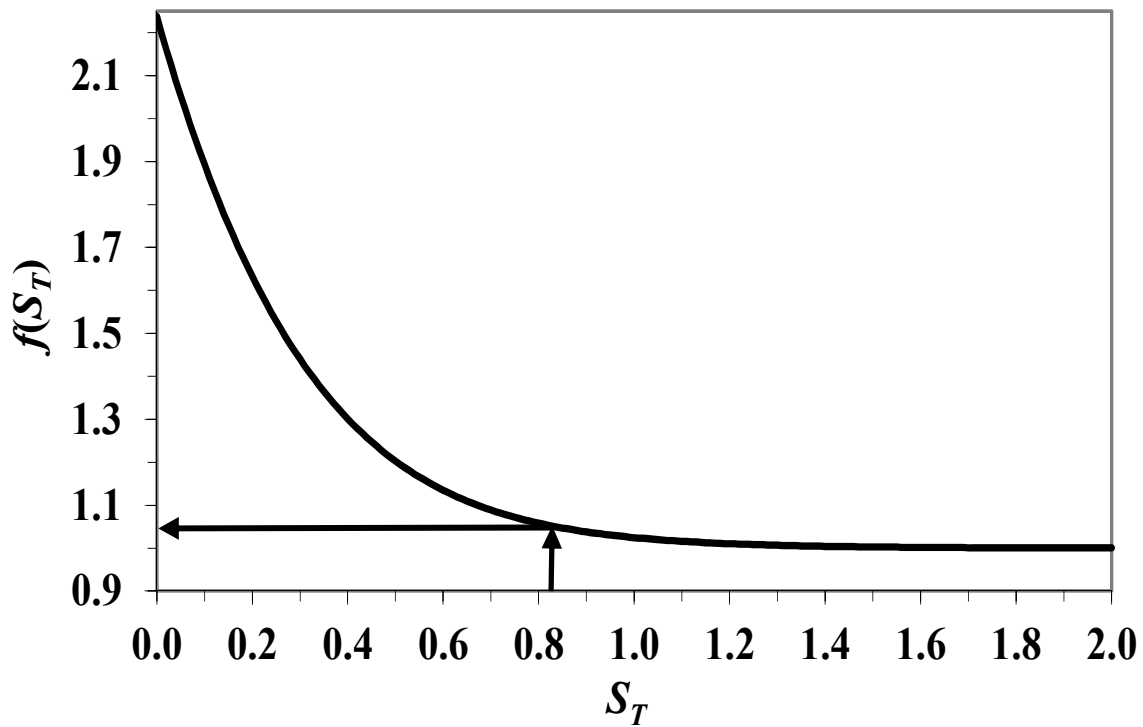


Figure 6.1 The functional dependence of $f(S_T)$ on air temperature skewness S_T (Equation 6.18) showing that for skewness values $S_T > 0.83$, $f(S_T) < 1.05$.

stability corrections that require friction velocity or wind speed measurements (Hsieh *et al.*, 1996). The intention of this study was not to require wind speed measurements and that the stability correction is performed online, thereby allowing near real-time stability-corrected flux variance estimates of sensible heat flux.

6. 3.3 Surface renewal-dissipation theory (SRDT)

For this combination dissipation theory and SR method, which uses dimensional analysis,

$$\alpha = \frac{1.66 a (z-d)}{\pi z \sigma_T} \quad (6.20)$$

(Castellví and Snyder, 2009) from which

$$H_{SRDT} = 1.66 \frac{a}{|a|} (z - d) \frac{\rho_a c_p a^2}{\pi \sigma_T \tau} \quad (6.21)$$

was determined where $a/|a| = 1$ for unstable conditions and $a/|a| = -1$ for stable conditions. The zero plane displacement height, d (m), was taken as $2/3 h$ where h (m) is the canopy height. The advantage of the SRDT method is that α (Equations 6.20) is calculated whereas in the case of Equation 6.10, α is usually determined from simultaneous eddy covariance and SR measurements. Alternatively the method of Castellví *et al.* (2012), for which horizontal wind speed measurements, leaf area index, canopy height and the vertical extent of the foliage are required, could be used.

6.4 Materials and methods

Net irradiance was measured above short grass using a four-component net radiometer, attached to Mast 1 (Figure 1.3), at a height of 2.6 m (CNR1, Kipp & Zonen, Delft, The Netherlands). Soil heat flux was measured at a depth of 80 mm using a self-calibrating heat flux plate (HFP01-SC, Hukseflux, Delft, The Netherlands). The datalogger used was programmed to perform a plate calibration every four hours from which a new calibration factor was determined and used for the measured plate voltages for the next four-hour period. Stored heat flux above the plate was calculated from soil temperature using type-E thermocouples (TCs) placed at 20- and 60-mm soil depths and soil water content (Hydra Probe, Stevens Water Monitoring Systems, Inc., Oregon, USA) buried horizontally at a depth of 25 mm. All sensors were connected to a Campbell CR1000 datalogger with an AM16/32A relay multiplexer.

For measurement of sensible heat flux, two unshielded type-E fine-wire TCs (75- μ m diameter, model CHCO-003, Omega Inc., Stamford, Connecticut, USA) were used. The ends of two fine-wire thermocouples, in parallel, were welded to 24-gauge type E extension thermocouple wire (Omega model EXTT-E-24). The fine-wire thermocouples were placed at 0.275 and 0.465 m above the soil surface of the short grass and were connected to a Campbell CR3000 datalogger (Mast 2, about 22 m from Mast 1, Figure 1.2). The fine-wire thermocouples proved to be virtually maintenance-free. They were in any case checked weekly for cleanliness. Occasionally, there was a need for removal of spider Webs and debris. Annually, the thermocouples were cleaned using an acetone wash and blow-dry. A terminal strip cover was used to reduce temperature gradients across the datalogger wiring panel. Measurements were at 10 Hz with datalogger calculations of H_{SR} , H_{TV} , H_{TVST} and H_{SRDT} performed in near real-time and displayed on the Web. Only the low frequency output data files, containing the flux calculations, ramp amplitude, total ramp period, second-, third- and fifth-order air temperature structure functions, and air temperature statistics, were scheduled using the Web-based data and information system for regular updating – every 10 min. These data files, in addition to the high frequency data, were stored on a 2-Gbyte compact flash memory card which was removed and replaced by a blank one every month. The high frequency air temperature data were archived in binary and ASCII formats for possible later use.

For the SR and SRDT methods, lag times of 0.4 and 0.8 s were used and the second- (S_T^2), third- (S_T^3) and fifth-order (S_T^5) air temperature structure functions determined in real time and stored in datalogger memory together with other temperature statistics. An iterative procedure, applied in the logger program, was used to calculate the air temperature ramp amplitude and the (sum of) quiescent and ramping periods (τ) for each time lag from which H_{SR} and H_{SRDT} were calculated. For the TV method, the mean, variance and statistical moment of order 3 and hence the skewness of air temperature were calculated from the high frequency air temperature measurements from which H_{TV} and H_{TVST} was calculated in near real-time.

The datalogger of Mast 1 was physically connected to that at Mast 2 by cross-wiring TX (transmit) and RX (receive) ports of a single COM (RS-232) port of both dataloggers with the dataloggers common grounded. The respective COM ports were reconfigured as RS-232 with a baud rate of 38400, a beacon interval of 15 s, verify interval of 15 s and configured as a router. A Campbell RF416 radio was connected to the datalogger at Mast 1 and another radio on the roof of a nearby building which was in turn connected to a server running LoggerNet and RTMC Pro (Campbell) software for display of near real-time fluxes, including LE , and totals for the current week/month.

6.5 Results and discussion

6.5.1 Lag times

For the 0.275- and 0.465-m heights, the time lag of 0.4 s corresponded to the maximum of $-(S_r^3/r)^{1/3}$, used by Chen *et al.* (1997) in their SR analysis using a ramp model with finite microfront period, for unstable conditions (Figure 6.2, for the 0.275-m height only). The value of $-(S_r^3/r)^{1/3}$ decreased slightly for lag times greater than 0.4 s, as indicated by the vertical arrows in Figure 6.2, but not greatly. While the use of a shorter time lag may be too short for the formation of air temperature ramps, the use of a longer time lag such as 0.8 s may be too long and therefore possibly resulting in a different H_{SR} estimate. As a result, the 0.4-s time lag was used for all subsequent calculations for the SR and SRDT methods.

6.5.2 Surface renewal near real-time iterative procedure

For stable and unstable periods (20 July to 1 September 2012 inclusive) for the 0.475-m height and 0.4-s time lag, the near real-time 30-min H_{SR} calculated using the iterative procedure used within the datalogger compared well with an offline spreadsheet procedure used by Savage (2010) (slope = 1.0065, intercept = 0.04 W m⁻², $R^2 = 1.0000$, root mean square error (RMSE) = 0.19 W m⁻²) (Figure 6.3). For the near real-time procedure a was determined to within 0.005 °C with the method finding a solution for ramp amplitude a for 2031 out of a total of 2108 half-hourly events (more than 95 %) compared to 2019 using the spreadsheet method. Solutions not found were mostly for stable conditions and H_{SR} close to 0 W m⁻².

The use of a 0.4-s lag time, compared to 0.8 s, generally resulted in an increased air temperature ramp amplitude and an increased ramp period. This reduced H_{SR} on occasion (Figure 6.4).

6.5.3 Surface renewal-dissipation theory combination method

The SRDT method, based on SR in combination with dimensional analysis and dissipation theory, depends on a^2 and τ (Equations 6.20 and 6.21). For data for 20 to 28 July 2012, there was a consistent bias in H_{SRDT} vs H_{SR} (Figure 6.5) but small random error (RMSE = 3.1 W m⁻²). Bias using the SRDT method was confirmed using data for stable and unstable conditions for maize (4th March to 10th April 2011) (slope = 0.796, RMSE = 8.6 W m⁻² for a time lag of 0.2 s and slope = 0.800, RMSE = 6.9 W m⁻², for a time lag of 0.4 s (data not

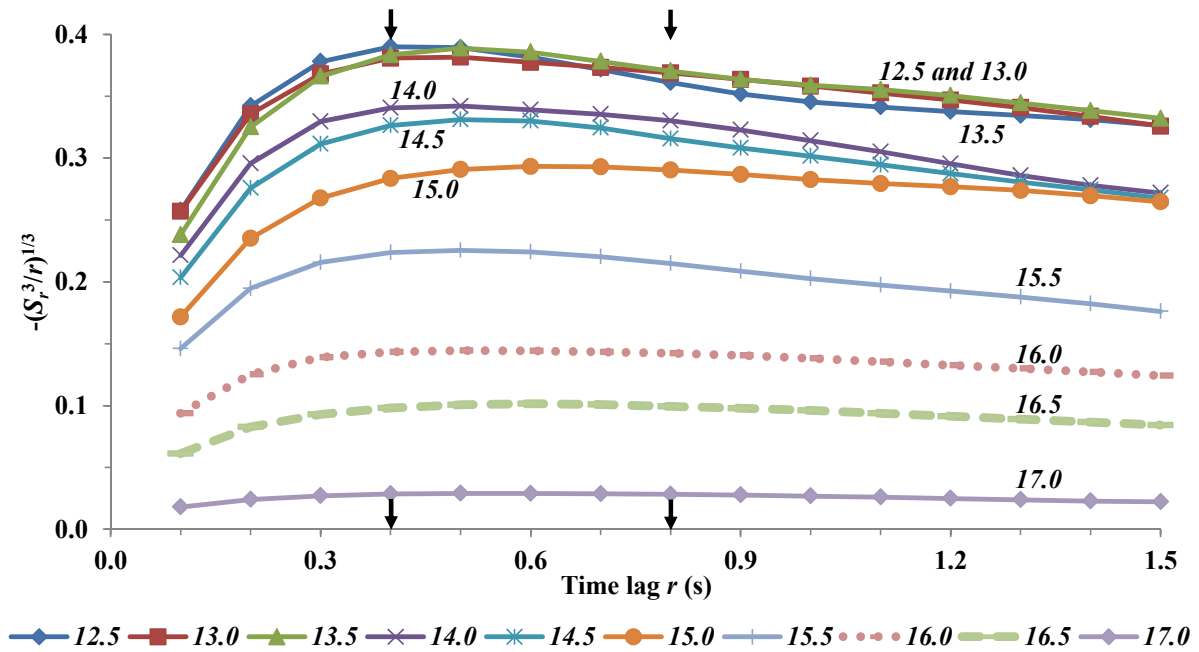


Figure 6.2 Measured half-hourly averages of $-(S_r^3/r)^{1/3}$ vs time lag r (s) at 0.275 m above the ground surface for measurements for 14th June 2012 from 12h30 (12.5) to 17h00 showing a maxima corresponding to $r = 0.4$ s for each time period.

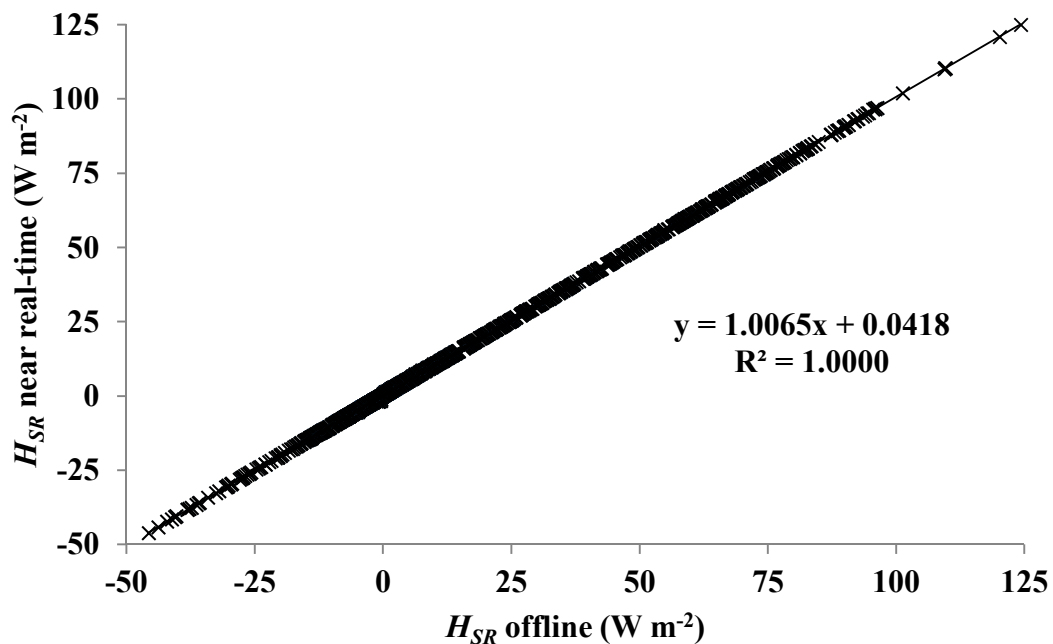


Figure 6.3 A comparison of the half-hourly SR sensible heat fluxes determined offline (x-axis) in a spreadsheet with the near real-time estimates (y-axis) for the period 20th July to 1st September 2012 for the 2.75-m height.

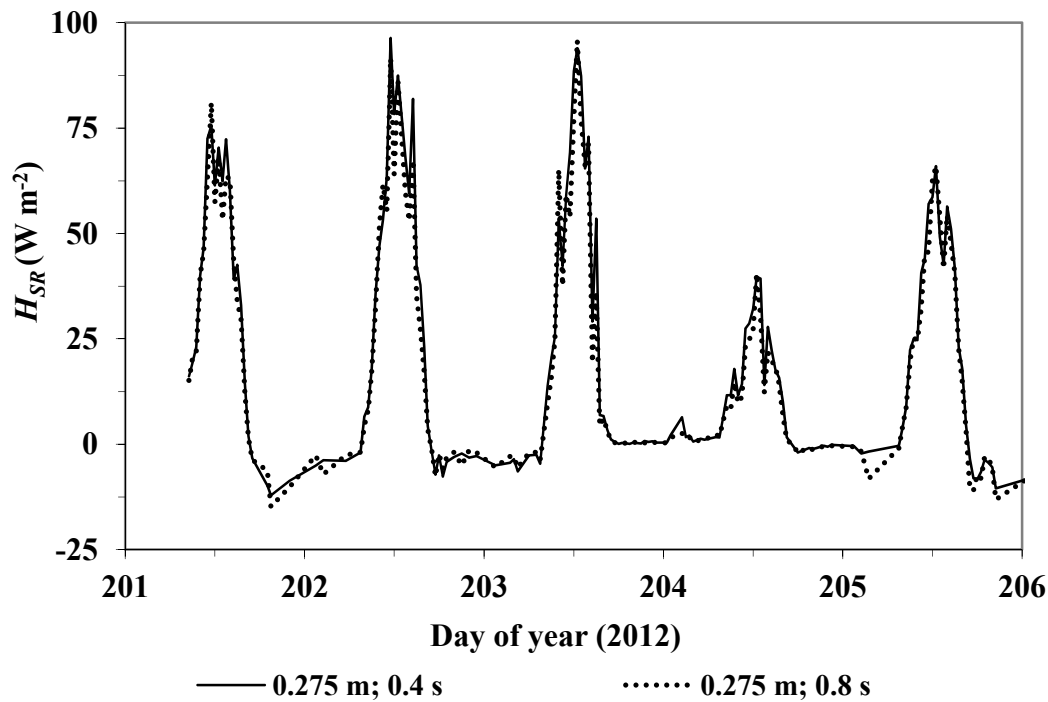


Figure 6.4 A temporal plot of the half-hourly SR sensible heat fluxes determined in near real-time for the 0.275-m height and lag times of 0.4 and 0.8 s for the period 20th to 24th July 2012 inclusive.

shown). The maize data showed a curvilinear relationship compared to only slight curvilinearity in Figure 6.5. Further research is needed to determine the reason(s) for the consistent bias in H_{SRDT} compared to H_{SR} .

6.5.4 Temperature variance with and without skewness

In the case of high frequency measurements of air temperature obtained with a defined output period, a moment value of 0 °C³ (Equation 6.8), or a skewness value of 0 (Equation 6.7), occurs when, within the averaging time interval the distribution of air temperature is symmetric with respect to the average temperature. As noted in books on statistics, positive skewness occurs when the mode for the averaging period is greater than the average and negative skewness occurs when the mode is less than the average. An examination of the data collected in this study showed that for unstable conditions, typical skewness values ranged between 0 and 1. Occasional negative skewness values occurred and in such cases, the skewness correction for stability was not applied. For $f(S_T)$ greater than 2.25 (Figure 6.1), corresponding to negative skewness values, sensible heat flux corrections for stability would be unrealistic.

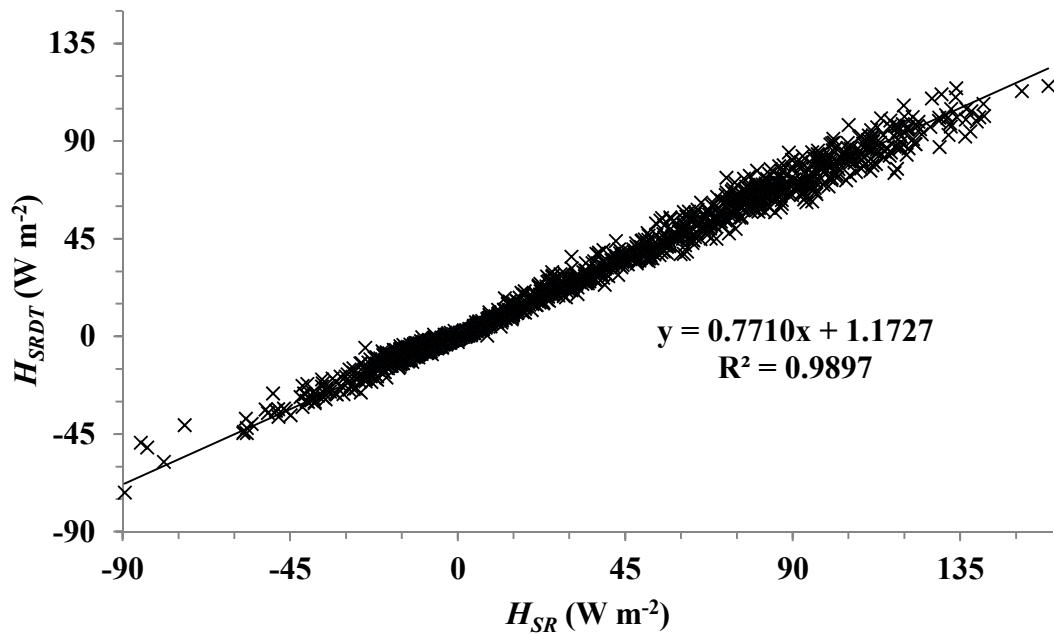


Figure 6.5 A comparison of the half-hourly sensible heat fluxes determined in near real-time using SR (x -axis) and SRDT methods (y -axis) for the 0.465-m height for the period 20th to 28th July 2012 for all stability conditions experienced.

Following stability correction of H_{TV} in near real-time, using skewness, the agreement between 30-min H_{SR} (with $\alpha = 1$) and H_{TVST} was good (20 to 28 July 2012, Figure 6.6) but with random error (slope = 1.0382, intercept = 1.09 W m⁻², $R^2 = 0.9007$ and RMSE = 13.57 W m⁻²). The greatest differences occurred at large H values and for H approaching 0 W m⁻². Without adjustment for stability using skewness, H_{TV} estimates were biased compared to H_{SR} (slope = 0.6120, intercept = 5.09 W m⁻², $R^2 = 0.8715$ and RMSE = 9.25 W m⁻²), data not shown for brevity.

6.5.5 Surface energy balance in near real-time

The net irradiance and soil heat flux, including the stored soil heat flux, for a week for which the first two days were overcast and the remaining five days were almost cloudless, are shown in Figure 6.7. For the five-day period, LE dominated, exceeding 400 W m⁻², with H_{SR} less than 200 W m⁻². In an inset graph, bottom right, energy balance components for the current day are shown. Two tables at the bottom right allow the user to download the half-hourly R_{net} , S data and sensible heat flux data.

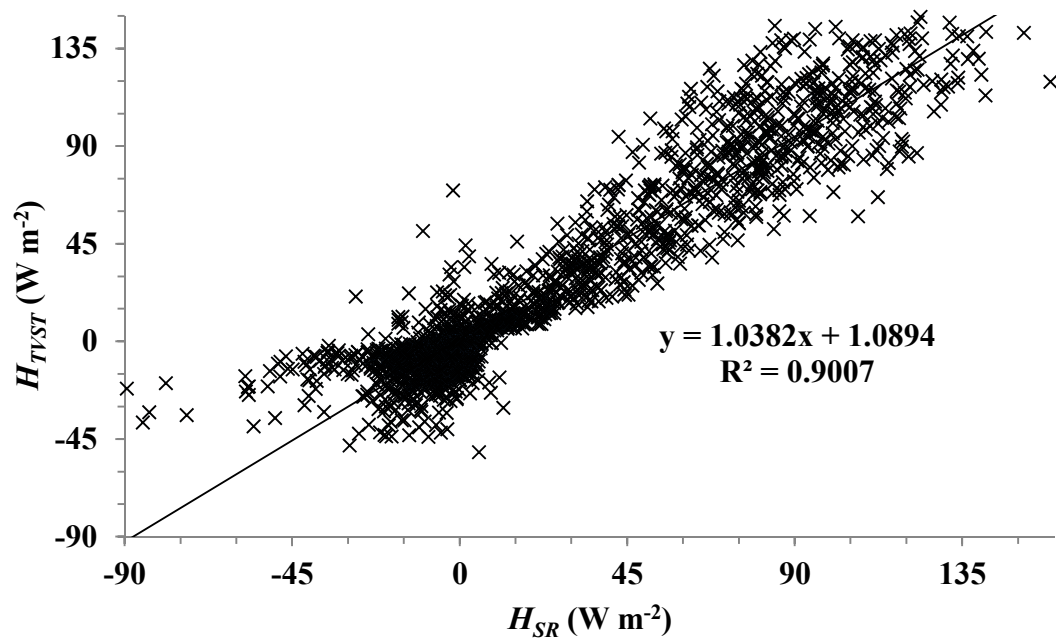


Figure 6.6 A comparison of the half-hourly sensible heat fluxes determined in near real-time using SR (x-axis) and TV method with skewness applied (y-axis), for the 0.465-m height for the period 20th to 28th July 2012 for all stability conditions experienced.

Near real-time surface energy balance for a short-grass surface

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Consider a system consisting of air, water, and soil with solar irradiance from the sun and infrared irradiance emitted by the earth's surface with some of it returned by clouds and greenhouse gases. For a given net irradiance R_{net} , it is assumed that some of this is used to evaporate water (LE), and some used to heat the air (H) and soil (S). The shortened surface energy balance is therefore defined by $R_{net} = LE + H + S$ where LE is the latent energy flux density (W/m^2), H the sensible heat flux density (W/m^2) and S the soil heat flux density. If R_{net} is measured using a net radiometer, S measured using sensors buried in the soil, and H is measured, then LE is assumed equal to $R_{net} - H - S$.

If all of the terms of the energy balance are independently measured, then a test of the equality of R_{net} with $LE + H + S$ can be performed. If there is equality, then the energy balance is said to be closed. Many methods of estimating LE, such as the Penman-Monteith method, Priestley-Taylor and other methods assume that the energy balance is closed and hence calculate LE as a residual: $LE = R_{net} - H - S$. This approach is adopted here. In the case of the eddy covariance method, LE and H can be measured separately, allowing closure to be checked. Usually for the eddy covariance method, the energy balance is not closed with $H + LE < R_{net} - S$. Some researchers have recommend closure by assuming that the Bowen ratio (H/LE) remains the same before and after adjustment for non-closure.



Temperature-based methods may be used for determining H - such as the surface renewal and temperature variance methods, the latter with and without adjustment for skewness. These methods allow near real-time estimation of the surface energy balance. These methods require high frequency measurement of air temperature. At Tower 2, two fine-wire thermocouples are used for these measurements. For the surface renewal method, lag times of 0.4 and 0.8 s are used and an iterative procedure applied in the logger program calculates the air temperature ramp amplitude and the quiescent and ramp period over 30 min. For the temperature variance method, the mean, variance and skewness of air temperature is calculated from the high frequency measurements and used to calculate H in near real-time.

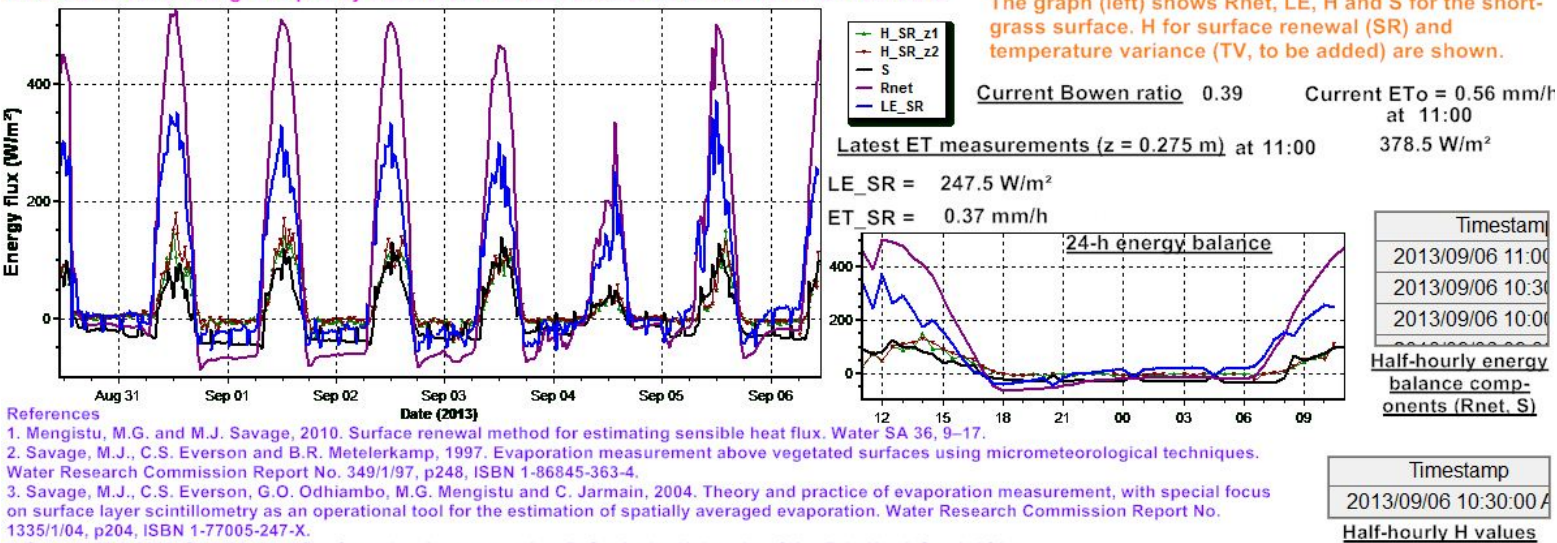


Figure 6.7 The near real-time energy balance screen for August 31st to September 6th 2013 inclusive, for which there are brief details of the SR, TV and SRDT methods, graphical display of the energy balance components and data tables containing downloadable data.

6.6 Conclusions

1. Near real-time display of surface energy balance component fluxes in graphical and table form was demonstrated. Sensible heat fluxes (H) were determined using surface renewal (SR), temperature variance (TV) with skewness stability-correction and surface renewal-dissipation theory (SRDT) methods with LE determined as a residual of the shortened energy balance.
2. In the case of the SR method for determining H , the air temperature ramp was determined by the datalogger using a near real-time iterative method. The method compared very well with the offline iterative procedure for estimating H_{SR} .
3. The SRDT method underestimated H compared to SR and TV (with skewness) methods. With adjustment for stability using skewness, the TV method showed good agreement with the SR method ($\alpha = 1$) with a slope of 1.0382 and root mean square error of 13.57 W m^{-2} .

6.7 Acknowledgements

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7 Conclusions and recommendations for future research

7.1 Introduction

In this study, selected agrometeorological applications involved leaf wetness duration, frost duration, nowcasting of the daily minimum temperature above short-grass and estimation of grass-surface energy balance components, including evaporation. These applications were used together with the Web-based data and information teaching, learning and research system that allowed near real-time reporting of data, graphics and information as well as alerts via email and SMS. The time scale of the reported and displayed data ranged from sub-hourly to monthly.

Undergraduate students studying agrometeorology initially find the subject matter difficult since many of the key concepts are new to them. Also, many of the students have a first language for which the words "meteorology" and "agrometeorology", for example, do not exist. Students often regard agrometeorology as a fearful subject – most agro-environmental students have never met the subject until possibly their second or third year of study. And even then, the subject matter remains a challenge – a mixture of theory and application, field and laboratory work, and a combination of meteorology, mathematics, physics and physiology applied to the biophysical agro-environment.

Many university students have a poor conception of the environment and of climate change, poor numeracy ability, and poor interpretation of graphical data and limited ability of statistically manipulating large data sets. Often, this is due to a lack of exposure to data representing the environment. Introductory agrometeorology and environmental biophysics therefore presents a significant challenge for students. In an attempt to offset the difficulties of many students, and to provide a data and information resource for students, staff and researchers, a Web-based system for selected near real-time agrometeorological applications was designed and implemented. Prior to the study, no similar system existed for the purposes described. The system was also implemented so as to raise the awareness, through display of near real-time data, of adverse weather using an open system.

The Web-based data and information system is described. Three questionnaires by users were evaluated with the system used in four selected agrometeorological and micrometeorological applications. The system, used by undergraduates, postgraduates and academic staff, was developed for near real-time agrometeorological and environmental applications. The system displayed data encompassing agricultural and environmental sciences in the form of tables and graphs and allows timely alerts, based on measurements, via emails. Data were obtained from field-based measurement systems including an automatic

weather station (AWS) system with additional radiation sensors (including diffuse irradiance), and an infrared thermometer (IRT). Short-grass and tall-crop reference evapotranspiration (ET_o), energy balance and radiation balance components were calculated and displayed, while open-air carbon dioxide and water vapour concentration measurements were also displayed. On two occasions, the details of adverse weather events were made available to the public through newspaper articles. This resulted in further details being provided to the evidence leader and investigator of a tragic incident in which eight job applicants died following adverse weather on two days with a high heat index for long periods.

7.2 Aims and objectives

The main aim of the research was the development, testing and evaluation of use of the Web-based teaching, learning and research early-warning system for selected agrometeorological and environmental applications, data visualization and visual literacy, so as to provide a near real-time agricultural, earth and environmental sciences data and information resource system mainly for use by undergraduate and postgraduate Agriculture, Human Sciences and Science students. Use of the system, by undergraduates, postgraduates and staff, was evaluated through a questionnaire. Specifically, the selected agrometeorological applications reported on included: 1. estimation of leaf wetness duration (LWD) above a short-grass surface; 2. estimation of frost duration (FD); 3. nowcasting of grass-surface, grass and air temperature minima based on sub-hourly pre-dawn measurements; 4. grass-surface energy balance using surface renewal, temperature variance and dissipation theory.

7.3 Selected agrometeorological applications

The implementation of a near real-time Web-based teaching, learning and research system is described. The system allows undergraduates (and post-graduates and academic staff) to view data, in table and graphical form, and extract data for downloading. Tutorial-type worksheets for students were developed, including spreadsheet-based exercises. The results of three questionnaires on system usage, friendliness and improvement were presented. Specifically, the system allowed lecture material to be directly accessed using near real-time and historical data relevant to the following disciplines: agricultural engineering, agricultural plant sciences (crop science, horticultural science, and plant pathology), agrometeorology, biological sciences (ecology), environmental science, geography, geology, hydrology, irrigation science, soil science and others. The field-based product, available online at the URL <http://agromet.ukzn.ac.za:5355>, encompassed the meteorological, agricultural and environmental sciences, and was linked via radio telecommunication to a laboratory computer connected to the Internet with data regularly uploaded in table and graphic form. Pre-

programmed alerts, based on near real-time measurements and calculations, were possible in various forms including emails, FTP (File Transfer Protocol) or indicator buttons displayed by the graphical uploads to the Internet.

The innovation of the work is the integration of the many and varied applications across many disciplines and accessibility of near real-time agricultural and environmental data and information in a laboratory, LAN laboratory, lecture room or using a cell phone or Bluetooth. The Web-based system described was shown to be versatile in terms of allowing connection of a wide range of sensors and was easily upgradeable in terms of additional dataloggers, sensors and environments.

The various graphic screens supported the concept of visual literacy by displaying the graphics and data tables of near real-time Web-based data. There was easy and open access to such data and information through a range of media, including Web-enabled cell phones for use in the laboratory or lecture room for a wide range of disciplines in the agricultural, earth and environmental sciences, as well as early-warning of a topical event such as Berg winds, flood, frost and human comfort. Previous experiences had shown that students learn more quickly and have increased interest when using real and very recent data relevant to their chosen discipline. The Web-based system has been used as a tool in teaching and learning. Students are made more aware of the current weather and other environmental conditions via the frequently updated current data. Also through tutorials and projects, they handled large datasets, plotted and interpreted data graphically – thereby enhancing visual literacy.

In a questionnaire for which there were 63 respondents out of a potential total of 95, representing a return percentage of 68.4 %, more than 80 % indicated that use of the system had improved their appreciation of the ranges of the various weather elements. More than 60 % of the respondents indicated that they benefited from use of the system, that they had improved their ability to manipulate data in a spreadsheet and/or display data in graphic or table form, improved their appreciation/awareness of global climate change and/or global warming aspects and improved their appreciation/awareness of the graphical display, and trends, of agro-environmental and environmental data. The questionnaire also highlighted some of the weaknesses of the software used for displaying the graphics, in particular text enhancements, resolution and system interactivity. These weaknesses were overcome by a software upgrade in August 2013.

The system has also shown to be a very useful resource for projects for honours students. In 2012, two honours students completed their dissertations, having made intense use of the system. The one project enabled the use of the Web-based system for microclimatic measurement and control of an evaporative cooling system in a forestry nursery. The second project enabled estimation of sunshine duration from solar irradiance measurements for

implementation into the Web-based environmental monitoring system. A third honours project, completed in 2013, involved the implementation of the system as an early-warning system for fire through near real-time display of the lowveld fire danger index. Adverse Pietermaritzburg weather conditions in late December 2012, for which the heat index reached a high of 33.7 °C at Mast 1, resulted in the death of eight job-seekers. This example of the use of the system for reporting adverse weather demonstrated that the open near real-time weather data can provide timely and crucial information to planners of activities involving strenuous activity.

An early agrometeorological application of the Web-based system included LWD measurement using dielectric leaf wetness sensors (LWS). In the study, the measurement of LWD was investigated using dielectric, infrared grass-surface temperature, dewpoint temperature, grass temperature and RH measurements with near real-time data and information and alerts made available timeously via the Web-based system. Also, the Web-based teaching and learning data and information system was used as part of an undergraduate student practical focused on LWS and LWD. In a published study, leaf wetness duration measurements using collocated LWS units were shown to be consistent. The relative humidity (RH) and extended RH methods for estimating LWD yielded the largest LWD estimate for the five methods used. The IRT- and grass-temperature methods for estimating LWD involved comparing these temperatures with the dewpoint at 0.1- or 2-m heights. These two methods showed reasonable agreement with the latter underestimating compared to the LWS estimates. The IRT-temperature method showed reasonable agreement of daily LWD with the grass-temperature method. There was poor agreement between the IRT-temperature LWD estimates and the LWS estimates even if rain days were excluded, underestimating for $LWD < 5.5$ h, although there were days for which LWS units registered no LWD with the IRT surface-temperature method indicating surface wetness and *vice versa*. Theoretically, the IRT surface-temperature method should yield the correct estimate of LWD and has the advantage of a greater surface-area representation, but the method is more expensive and requires RH data for a sensor adjacent to the surface. To increase the value of AWS measurements, AWS systems should also include grass temperature using a freely exposed thermometer that could possibly be used to estimate LWD if RH measurements are also available. Furthermore, timeous email and SMS alerts with near real-time data and graphics of LWD for the current day, week and month displayed on the Internet, as used in this investigation, would considerably enhance the data product. The inclusion of a screen on leaf wetness provided significant benefit to the Web-based system, was relevant to the agricultural plant sciences and biological sciences students and intermeshed the role of the environment in biological systems.

In another published study, dielectric leaf wetness sensor measurement of FD was found to be problematic. Dry-to-wet and wet-to-dry transitional condensing events without freezing followed by drying typically corresponding to LWS voltage increases from around 260 mV (dry) to in excess of 320 mV (wetness), and *vice versa*, had to be identified and excluded. These transitional events were identified using sub-hourly measurements by excluding LWS voltage rates of change that were greater than or equal to 10 mV h^{-1} for 4 min but at the same time including events for which the LWS voltage was between the 274 and 284 mV lower and upper limits respectively. The FD estimated using dielectric LWS units at 100 mm tended to underestimate FD compared to that estimated using the IRT grass-surface and grass (25 to 50 mm above the surface) temperature methods, presumably because of the fact that the LWS sensors were at a greater distance (100 mm) from the surface compared to IRT sensors that measure surface temperature. The air temperature measurements at 1 m, or higher, were rarely less than 0°C and should not be used to define grass-surface frost events without adjustment for the 1-m or higher air temperature gradient for the measurement height difference. None of the methods used could detect black frost events, which did not occur for the high nocturnal relative humidity experienced at the study site. The grass- and IRT-temperature methods would indicate less than 0°C for black frosts with the LWS method yielding no indication of black frost unless further temperature decreases caused sublimation. Air temperature gradients between the surface and 2 m for cloudless nocturnal frosted and windless conditions were about $2.25^\circ\text{C m}^{-1}$, typically resulting in the 2-m air temperature measurements more than 4°C greater than at the grass surface. The Web-based system used allowed for timeous email and SMS alerts of frost with near real-time data and graphics of FD displayed for the current day, week and month for the various methods. To increase the value of AWS measurements, it is recommended that AWS systems should also include grass temperature that could be used to estimate FD. The Web-based system performed well in assisting undergraduate students in understanding the causes and characteristics of frost as well as the importance of the downward infrared irradiance in influencing the daily minimum grass-surface temperature. Through project work, as an application of a radiative frost, the students revised the coefficients of Brunt's equation for estimation of the downward infrared irradiance and were able to assess, in near real-time, the suitability of the revised coefficients.

Technological advances over the past several decades now allow AWS systems to perform hourly, even sub-hourly, temperature measurements including grass-surface, grass and air temperatures. The investigation on nowcasting the daily minimum air temperature, similar in many ways to the concept of complex event processing, used for the observation and management of business processes, used a Web-based nowcasting system based on sub-hourly temperature measurements. For this purpose, four temperature models were tested, using 12-months of historic data from four locations varying in altitude, for their ability to nowcast 2- or 4-h ahead of sunrise the minimum temperature – Cedara, Cathedral Peak and

Pietermaritzburg, KwaZulu-Natal, South Africa and Marianna, Florida, USA. The models used employed either the exponential or square root function to describe the rate of nighttime temperature decrease. The models were also applied in real-time using a Web-based system. Exponential and square root models for nowcasting the daily minimum air temperature for grass-surface, grass and air temperature 2 and 4 h ahead of sunrise were successfully applied using sub-hourly temperature measurements from four locations with very different altitudes. Using the historical data, for both the 2- and the 4-h-ahead nowcasts, model 1 (exponential) usually yielded the lowest RMSE – less than 1.0 °C for the former and 1.3 °C for the latter. For the 4-h nowcasts, the intercept of the comparison of the nowcasted temperature (T_{pn}) with the measured temperature (T_n) was much larger, sometimes as large as 1.4 °C compared to 0.5 °C for the 2-h nowcasts. Except for Marianna (Florida, USA), all T_{pn} vs T_n comparisons yielded slope values not statistically different from unity. Model 3 (square root) 2-h-ahead nowcasts usually had an increased RMSE for the T_{pn} vs T_n comparison and greater for the 4-h-ahead nowcasts. The T_{pn} vs T_n comparisons for grass-surface and grass minimum temperatures were more variable with a significant increase in RMSE. For the nowcasts, in general, model 1, for which the rate of reduction in nighttime temperatures were determined by covariance and variance instructions in the datalogger, yielded the best statistical comparisons for which RMSE values were less than 1 °C.

Measurement of surface energy balance components is fundamental to Agrometeorology. Increasingly, near real-time evaporation and surface energy fluxes are required, for example, for comparison with satellite flux model estimates or for use when remotely-sensed model estimates are compromised either by the lack of data or by the occurrence of cloud particularly for summer-rainfall areas. Prior to the current study, no reports of near real-time surface energy balance studies were found. Net irradiance and soil heat flux components of the shortened surface energy balance for short grass were measured with the sensible heat flux (H) determined in near real-time using surface renewal (SR) and temperature variance (TV) methods and using a surface renewal-dissipation theory (SRDT) method. Measurements of air temperature from an unshielded fine-wire thermocouple placed at heights of 0.275 and 0.465 m above the soil surface were obtained at a frequency 10 Hz. From these measurements, the following air temperature statistics were determined every 30 min: mean, variance, skewness, and air temperature structure functions of order 2, 3 and 5 for lag times of 0.4 and 0.8 s. For cloudless conditions, the 0.4-s lag corresponded to the maximum of the negative of the structure function of order three divided by the time lag and this lag was therefore used for the calculation of H using the SR and SRDT methods. The SR method requires calculation of the air temperature ramp amplitude and the sum of quiescent and ramping periods for a 30-min period. Prior to this work, there was no simple methodology nor no near real-time methodology proposed for the solution of the real roots of the van Atta (1977) cubic equation. For the air temperature ramp amplitude, the roots of a

cubic polynomial were obtained in real-time using a datalogger program employing an iterative procedure for which the ramp amplitude was determined to within 0.005 °C from which H was determined using a SR weighting factor of 1. For the TV method, the direction of H was determined from the sign of the third-order air temperature structure function and the magnitude of H determined from the mean, variance and skewness of air temperature with adjustments for skewness applied for positive skewness and unstable events. The near real-time Web-based display of surface energy balance component fluxes in graphical and table form was demonstrated. Sensible heat fluxes were determined using SR, TV with skewness stability-correction and SRDT methods with LE determined as a residual of the shortened energy balance. In the case of the SR method for determining H , the air temperature ramp was determined by the datalogger using a near real-time iterative method. The method compared very well with the offline iterative procedure for estimating H_{SR} . The SRDT method underestimated H compared to SR and TV (with skewness) methods. With adjustment for stability using skewness, the TV method showed good agreement with the SR method ($\alpha = 1$).

7.4 Challenges

The greatest challenge in the use of the Web-based system, besides the learning curve associated with datalogger-to-datalogger connection, the time spent becoming familiar with the reporting software (RTMC Pro) and the challenges presented by the many and varied agrometeorological applications, was the lack of support in maintaining the grassed area and surrounds used in this study and the challenges in the timely procurement of equipment and replacement batteries. Since implementation, the WebServer software was intentionally stopped due to inadequate site maintenance and power problems due to a combination of poor-condition batteries needing replacement and cloudy weather for a few days together with low temperatures in April 2013. The support service was in general not satisfactory. In the future, a more stable system of support needs to be pursued. The third challenge relates to the frequent WebServer disconnects during the study. Initially, these were not that frequent but subsequently, they were much more frequent. The disconnects necessitated a manual reset of the WebServer software, even over weekends. This problem was overcome somewhat through the use of desktop sharing software (www.teamviewer.com) that was used to reset the WebServer software using a remote computer.

7.5 Future teaching, learning and research possibilities

There are many future research areas involving this system that need attention. Two areas that have already been developed and researched to an advanced stage but not fully reported on here, and part of three honours dissertations, include the estimation of sunshine duration,

Web-based microclimatic measurement and control of an evaporative cooling system in a forestry nursery, the micrometeorology study of a wet-walled and misted polycarbonate greenhouse and a Web-based fire alert system. Other applications, for which there was little reporting in the dissertation, included a screen for chill units and the nowcasting of Berg winds and fire hazard.

Further research is needed in order to apply the various fire indices in near real-time and develop an early-warning system for application over a large area for grassland and forestry areas. The research already conducted on a near real-time lowveld fire danger index, as well as the work not reported on the nowcasting of Berg winds, could serve as a useful basis.

Another area of future research is the application of the system to high and junior schools. It is envisaged that a screen describing and displaying the weather elements be designed and used by school learners. In this regard, the role of visual literacy in teaching and learning needs further research.

The research on the nowcasting of the minimum grass-surface, grass and air temperature minima based on sub-hourly pre-dawn measurements needs to be extended to other surfaces such as agronomic and horticultural crops. Similarly, the research on the near real-time energy balance using surface renewal could also be extended to other vegetation types.

While the system has not been used to display data from other locations, this can be achieved by using a private network and a PC-connected and datalogger-connected GSM modem. To reduce the cost of bandwidth, the frequency of scheduled data downloads would have to be reduced.

The current system has many screens and it has become necessary to consider splitting the system, thereby necessitating the use of a second open http port. Two versions of the same software running on the same server would allow two distinct but hot-spot linked data and information displays. The one system could be devoted to teaching and learning and the other to research.

Explored to some extent in this current study, and pertinent to South African students and based on personal experience, is that use of graphics and data in teaching and learning may transcend language differences between students and between student and staff, more than does written text and other resources. In the present study it was assumed that graphical and table displays of data reduced the role of language and assisted in the cognitive retention of information. In a second questionnaire, more than 75 % of respondents indicated that the graphical display of data had enabled further understanding of the agro-environmental

concepts irrespective of language. The role of language, visual literacy and use of the system deserves further attention in the future as trans-disciplinary research projects.

Future research could also explore desktop sharing and online collaboration by students for their projects and the role of the system as a near real-time system for arriving at visual comparison of research data. Regression and/or temporal graphs, based on fuzzy logic expressions, updated regularly and shared online by different groups could allow for the automatic update of data that allows research decisions for the future to be taken. Through the use of additional software, individual members of the research group could be allowed to tweak the underlining code used, allowing a form of fuzzy-logic to be used to replot the near real-time plots. The members therefore do not need access to the actual measurement data but rather develop the thinking behind what to do with the measurements – which could be in time and space.

7.6 Final comments and summary conclusions

The Web-based system has proved to be a useful resource for agrometeorological teaching, learning and research and a vehicle for reporting many biophysical agro-environmental concepts and measurements. From an agrometeorological point of view, the system has been used to illustrate to undergraduates important concepts such as the radiation balance, the energy balance, ETo, human comfort, Stefan-Boltzmann law, Brunt's law, and to postgraduates complex concepts such as leaf wetness and frost duration estimation, minimum temperature nowcasting, and surface renewal and temperature variance for estimating sensible heat flux. The system was a particularly useful aid for research, illustrating measurement comparisons or measurement methods in near real-time. This allowed for easy decision making of research results since different researchers could visualise the results online. Online sharing of automatically-processed data and information was a very useful feature of the system.

The system was evaluated through the use of three questionnaires, completed mostly by undergraduate students. The evaluations demonstrated that more than 60 % (82 % for the second questionnaire) of the respondents indicated that they benefited from use of the system, and that their appreciation of the ranges of the various weather elements had improved. They also indicated that system use had improved their ability to manipulate data in a spreadsheet and/or display data in graphic or table form, improved their appreciation/awareness of global climate change and/or global warming aspects. System use improved their appreciation/awareness of the graphical display, and trends, of agro-environmental and environmental data. A high percentage of 80 % (89 % for the second questionnaire) of respondents indicated that use of the system had improved their appreciation of the ranges of the various weather

elements. More than 75 % of the respondents indicated that the graphical display of data had enabled further understanding of the agro-environmental concepts irrespective of language compared to 6 % of the respondents indicating that it had not. Most of the respondents were first-language IsiZulu speakers and 72 % indicated "yes" that graphical displays of data enabled further understanding, compared to 80 % for first-language English speakers. About 78 % of the respondents of the third questionnaire indicated that they were comfortable with English, in their Agrometeorology modules, as the language of instruction. This high response could be due to the fact that many of the technical terms in English used for the agro-environmental sciences do not have a corresponding term in isiZulu. For the future, there is therefore an urgent need to create a list of isiZulu technical terms specific to Agrometeorology and allied disciplines – and therefore to assess the impact of the use of the list on learning and adoption by the learners. The list could be created, and continually updated, by past and current Agrometeorology students.

The system needs to be expanded on the one hand and simplified on the other through the use of a second open http port. Two versions of the same software running on the same server would allow two distinct but hot-spot linked data and information displays, one devoted mainly to undergraduate teaching and learning and the other for research.

The Web-based system has proved to be a useful and contemporary resource for teaching and learning and has the potential to become a very useful research tool. Initially, the Web-based system consisted of a single AWS mast and few sensors but has been expanded to eight stations over a period of less than two years with more than 300 students exposed to the system for teaching, learning and research. The system enabled further understanding by students of biophysical agro-environmental concepts irrespective of language through the emphasis of visual literacy. The system is now used regularly by undergraduates and postgraduates with the potential for use in junior and high schools. The system has also provided an avenue for research in a number of areas not previously pursued: frost duration, leaf wetness duration, nowcasting of temperature and near real-time surface energy balance.

Supplementary materials

Web-based teaching, learning and research using real-time data from field-based agrometeorological measurement systems

by

MICHAEL J. SAVAGE

1. Press release: The Mercury, Final Edition, Tertiary Times, p9, 27th September 2011. UKZN web-based system a first for South Africa.SM4
2. Abstract: Savage MJ*, Abraha, MG, Moyo NC and Babikir, ESN. 2012. Web-based teaching and learning early-warning system for real-time data and information for the agricultural, earth and environmental sciences. Sixth Annual University Teaching & Learning Conference, UKZN, Durban, South Africa, 25 to 27th September 2012. Presented by MJ Savage.SM5
- * Corresponding author
3. Abstract: Savage MJ. 2012. Web-based near real-time surface energy balance for short grass using surface renewal, temperature variance and dissipation theory. Poster presentation to ASA, CSSA and SSSA Annual Meetings (Cincinnati, Ohio, USA, 21 to 24th October, 2012).SM7
4. Published paper: Savage MJ. 2012. Estimation of frost occurrence and duration of frost for a short-grass surface. S. Afr. J. Plant Soil 29: 173–181.SM8
5. Published paper: Savage MJ, 2012. Estimation of leaf wetness duration for a short-grass surface. S. Afr. J. Plant Soil 29: 183–189.SM18
6. Abstract: Grant BR and MJ Savage*. 2013. Estimation of sunshine duration from solar irradiance measurements for implementation into a web-based environmental monitoring system. Paper presentation to the Combined Congress 2013, South African Society for

Supplementary materials:

Web-based system for selected near real-time agrometeorological applications SM2

Horticultural Sciences, Weed Science Society, Crop Production Society and Soil Science Society of South Africa, 21st to 24th Jan, 2013, Durban, South Africa. Paper presented by MJ Savage.SM26

* Corresponding author

7. Abstract: Kaptein ND and MJ Savage*. 2013. A web-based microclimatic measurement and evaporative cooling control system in a forestry nursery. Paper presentation to the Combined Congress 2013, South African Society for Horticultural Sciences, Weed Science Society, Crop Production Society and Soil Science Society of South Africa, 21st to 24th Jan, 2013, Durban, South Africa. Paper presented by ND Kaptein.SM28

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8. Abstract: Savage MJ, 2013. Web-based near real-time surface energy balance system above short grass. Poster presentation to the Combined Congress 2013, South African Society for Horticultural Sciences, Weed Science Society, Crop Production Society and Soil Science Society of South Africa, 21st to 24th Jan, 2013, Durban, South Africa.SM30

9. Abstract: Savage, MJ*, Abraha MG, Moyo NC and Babikir ESN. 2013. Web-based system for near real-time agrometeorological applications. Paper presentation to the Combined Congress 2013, South African Society for Horticultural Sciences, Weed Science Society, Crop Production Society and Soil Science Society of South Africa, 21st to 24th Jan, 2013, Durban, South Africa. Paper presented by MJ Savage.SM32

* Corresponding author

10. Abstract: Savage MJ. 2013. Air temperature measurement errors. Paper presentation to the South African Society of Atmospheric Sciences, 26th to 27th Sept, 2013, Durban, South Africa. Paper presented by MJ Savage.SM34

11. Abstract: Strydom S and Savage MJ*. 2013. A near real-time fire danger index measurement system. Paper presentation to the South African Society of Atmospheric Sciences, 26th to 27th Sept, 2013, Durban, South Africa. Paper presented by S Strydom.SM38

* Corresponding author

12. Press release: South Africa Press Association (SAPA), 7th August 2013. Weather warning before KZN fitness test. Published in IOL News. <http://www.iol.co.za/news/south-africa/kwazulu-natal/weather-warning-before-kzn-fitness-test-1.1559209> Accessed 8th August 2013.SM42

Supplementary materials:

Web-based system for selected near real-time agrometeorological applications SM3

This press release was published in various local and national newspapers on the 7th and 8th August 2013.

13. Press release: South Africa Press Association (SAPA), 8th August 2013. Weather warning before KZN fitness test. Published in IOL News. <http://www.iol.co.za/news/south-africa/kwazulu-natal/about-200-treated-at-rti-fitness-test-1.1559932> Accessed 9th August 2013.SM43

This press release was published in various local and national newspapers on the 8th and 9th August 2013.

14. Published paper: Savage MJ*, Abraha MG, Moyo NC and Babikir ESN. 2014. Web-based teaching, learning and research using accessible real-time data obtained from field based agrometeorological measurement systems. S. Afr. J. Plant Soil 31. In press.SM44

* Corresponding author



THE MERCURY

TERTIARY Ψ π TIMESMERCURY (Final Edition)
27 Sep 2011, p.9

UKZN web-based system a first for South Africa

VICKY CROOKES

WITH climate change upon us it is imperative, now more than ever, for students to understand the environment so they can relate to the problems of our uncertain agricultural and environmental future. UKZN Agrometeorologist on the Pietermaritzburg Campus, Professor Michael Savage, has taken this to heart: and he has developed South Africa's first web-based teaching and learning early-warning system for real-time agricultural, earth and environmental sciences data and information.

Having lectured at the university for 35 years, Savage is cognisant that many students leave with a degree which has not equipped them with a first-hand understanding of the environment. "Often, this is due to the lack of exposure to the important concepts making up their environment. Students also lack a basic understanding of concepts such as temperature, temperature scales, and the graphical display of information," said Savage.

This problem is particularly noticeable at second-year level when students have to start collecting data for practicals and projects. Savage maintains they lack the understanding of how to interpret the data they have collected or the data that has been made available to them.

Hailed as a dynamic approach to teaching and research, this web system is centred on a field-based



UKZN's Agrometeorological team with their automatic weather station. From left: Dr Michael Abrahams, Jothi Manickum, Nicolas Moyo, Professor Michael Savage, and Dr Eltayeb Nile Babikir.

weather station located on the Pietermaritzburg Campus. However, it is much more than your traditional weather station. It includes a wide range of instrumentation not normally found at automatic weather stations such as soil-water content and soil-electrical conductivity and soil-salinity sensors; infrared sensors for remote sensing; sensors for measuring leaf wetness, systems to compute grass reference evaporation, and a profile of air temperature sensors. The system can also accommodate calculations related to heat index, wind chill, day length, sunrise and sunset times.

An important feature of the project enables students to see a real-time display of the information as well as a display of the historical weather data. Undergraduate and postgraduate students are able to access this information via a LAN connection or through Bluetooth. They can extract data which they can manipulate, thereby reinforcing their computer literacy,

numeracy, statistical and graphical capabilities.

In addition the system has been designed so that it can alert groups of students, via e-mail, when a significant environmental event occurs, e.g. when the soil-water content is very high, resulting in considerable surface run-off. A television monitor, located in a corridor in the Rabie Saunders Building, offers agriculture students a display of all the information and measurements, which is updated every five minutes.

One of the most powerful aspects of Savage's innovation is its applicability to a vast range of disciplines including agricultural plant sciences, agricultural engineering, agrometeorology, environmental science, geography, geology, hydrology and soil science. It could even be extended to other important areas such as atmospheric chemistry and water chemistry.

In addition to the system being a valuable data-resource tool for many disciplines, it can

also be used as an early-warning system. For example, 15 percent of the world's food supply is reduced due to disease. This is encouraged by high relative humidity and continual condensation. Since leaf-wetness sensors are part of the system, one would be able to determine the duration of the wetness of a leaf from one day to the next which could be used as an indicator of plant disease.

In the same way, floods or flooding conditions could be predicted based on the rainfall conditions, the saturation soil-water content and the soil physical parameters. It may also be possible to predict frost two or three hours before it occurs, triggering an alarm in the system which informs a user, via e-mail, before frost conditions occur.

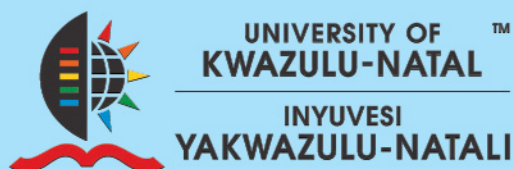
At this stage there are no immediate plans to implement a similar system for the Durban area, although there is significant scope for its use. The College of Health Sciences, for example, could use this type of

resource to monitor the impact of atmospheric pollution on human health or the impact of weather on sport science. Savage is currently assisting a Masters student who is using micrometeorological data to calculate heat indices and is investigating their role in soccer training. Another untested area is alternative energy sources: solar, wind and wave energy capture.

The resource is being funded by the UKZN Teaching and Learning Office through a 2011 Teaching Innovation and Quality Enhancement grant. Although there has been limited exploration of the use of the system outside UKZN, this is a natural progression for the project. Real-time data that encompasses such a vast array of measurements would be invaluable to businesses, municipal planners, agriculturalists, and the public. It could also play a significant role in high school education.

"We believe that the resource, if used with teacher guidance, may be an exciting and valuable resource for scholars in geography, mathematics, physics, computer science, geography, biology and chemistry," said Savage.

Although Savage knows of no similar system at any other South African university, the various parts of the system are commercially available. "The innovation is the integration of the various applications across many disciplines and real-time application in a laboratory, LAN laboratory or lecture room," he said.



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INSPIRING GREATNESS

#135. Web-Based Teaching and Learning Early-Warning System for Real-Time Data and Information for the Agricultural, Earth and Environmental Sciences

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Many university students have a poor conception of the environment and of climate change, poor numeracy ability, poor interpretation of graphical data and limited application of statistically manipulating large datasets. Often, this is due to a lack of exposure to data representing the environment. Students, for example, lack a basic understanding of concepts such as temperature, temperature scales, and graphical display of information. Often, students find it difficult to "read" graphs and lack the ability to display data graphically. Our experience is that many students also do not appreciate the difference between temporal and regression graphs. Such deficiencies are particularly noticeable in second-year when students collect or use data for tutorials, practicals and projects and then cannot interpret collected data or data made available. The web-based project described here uses near real-time field-based measurement systems, including an automatic weather station and radiation and temperature station, to collect and display frequently-updated current and previous data in graphs/tables, using the Internet. An important feature of the project is that it enables real-time display in the lecture room or laboratory via Bluetooth. The real-time web-based early-warning teaching and learning system encompasses the agricultural, earth and environmental sciences. It is a valuable data resource tool for many disciplines. The main objectives are to present the details of the system that is currently used by undergraduate and postgraduate students, as well as staff, to access a real-time agricultural and environmental measurement system using the Internet for tutorials, practicals, projects and lectures. The system displays graphics of real-time and historic weather data but not exclusively so. Data can be extracted and manipulated, thereby reinforcing computer literacy, numeracy – including statistical ability – and graphical capabilities. The objective is to ensure that these abilities are improved while at the same time obtaining a deeper understanding of the environment.

Keywords: environmental data, internet display



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76699 Web-Based near Real-Time Surface Energy Balance for Short Grass Using Surface Renewal, Temperature Variance and Dissipation Theory.

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Increasingly, near real-time evaporation and surface energy fluxes are required, for example, for comparison with satellite flux estimates or for use when remotely-sensed estimates are compromised by the occurrence of cloud, particularly for summer-rainfall areas. Net irradiance and soil heat flux components of the shortened surface energy balance for short grass were measured with the sensible heat flux (H) determined in near real-time using surface renewal (SR) and temperature variance (TV) methods and using a surface renewal-dissipation theory (SRDT) method. Measurements of air temperature from an unshielded fine-wire thermocouple placed at a height of 0.46 m above the soil surface were obtained at 10 Hz. From these measurements, the following air temperature statistics were determined every 30 min: mean, variance, skewness, and air temperature structure functions of order 2, 3 and 5 for lag times of 0.4 and 0.8 s. For cloudless conditions, the 0.4-s lag corresponded to the maximum of the negative of the structure function of order 3 divided by the time lag and was therefore used for the calculation of H using the SR and SRDT methods. The SR method requires calculation of the air temperature ramp amplitude and the quiescent and ramping periods for a 30-min period. For the air temperature ramp amplitude, the roots of a cubic polynomial were obtained in real-time using a datalogger program employing an iterative procedure for which the ramp amplitude was determined to within 0.005°C from which H was determined using a SR weighting factor of 1. For the TV method, the direction of H was determined from the sign of the third-order air temperature structure function and the magnitude of H determined from the mean, variance and skewness of air temperature with adjustments for skewness applied for positive skewness and unstable events. The SRDT method, which uses the square of the SR ramp amplitude, the ramp period and the variance of air temperature, tended to underestimate H compared to SR and TV methods (for the SRDT vs SR method: slope = 0.771, coefficient of determination (R^2) = 0.990, root mean square error (RMSE) = 3.1 W m^{-2}) using data from 1 June to 28 July 2012. With adjustment for skewness, the TV method showed good agreement with the SR method (slope = 1.035, R^2 = 0.905, RMSE = 13.2 W m^{-2}). A shortened surface energy balance was used to determine the latent energy from measured net irradiance from two- and four-component net radiometers, the measured soil heat flux and H , the latter using SR, TV and SRDT methods. The fluxes, updated half-hourly, are displayed on a web-based system: (<http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Energy%20balance>). Current daily, weekly and monthly totals are reported as well as a temporal plot of the energy balance components for a five-day period. Half-hourly energy balance components are tabulated.

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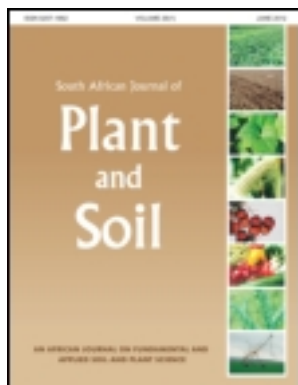
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Estimation of frost occurrence and duration of frost for a short-grass surface

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Estimation of frost occurrence and duration of frost for a short-grass surface

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The estimation of frost duration (FD) was investigated using dielectric, infrared surface temperature and grass temperature subhourly measurements. Near real-time FD data and information displays and alerts were also made available via a web-based system. FD was estimated using a dielectric leaf wetness sensor (LWS) method, for which the sensor voltage was between 274 and 284 mV with a voltage rate of change less than 10 mV h⁻¹ for a 4 min period, and two temperature methods for which infrared thermometer (IRT) and grass temperatures were compared with 0 °C. FD estimation using the LWS method ensured that most of the transitional dry-to-wet and wet-to-dry events were not included in the FD count. Generally, the IRT method yielded the largest estimate of FD, grass temperature method lower and LWS method lowest. Micrometeorological measurements showed consistent air temperature gradients of 2.25 °C m⁻¹ for cloudless nocturnal frosted conditions with few air temperature measurements at 1 m and none above indicating frost occurrence. At the very least, automatic weather station systems should contain a grass thermometer or preferably an IRT for determination of FD with near real-time data and graphics displayed, including timeous alerts of frost occurrence and FD, using the Internet.

Keywords: dielectric constant, grass-surface temperature, ice

Introduction

“Frost damage is the leading weather hazard, on a planetary scale, as far as agricultural and forest economic losses are concerned” (Garcia et al. 2010). Past and future estimates of frost occurrence are useful in crop production agroecological zoning systems for which data and models may be used to construct crop production suitability maps (Garcia et al. 2010). In spite of the importance of frost as a weather hazard, near real-time reporting of conditions relevant to its occurrence is rare.

Definitions of frost in the published literature vary. Some say frost is the occurrence of a temperature at or less than 0 °C, measured in a Stevenson screen or equivalent, at a height of between 1.25 and 2 m (Hogg 1950, Lawrence 1952, Hogg 1971, Snyder and de Melo-Abreu 2005). For the present study, however, the following definition is used: frost is the condition for which the surface and earthbound objects have a temperature at or below 0 °C, often resulting in ice on leaves and soil if the temperature of the surface, or air near the surface, is less than or equal to the dewpoint temperature. This definition recognises that frost is a surface phenomenon with surface conditions, or those just above, having greater relevance than conditions 1–2 m above. This definition also recognises the fact that for frost occurrence either the latent energy phase change of water vapour to ice (sublimation) or the freezing of dew or vegetation may occur.

Two types of frost are freeze (advection) frosts and radiative frosts. In South Africa, radiative frosts are more common, although freeze frosts may occur and then later spurn radiative frosts. There are two types of radiative

frosts: hoar and black frost. A white frost is a relatively heavy coating of a hoar frost. In black frosts, there is no surface ice due to very low and negative dewpoints. The very cold conditions result in cell sap freezing and cells rupturing with vegetation appearing black. Surface ice, however, could occur after black frost occurrence if there is further cooling with air temperature approaching the dewpoint. Hoar frosts occur when atmospheric conditions above the surface are cool, calm, clear and dry with an air temperature inversion for many tens of metres above the surface, although these conditions often also apply to black frosts. The slightest breeze can destroy the air temperature inversion that develops on calm nights. Wind results in convective air movement – warm air from above mixes with cooler air from below, resulting in warmer surface conditions. Virtually cloud-free sky conditions are required for frost because nocturnal clouds are effective in increasing the returned infrared irradiance resulting in elevated surface temperatures. Dry atmospheric conditions, or more correctly low water vapour pressure conditions, are required since water vapour is a greenhouse gas that effectively returns infrared irradiance to the surface, elevating temperatures. The cool, calm, clear, dry and inversion requirements for frost need to occur simultaneously because if any of these are not met, the chance of frost is reduced. Atmospheric measurements from an automatic weather station (AWS) system, usually at 2 m above the soil surface, may not represent the conditions at and just above the surface and such measurements are therefore not easily applied to determining frost occurrence

or for calculating frost duration (FD). However, the inclusion of an inexpensive exposed temperature sensor in contact with blades of grass could yield valuable information on conditions just above the surface and therefore information on frost occurrence. Negative surface temperatures, measured using an infrared thermometer (IRT), satisfy the definition of frost occurrence. Furthermore, the detection of ice may be possible using dielectric measurements close to the surface because the dielectric constant for air (1), ice (5) and liquid water (80) are different.

The main aim of the study was to determine the occurrence of frost and FD for a short-grass surface for a relatively high relative humidity site using various measurement methods that may be applied at any location, including dielectric, infrared surface temperature and grass temperature methods. The study also aimed to demonstrate the importance of including a grass thermometer with a normal AWS system for determining frost occurrence and FD. For the purpose of timeous e-mail and SMS alerts for early-warning of frost, a web-based display of collected data and graphics was developed to enhance the use of the data and their display.

Materials and methods

Measurements reported on were collected from 19 April 2011 to 15 June 2012, Pietermaritzburg, KwaZulu-Natal, South Africa (altitude 684 m; 29.628° S, 30.403° E). Details of the measurement site and AWS system and sensors are summarised in Table 1, adapted from Savage (2012). Air temperature and relative humidity was measured in a naturally ventilated 12-plate Gill radiation shield at a height of 100 mm. A profile of naturally ventilated air temperature thermocouples, each in a seven-plate shield, was used to determine the environmental lapse rate. Grass temperature was measured using a freely exposed thermocouple, 25–50 mm above the soil surface, in contact with blades of grass (World Meteorological Organisation 2008). Grass-canopy surface temperature was measured using an IRT positioned at 45° to the horizontal, facing south and at a height of 2.5 m, sensing a target diameter of 1.9 m corresponding to an area of 2.8 m². The IRT was calibrated in the laboratory using a large radiator (Savage and Heilman 2009) and the grass-temperature thermocouple calibrated, in a water bath, against a reference PT1000

resistance thermometer (data not shown). Corrections were necessary for the IRT target temperatures but not for the grass temperatures.

The collocated leaf wetness sensors (LWS) were placed at a height of 100 mm above soil and at an angle of 45° with respect to the horizontal. Using an excitation voltage of 2 500 mV, a LWS voltage less than 274 mV corresponds to a dry LWS and a voltage greater than or equal to 284 mV to that of a wet LWS. Voltages between these two limits correspond to that of a contaminated LWS (Decagon Devices 2010). Voltage values and/or voltage changes could indicate frost on the sensor surface, or a temporary transitional change in surface conditions from dry-to-wet, wet-to-ice, wet-to-dry, ice-to-wet or from dry-to-ice (Figure 1). For the particular dielectric LWS used, the sensor radiation balance and thermodynamic properties including specific heat capacity and sensor area, thickness and density is similar to that of leaves and the sensor surface is hydrophobic (Decagon Devices 2010). Furthermore, since the LWS does not need to be painted, no calibration for individual units is necessary.

Methods for easy and remote detection of frost were investigated. Frost was judged to have occurred based on grass or IRT surface temperature. Frost was assumed to occur for 2 min when a measured average 2-min (IRT or

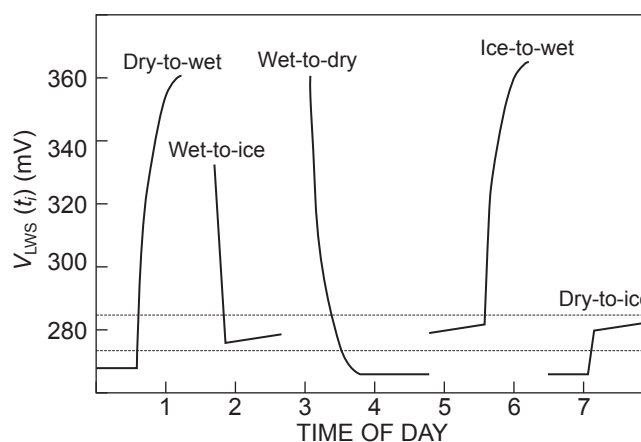


Figure 1: Voltage trace for an idealised leaf wetness sensor (LWS) subjected to (left to right) the following near-surface transitions: dry-to-wet, wet-to-ice, wet-to-dry, ice-to-wet and dry-to-ice

Table 1: Field-station measurement and relevant base-station system details

Station details		Field-station tower details	
Sensor	IRT ¹ at 2.6 m; at 0.1 m: RH and air temperature (CS215 ³); type-E thermocouples for grass temperature, air temperature in seven-plate Gill radiation shields at heights of 0.1, 1, 2, ..., 8 m; at 2 m: solar irradiance (CM3 ³), CS500 RH and air temperature ⁴ , wind speed and direction ⁵ model 03001; four-component net radiometer (CNR1 ³)		
Field dataloggers	CR1000 datalogger, multiplexer. All measurements were every 12 s and averaged/totalled every 2 min		
Field-to-base station communication	Datalogger-attached RF416 ² radio and antenna		

¹ Apogee IRT model IRR-P (half angle of 22°); Apogee Instruments, Inc., Logan, Utah, USA

² Campbell Scientific, Inc., Logan, Utah, USA

³ Kipp and Zonen B.V., Delft, The Netherlands

⁴ Vaisala Oyj, Helsinki, Finland

⁵ RM Young Company, Traverse City, Michigan, USA

grass) temperature less than or equal to 0 °C occurred, in keeping with the definition of frost. For timeous early warning of frost, e-mail and SMS alerts were issued for the first daily occurrence of a measured grass temperature of 2 °C or less occurring 2 h or more before sunrise. The first daily occurrence was determined and stored in the datalogger memory with the alerts issued using the base station computer software. The near real-time data of daily, weekly and monthly FD for the various methods were also displayed using a web-based data and information system: <http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Frost>.

For the dielectric LWS units, frost occurrence was based on:

$$V_L \leq V_{LWS}(t_i) < V_U \quad (1)$$

where V_L (mV) is the lower voltage corresponding to the start of contamination, $V_{LWS}(t_i)$ is the LWS voltage measured at time t_i (h) and V_U (mV) is the upper voltage corresponding to the end of contamination. Leaf wetness occurs when:

$$V_{LWS}(t_i) \geq V_U \quad (2)$$

with $V_{LWS}(t_i) < V_L$ for a dry LWS. The manufacturer recommends $V_U = 284$ mV and $V_L = 274$ mV.

The problem with the use of equation 1 for frost is that dry-to-wet and wet-to-dry voltage transitions could also be regarded as frost occurrence (Figure 1). Typically, during a condensing event followed by drying, $V_{LWS}(t_i)$ may increase from 265 to 320 mV and later decrease from 320 mV to around 265 mV and therefore satisfy equation 1 for two periods when in fact there was no frost (Figure 1, dry-to-wet and wet-to-dry).

Results and discussion

The 2-min output voltage for two LWS units, for a six-day period of frost (19–25 August 2011), is shown (Figure 2b) as well as the grass temperature and air temperatures at 1 m for confirmation of frost occurrence (Figure 2a). The occurrence of frost on five of the seven night/day periods is clear, because the LWS voltages stabilise between $V_L = 274$ and $V_U = 284$ mV (equation 1), and is confirmed by the negative grass temperatures. The change in LWS voltage for all units, corresponding to wet-to-ice and ice-to-wet transitions corresponding to the start and end of a hoar

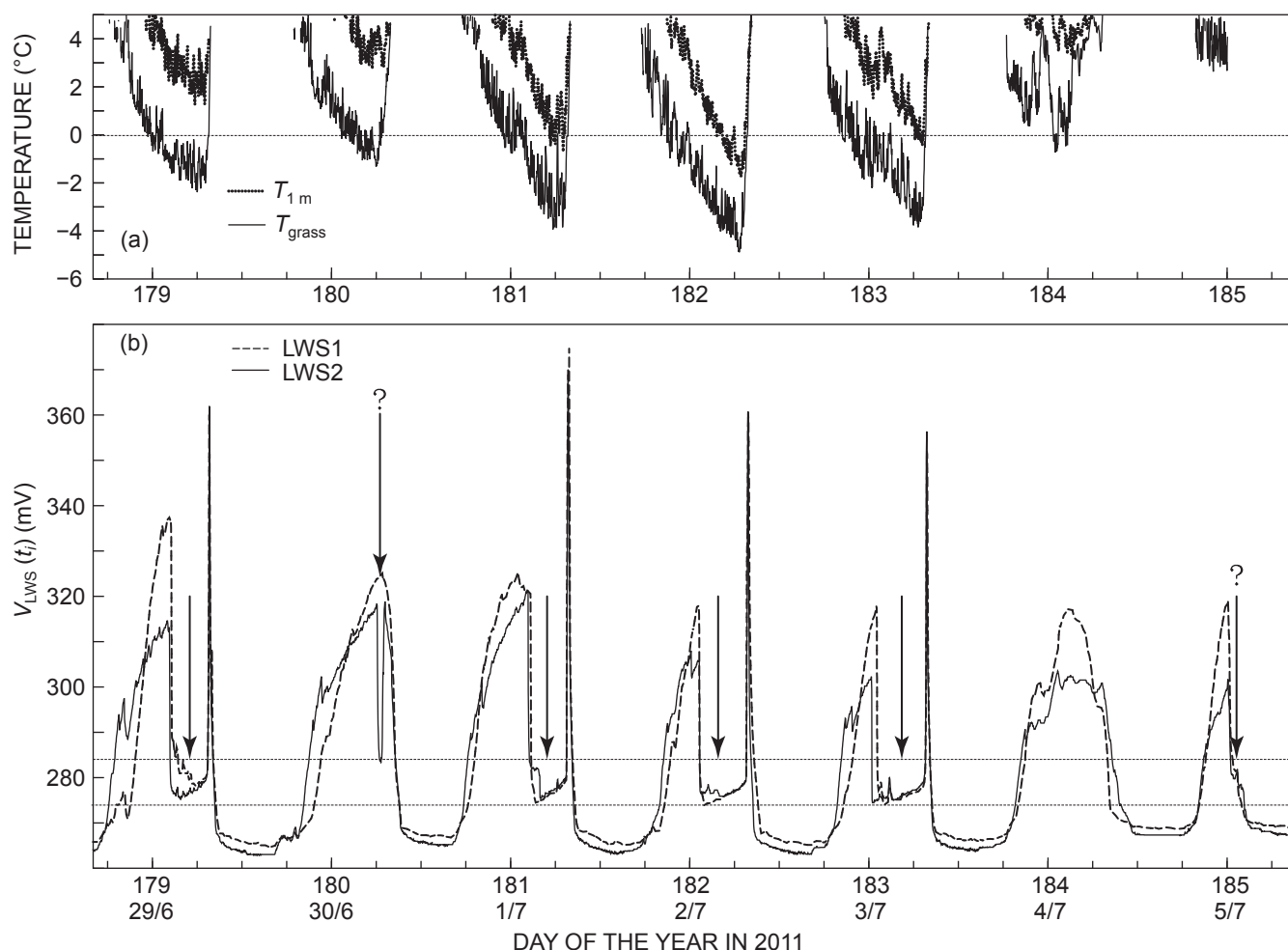


Figure 2: (a) Two-minute grass temperatures and 1 m air temperatures for a week of frost. (b) Two-minute voltage traces for two leaf wetness sensors (LWS). Frost is indicated by arrows with the question mark indicating possible frost

frost, respectively, generally occur at the same time. For some night/day periods it is not that clear if there was significant frost. Therefore, as previously alluded to, a clearer definition than that provided by equation 1 is required for frost determination. For days with significant frost, after ice has melted from the sensor surface – usually because of increases in solar irradiance at sunrise – the LWS voltage increases as ice melts and then rapidly decreases as the melted ice evaporates.

A second criterion, applied to all LWS units, was used to more accurately trap only frost events from LWS voltage measurements. The following criterion, based on consecutive 2 min voltage differences recalled from the datalogger memory every 2 min, was applied in the datalogger programme in conjunction with equation 1:

$$\sum_{i=1}^2 \left| \frac{V_{LWS}(t_{i+1}) - V_{LWS}(t_i)}{2(t_{i+1} - t_i)} \right| < \Delta V_{LWS} \quad (3)$$

where ΔV_{LWS} (mV h^{-1}) corresponds to a relatively small average rate of change in voltage, typically 10 mV h^{-1} which is equal to $0.1666 \text{ mV min}^{-1}$, compared to a much larger rate of increase for a dry LWS that suddenly became wet. Typically, at the start of a wetting event, the rate of change

of $V_{LWS}(t_i)$ can be more than twice ΔV_{LWS} , although after more of the surface is wetted, the measured voltage may become stable with the rate of voltage change decreasing but with voltages in excess of V_U (Figure 1, dry-to-wet). Hence use of $\Delta V_{LWS} = 10 \text{ mV h}^{-1}$ attempts to remove from the LWS record of frost those events that satisfy equation 1 but not equation 3.

The protocols for determining FD, for a period of five months (from 19 April 2011) using the LWS method were cross-checked against FD determined using IRT surface and grass temperatures less than or equal to 0°C . To investigate the impact of the constants used in equations 1 and 3 on FD estimation, the lower limit V_L of 274 mV in equation 1 was adjusted to 272 mV and the limit of $\Delta V_{LWS} = 10 \text{ mV h}^{-1}$ in equation 3 was adjusted to 5 and 20 mV h^{-1} (Figure 3). Although the FD totals for the five-month period for the IRT and LWS methods were in reasonable agreement using different constants (Figures 3c and d), there was an increased root mean square error (RMSE) and reduced coefficient of determination (r^2). For the constants used in the case of Figures 3a and b, the data comparisons for Figure 3a had slightly increased RMSE and reduced r^2 , but the FD total for the LWS method was more in agreement with the IRT method than that in Figure 3b. The limit

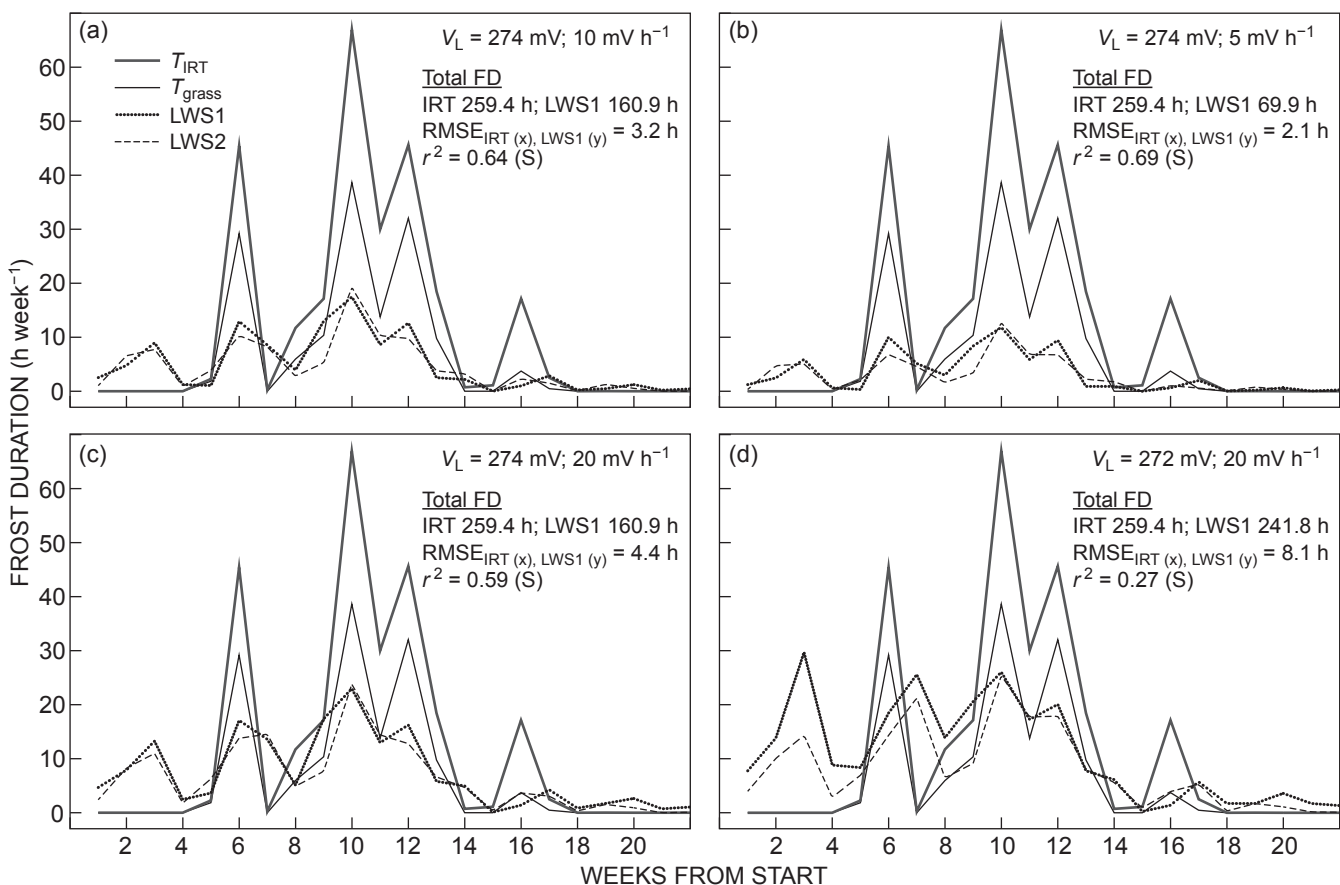


Figure 3: Measured frost duration, from 19 April 2011, using infrared thermometer (IRT) and grass temperature methods for which either is less than or equal to 0°C and leaf wetness sensors (LWS1 and LWS2) using equations 1 and 3: (a) with $\Delta V_{LWS} = 10 \text{ mV h}^{-1}$; (b) $\Delta V_{LWS} = 5 \text{ mV h}^{-1}$; (c) $\Delta V_{LWS} = 20 \text{ mV h}^{-1}$; and (d) with $V_L = 272 \text{ mV}$ in equation (1) and $\Delta V_{LWS} = 20 \text{ mV h}^{-1}$ in equation 3. The root mean square error (RMSE) and coefficient of determination (r^2) of the infrared thermometer (IRT; x) and leaf wetness sensor (LWS1; y) frost duration estimates are shown

constants of $V_L = 274$ mV, $V_U = 284$ mV and $\Delta V_{LWS} = 10$ mV h^{-1} were therefore used routinely for LWS estimation of FD.

Estimates of FD were usually greatest for the IRT method, next for grass-temperature method and least for the LWS method. This is expected since the IRT surface measurements are the coldest during non-advective nocturnal air temperature inversion conditions. The grass temperatures, about 25–50 mm away, were generally slightly greater by about 1.27 °C – the y intercept of the regression of the grass vs surface temperature relationship for the winter of 2011 for temperatures between midnight and 06:30 was 1.27 °C with a slope of almost 1 (Figure 2 of Savage 2012).

Leaf wetness sensor voltage measurements represent conditions on the LWS upper surface as well as those 10 mm above (Decagon Devices 2010). Thus if there is a thin layer of ice on the LWS surface, the measured dielectric constant would be between that of ice and air. This could result in a dielectric constant (measured voltage) between 1 (air, typically 265 mV) and 5 (ice, typically 280 mV) (Figure 1). Given the high nocturnal relative humidity of the study site for the duration of the experiment, black frost did not occur. LWS units do not detect black frost – unless with further temperature decreases after the occurrence of black frost, sublimation occurs. Both the grass- and IRT-temperature methods would, however, record temperatures below 0 °C in the case of a black frost but these methods cannot indicate if and when the vegetation freezes unless the freezing point of the vegetation is known.

In order to examine the correspondence in FD for the different methods, three night/day periods for which frost occurred, as judged by surface temperature at or below 0 °C, were examined (Figures 4–6). The environmental lapse rate ($\text{ELR} = dT/dz$; °C m^{-1}) between 0.1 and 2 m is surprisingly constant for cloudless and relatively windless nights for this site at around 2.25 °C m^{-1} (stable) with that between 2 and 4 m less than 1 °C m^{-1} (Figures 4a, 5a and 6a). The inference is that air temperature at 0.1 and 2 m were decreasing at similar rates for such nights for this site. Between 2 and 4 m, there is probably more atmospheric mixing with the air temperature difference being smaller. Sunrise, indicated by an arrow in Figures 4b, 5b and 6b, results in an increase in solar irradiance and a slight and slow increase in the downward (L_d) and upward (L_u) infrared irradiances. Following sunrise, both ELRs changed sign, corresponding to a change to unstable conditions. As expected, the 2–4 m ELR changed sign slightly later than that for the 0.1–2 m layer, with the surface warming more rapidly than air at higher heights.

The other factor affecting the ELR is wind speed. For windier nights (Figure 6a), the ELR is reduced with wind speeds in excess of 1 m s^{-1} decreasing the 0.1–2 m ELR to less than 1.5 °C m^{-1} compared to in excess of 2.5 °C m^{-1} for other nights (Figures 4a and 5a). Of particular importance with respect to the ELR on cloudless and windless nights and the definition of frost is that for an ELR in excess of 2.5 °C m^{-1} and a measured air temperature at 2 m of around 5 °C, for example, the surface temperature could be less than 0 °C and hence frost could occur. Hence, air temperatures measured at 1 m or higher by themselves are not good indicators of frost occurrence. This justifies the inclusion of grass temperature at AWS systems for

determination of frost occurrence and FD. Air temperatures at 1 m or higher may be good indicators of frost occurrence on cloudless and windless nights if the ELR is known or can be predicted accurately. In the former case, ELR measurements are, unfortunately, rare. In the latter case, the accurate prediction of surface temperature from air temperature at a standard height above the surface would require inputs not commonly available.

The voltage output for the LWS units for three frost mornings are shown (Figures 4c, 5c and 6c). Of the three, the morning depicted in Figure 6c had the least frost because of increased wind speed (Figure 6a) and a greater downward infrared irradiance (L_d , Figure 6b), the latter probably because of transient clouds. There was agreement between the LWS units apart from the morning with the lowest FD. This disagreement was presumably because of LWS exposure differences. For the mornings depicted in Figures 4c and 5c, LWS voltages are initially greater than 284 mV (leaf wetness) and then their decrease following the onset of frost (equation 1) is abrupt. The slope of the voltage during the transitional change from the larger voltage to between $V_L = 274$ and $V_U = 284$ mV is greater than $\Delta V_{LWS} = 10$ mV h^{-1} (equation 2) and depicted by small line segments labelled '10 mV h^{-1} ' (Figures 4c and 5c). Although it is difficult to determine whether the LWS had mostly ice or liquid water on its surface, these transitional changes in voltage and the voltage change when the ice melts were short in duration with occasional transitions from wet-to-dry after all the frost had melted being indicated as frost. For both mornings, the frost melted after sunrise (arrows in Figures 4b and 5b) and after positive solar irradiance values.

The various temperatures above and at the grass surface for three frost mornings are depicted in Figures 4a, 5a and 6a. Of particular note is that above-surface temperatures, apart from those within 100 mm of the surface, rarely recorded less than 0 °C. For nocturnal conditions, grass temperatures were almost always greater than IRT surface temperatures. The duration of frost, as recorded by surface temperatures at or below 0 °C, are indicated (Figures 4d, 5d and 6d). These durations are more than double those recorded by LWS units positioned at a mid-position height of 100 mm above the surface.

Conclusions

Dielectric leaf wetness sensor measurement of frost duration (FD) was problematic. Dry-to-wet and wet-to-dry transitional condensing events without freezing followed by drying typically corresponding to LWS voltage increases from around 260 mV (dry) to in excess of 320 mV (wetness), and vice versa, had to be identified and excluded. These transitional events were identified using subhourly measurements by excluding LWS voltage rates of change that were greater than or equal to 10 mV h^{-1} for 4 min but at the same time including events for which the LWS voltage was between the 274 and 284 mV lower and upper limits, respectively. FD estimated using dielectric LWS units at 100 mm tended to underestimate FD compared to that estimated using the infrared (IRT) surface- and grass- (25–50 mm) temperature methods, presumably because of the fact that the LWS sensors are at a greater

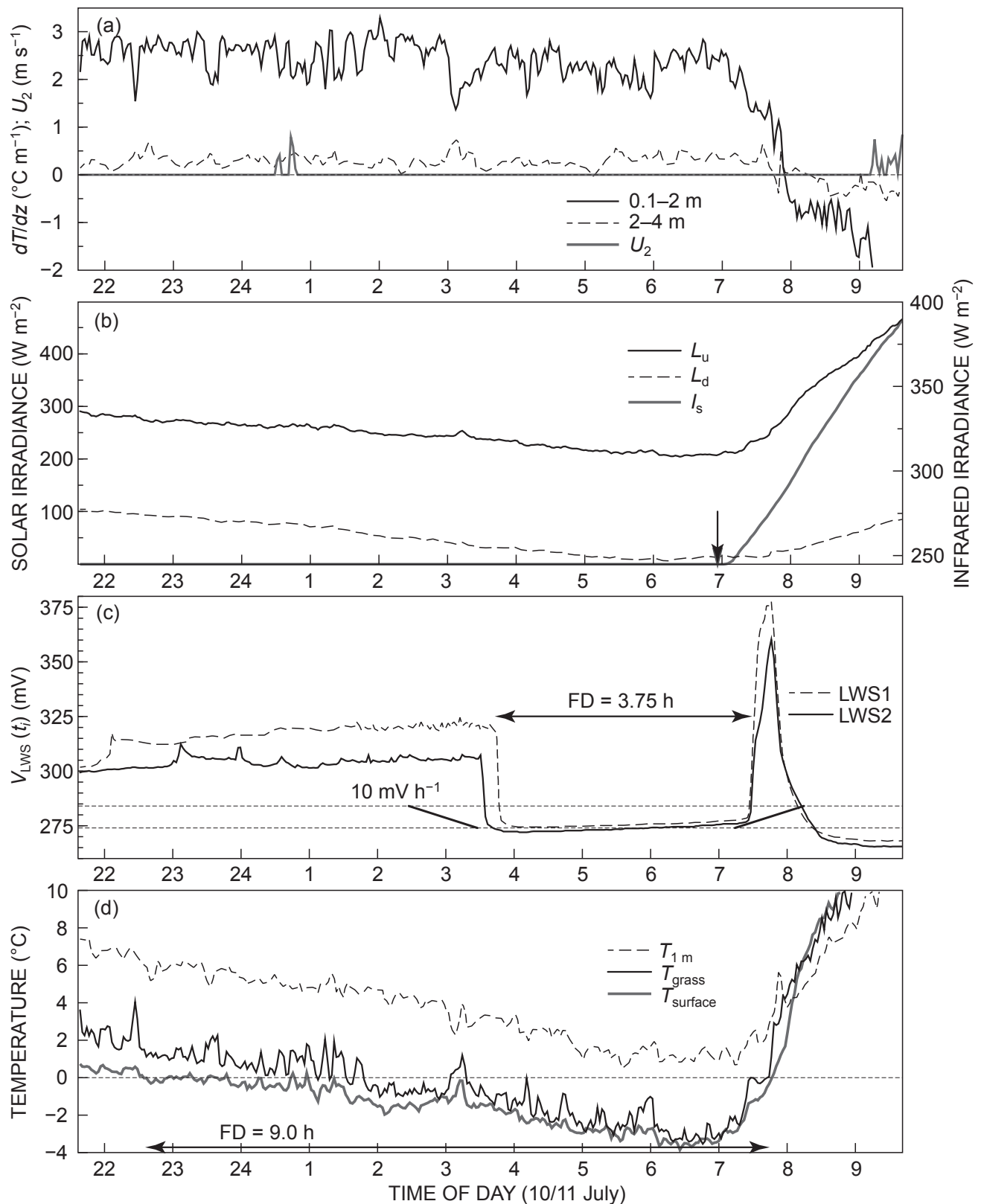


Figure 4: Conditions for a night/day in winter (10/11th July 2011) with significant frost. (a) The environmental lapse rate (dT/dz) and wind speed (U_2); (b) the outgoing (L_u) and downward (L_d) infrared and solar irradiances (I_s); (c) the LWS voltage traces for two units for which the average frost duration (FD) is 3.75 h. The ΔV_{LWS} value, used to exclude the wet-to-dry and dry-to-wet transitions, is shown by the line segments marked 10 mV h^{-1} ; (d) the air temperature at 1 m ($T_{1\text{ m}}$), grass temperature (T_{grass}), and infrared thermometer (IRT)-measured surface temperature (T_{surface}). The frost duration (FD) is 9.0 h based on the duration for which surface temperature is less than or equal to 0°C .

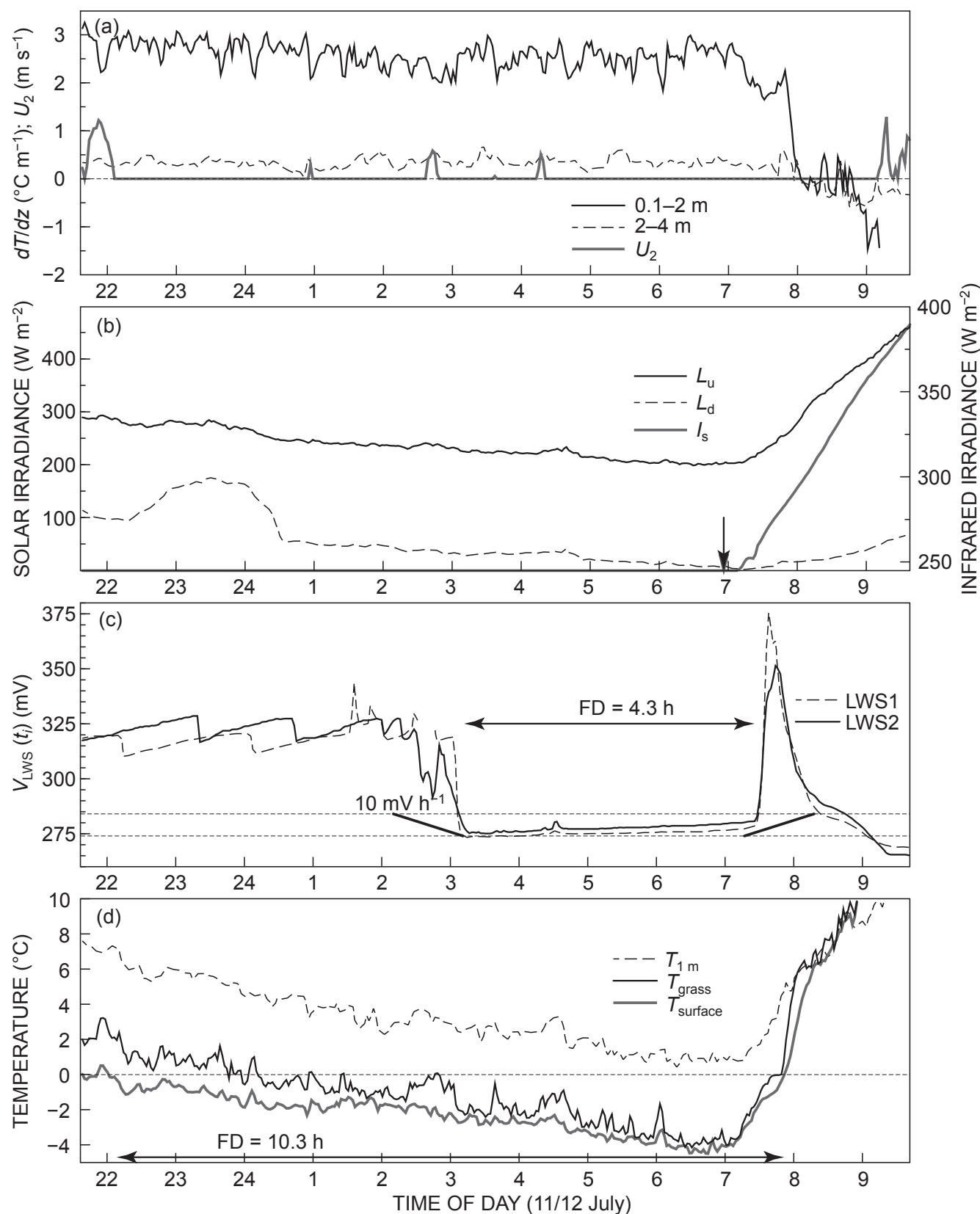


Figure 5: Conditions for a night/day in winter (11/12 July 2011) with significant frost. (a) The environmental lapse rate (dT/dz) and wind speed (U_2); (b) the outgoing (L_u) and downward (L_d) infrared and solar irradiances (I_s); (c) the leaf wetness sensor (LWS) voltage traces for two units for which the average frost duration (FD) is 4.3 h; (d) the air temperature at 1 m ($T_{1\text{ m}}$), grass temperature (T_{grass}), and infrared thermometer (IRT)-measured surface temperature (T_{surface}). The frost duration (FD) for the IRT method is 10.3 h

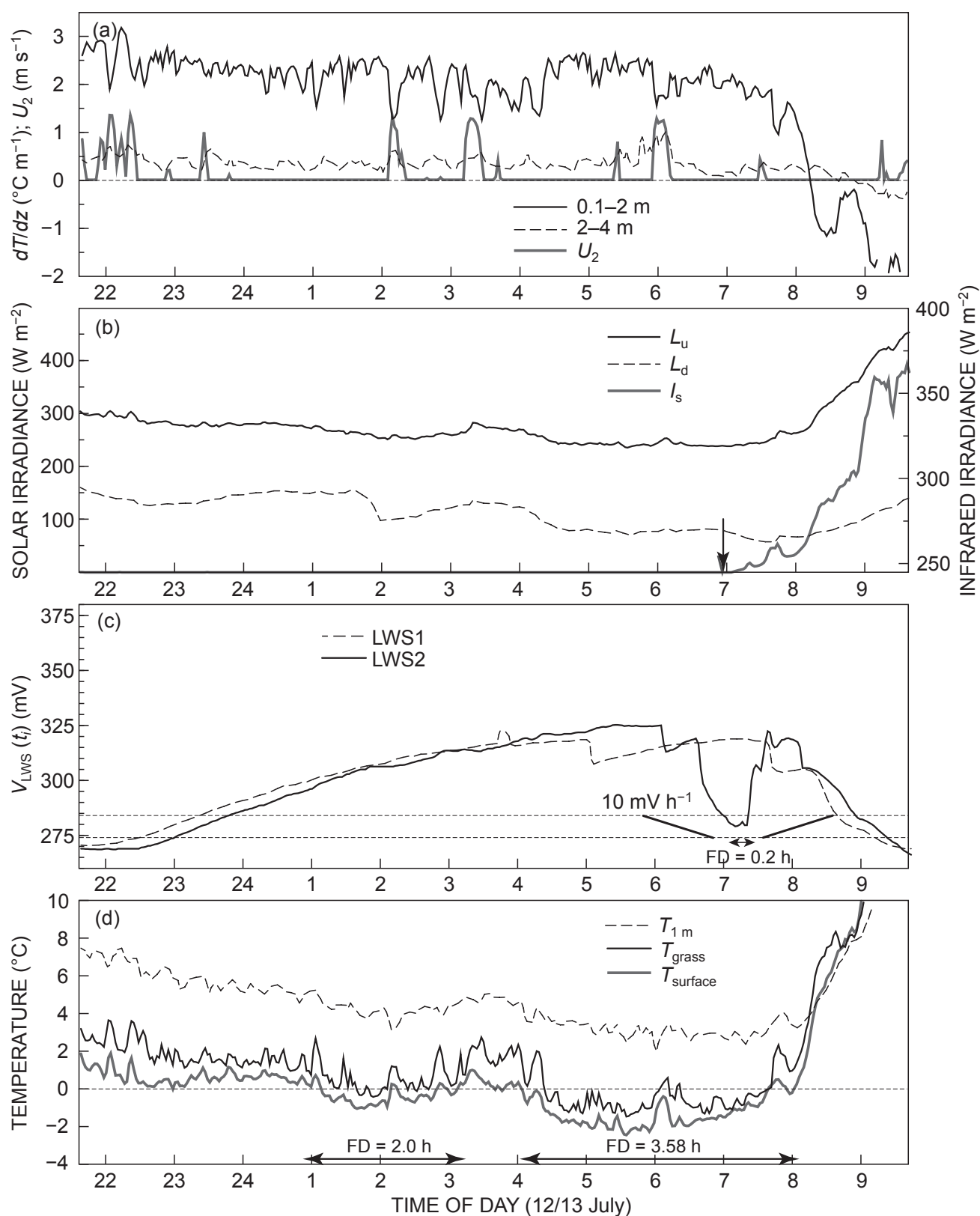


Figure 6: Conditions for a night/day in winter (12/13 July 2011) with slight frost and windier conditions. (a) The environmental lapse rate (dT/dz) and wind speed (U_2); (b) the outgoing (L_u) and downward (L_d) infrared and solar irradiances (I_s); (c) the leaf wetness sensor (LWS) voltage traces for two units for which the average frost duration (FD) is 0.2 h for the one LWS with none recorded for the other; (d) the air temperature at 1 m ($T_{1\text{ m}}$), grass temperature (T_{grass}), and infrared thermometer (IRT)-measured surface temperature (T_{surface}). The total FD for the IRT method is 5.58 h

distance (100 mm) from the surface compared to IRT sensors that measure surface temperature. The air temperature measurements at 1 m, or higher, were rarely less than 0 °C and should not be used to define grass-surface frost events without adjustment of the 1 m or higher temperature for the measurement height difference. None of the methods used could detect black frost events, which did not occur for the high nocturnal relative humidity experienced at the study site. The grass- and IRT-temperature methods would indicate less than 0 °C for black frosts with the LWS method yielding no indication of black frost unless further temperature decreases caused sublimation. Air temperature gradients between the surface and 2 m for cloudless nocturnal frosted and windless conditions were about 2.25 °C m⁻¹, typically resulting in the 2 m air temperature measurements more than 4 °C greater than those at the grass surface. The web-based system used allowed for timeous e-mail and SMS alerts of frost with near real-time data and graphics of FD displayed for the current day, week and month for the various methods. To increase the value of AWS measurements, it is recommended that AWS systems should also include grass temperature that could be used to estimate FD.

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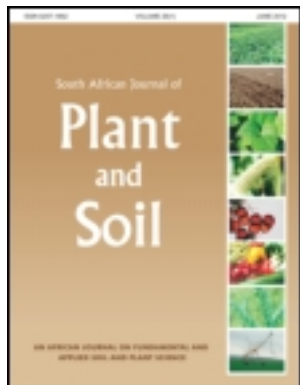
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Estimation of leaf wetness duration for a short-grass surface

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Estimation of leaf wetness duration for a short-grass surface

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The measurement of leaf wetness duration (LWD) was investigated using subhourly dielectric, infrared surface temperature, dewpoint temperature, grass temperature and relative humidity (RH) measurements. Near real-time LWD data and information displays and alerts were made available timeously via a web-based system. LWD was estimated above a short-grass surface using five methods: dielectric leaf wetness sensors (LWS); a constant RH for which wetness events were registered for RH greater than 87%; RH between 70–87% if RH increased by more than 3% in 30 min; and two dewpoint depression-based methods for which surface-measured temperature, using an infrared thermometer (IRT), and grass temperature were compared with the dewpoint at either 0.1 or 2 m. The RH methods generally overestimated LWD compared to the other methods. There was reasonable agreement between IRT- and grass-temperature methods if rain days were excluded but these methods showed poor agreement with LWS measurements of LWD. Microclimatic and radiative conditions, during nocturnal condensing events, are reported. Automatic weather station data would have more value if grass temperature was included for determination of LWD by comparison of grass temperature with a measured dewpoint, with timeous alerts and web-based display of near real-time LWD data and graphics.

Keywords: dielectric leaf wetness sensor, grass-surface temperature, nocturnal grass temperature

Introduction

About 14.1% of crops are lost because of plant diseases annually. This loss corresponds to an annual cost of about US\$220 billion (Agrios 2005). Early prediction of disease and timeous dissemination of data and information relating to leaf wetness measurement or estimation is one attempt to lower this cost. The estimation of surface wetness on plants and the role and importance of leaf wetness by rain, dew, guttation from leaves and irrigation, for the prediction of leaf diseases, has been reviewed by Magarey et al. (2005). As has been mentioned by Savage (2012) with respect to the rare reporting of conditions relevant to a weather hazard such as frost occurrence, the near real-time reporting of leaf wetness and leaf wetness duration is also rare.

Various methods have been used for determining dew duration or dew events. Direct measurements of dew and rates of dew accumulation have been reported (Monteith 1957, Wilson et al. 1999). Dew drops forming on wood blocks (Duvdevani 1947), electrical resistance grids (Gillespie and Kidd 1978), and dielectric sensors (Decagon Devices 2010) have been used as leaf proxies. A remote optical wetness sensor has been used for sand-crusts and desert shrub surfaces (Heusinkveld et al. 2008). Kruit et al. (2004) used four methods for estimating grassland leaf wetness duration (LWD). They found that although none perfectly predicted LWD, an extended threshold relative humidity (RH) method worked best. They used a RH threshold value of 87% for leaf wetness, but extended this to 70–87% for RH increases of more than 3% in

30 min, as leaves were assumed to be wet under these conditions. A Penman–Monteith model has been used as a 'reference' index to estimate crop LWD using automatic weather station (AWS) and net irradiance measurements (Sentelhas et al. 2006).

Empirical methods for estimating LWD have also been used, usually based on AWS data (Kim et al. 2005). These authors' measurements of wind speed were adjusted to the height of leaf wetness measurements but there is currently no simple method known for adjusting air temperature and RH measurements at a standard height to that of leaf wetness measurements. Sentelhas et al. (2004) found that LWD measured by sensors near the standard screen height over turfgrass differed considerably from LWD measured by sensors in a maize canopy, especially during periods with LWD less than 15 h. They found that sensors at 300 mm above turfgrass, at angles between 15° and 45° to the horizontal, provided much more accurate estimates of crop LWD and potential for use in operational plant disease management.

A dielectric (capacitance) leaf wetness sensor (LWS) measures the ability of material on and near its surface to store electrical charge, giving important information about surface and near-surface conditions if the LWS is positioned close to a grass surface. Since the dielectric constant for air is 1 and 80 for liquid water, it is possible to determine whether there is liquid water (dew) on the surface or if the LWS is dry. For the LWS to mimic a leaf, it needs to have similar optical properties – reflection coefficient

and emissivity – and similar physical properties – specific heat capacity, density, length, breadth and thickness – of a typical leaf. The sensor surface also needs to be hydrophobic. More importantly, however, the ideal LWS should require no individual calibration.

The internet provides a mechanism for the instant placement of data and information. Near real-time field-based measurement systems, such as described here, allow AWS data to be collected, displayed in the form of graphs/tables and data, and updated automatically and frequently using the internet. Furthermore, advances in telecommunications in addition allow automatic email and SMS alerts and early warning of agricultural and environmental events based on near real-time measurements. The telecommunication can be initiated directly using a datalogger programme with a connected GSM modem, or equivalent, or initiated using base-station computer software that has telecommunication capability.

In this study, the measurement of LWD is investigated using dielectric, infrared surface temperature, dewpoint temperature, grass temperature and RH measurements with near real-time data and information and alerts made available timeously via a web-based system.

Materials and methods

Measurements were obtained for the winters of 2011 and 2012 from 19 April 2011 to 15 June 2012 at Pietermaritzburg, KwaZulu-Natal, South Africa (altitude 684 m; 29.628° S, 30.403° E). The long-term average annual rainfall total is 839 mm with relatively mild rainless winters and long-term average of 13 frost days per annum and mean daily minimum air temperatures for April to October of 13.3, 9.4, 5.8, 6.0, 8.6, 11.0 and 13.2 °C, respectively.

An AWS system was attached to a 3 m instrumentation tower with additional air temperature sensors extending to 8 m (Table 1). Based on World Meteorological Organisation

(2008) recommendations, the tower AWS measurements satisfied the requirements for the minimum distance away from obstacles. A single thermocouple was used to measure grass temperature at a height-above-canopy between 25 and 50 mm (World Meteorological Organisation 2008). In addition, a single infrared thermometer (IRT) was used to measure the grass surface temperature. The instrument (Table 1) was attached to the tower and positioned at 45° to the horizontal, facing south and at a height of 2.5 m, sensing a target diameter of 1.9 m. Cost limitations and insufficient datalogger channels prevented replication of the grass and IRT measurements. To avoid night-time condensation on net radiometer sensors, a four-component net radiometer (Table 1) was heated, under datalogger control, during night-time whenever the RH at 2 m exceeded 95%. Increased net irradiance measurement errors would result without the heating. Solar irradiance (I_s) measurements were used to indicate sunrise and outgoing (L_o) and incoming (L_i) infrared irradiances used for determining nocturnal radiative conditions.

Dielectric LWS units (Table 1) were co-located, 45° to the horizontal, with their centre position 100 mm above the soil surface. Following a 2 500 mV excitation, the measured LWS voltage depends on the dielectric constant of a zone 10 mm from the upper sensor surface (Decagon Devices 2010). The average LWS voltage was determined, from ten 12 s measurements, every 2 min because 60-min data were inadequate for LWD determination. The manufacturer recommends that a LWS voltage less than 274 mV corresponds to a dry LWS (dielectric constant of 1) and that greater than or equal to 284 mV corresponds to a wet LWS (dielectric constant of 80). Field calibration for the individual LWS used here was not required – in contrast to the electrical impedance grid units used by Gillespie and Kidd (1978), which required field determination of the wet-to-dry resistance transition point. For timeous early

Table 1: Field-station measurement and relevant base-station system details

Station details	Field-station tower details
Sensor	Type-E thermocouples for grass temperature, air temperature in seven-plate Gill radiation shields at heights of 0.1, 1, 2, ..., 8 m; at 0.1 m: leaf wetness sensors ¹ , RH and air temperature (CS215 ²); raingauge ³ – rim at 1 m; at 2 m: solar irradiance (CM3 ⁴), CS500 RH and air temperature ^{2,5} , wind speed and direction ⁶ model 03001 and IRT ⁷ at 2.6 m; four-component net radiometer (CNR1 ⁴) at 3 m
Field dataloggers	CR1000 ² datalogger, AM16/32 multiplexer ²
Field-to-base station communication	Datalogger-attached RF416 ² in turn connected to a panel antenna ⁸ in line-of-sight with the base station
Grounding at field station	Field station antenna connected to an arrestor, in turn connected to the radio. The datalogger was earthed
Base station for connecting to field station	A RF416 radio connected to an 8 m antennae and surge-protector
Software	Base station software included Loggernet ² for data downloads. RTMC Pro version 3.0 ² was used to create a web-based display of data, graphics and alerts of daily, weekly and monthly LWD totals

¹ Model LWS, Decagon Devices Inc., Pullman, Washington State, USA

² Campbell Scientific, Inc., Logan, Utah, USA

³ Pronamic RAIN-O-MATIC (0.254-mm resolution), Pronamic ApS, Ringkøbing, Denmark

⁴ Kipp and Zonen B.V., Delft, The Netherlands

⁵ Vaisala Oyj, Helsinki, Finland

⁶ RM Young Company, Traverse City, Michigan, USA

⁷ Apogee IRT model IRR-P (half angle of 22°): Apogee Instruments Inc., Logan, Utah, USA

⁸ Poynting antenna POY-A-PANL-0005, Poynting Direct (Pty), Johannesburg, Gauteng, South Africa

warning of LWD, near real-time data and graphics were displayed on the internet using a web-based data and information system (<http://agromet.ukzn.ac.za:5355/?comm=RTMC&screen=Leaf%20wetness>) using commercially available software (Table 1). Daily e-mail and SMS alerts were easy to implement using the base-station computer software, allowing automatic alerts and early warning and reporting of daily, weekly and monthly LWD totals for the different methods. The LWD totals were determined using the datalogger programme and stored in the datalogger memory every 2 min.

Various micrometeorological measurements (19 April to 20 September 2011) were examined, selected from the full data set for 2011 and 2012, and the dielectric LWS measurements. Leaf wetness was also inferred by comparing surface and grass temperatures with the dewpoint measured at 0.1 or 2 m and by using the two RH methods (Kruit et al. 2004).

Results and discussion

Output voltage for two LWS units, for a six-day period, is shown (Figure 1). Changes in upper-surface LWS conditions from dry-to-wet, which corresponds to voltages increasing from about 265 mV to more than 300 mV, are clear (Figure 1, with the maximum LWS voltage limited to 380 mV for clarity of the events between 274 and 284 mV). The oscillatory nature of the voltage for a wetted LWS, on 21 August 2011 (day 232) and 26 August, could be caused by droplets dripping off the upper surface of the angled-LWS followed by more wetting given further decreases in temperature, and so on. Once the LWS units are wet,

the voltages are different. However, the large and abrupt changes, corresponding to dry-to-wet and wet-to-dry transitions occur at almost the same time for the different units (Figure 1). For LWS measurements, RH and air temperatures in the 0–0.1 m region are important.

Night-time grass temperatures were field-checked by comparison with IRT surface temperature for wetness and frost conditions (Figure 2, with both restricted to less than 7.5 °C to encompass most nights). There are very few grass

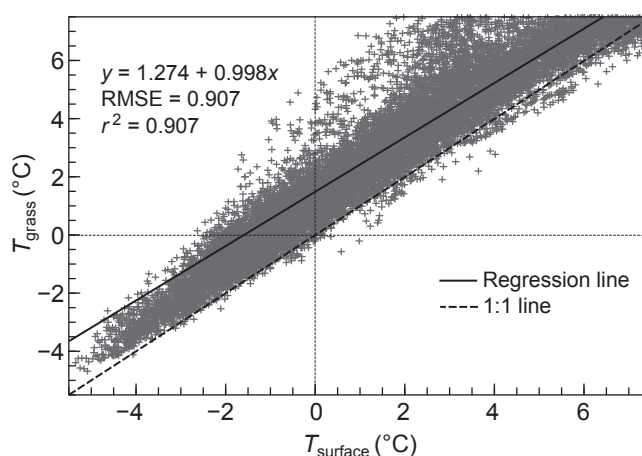


Figure 2: Field measurements (2 min) and statistics for IRT-measured surface temperature (T_{surface}) vs grass temperature (T_{grass}) for nocturnal conditions (midnight to 06:30) for 22 April to 20 September 2011. Both axes have been restricted to less than 7.5 °C to encompass most nights with frost

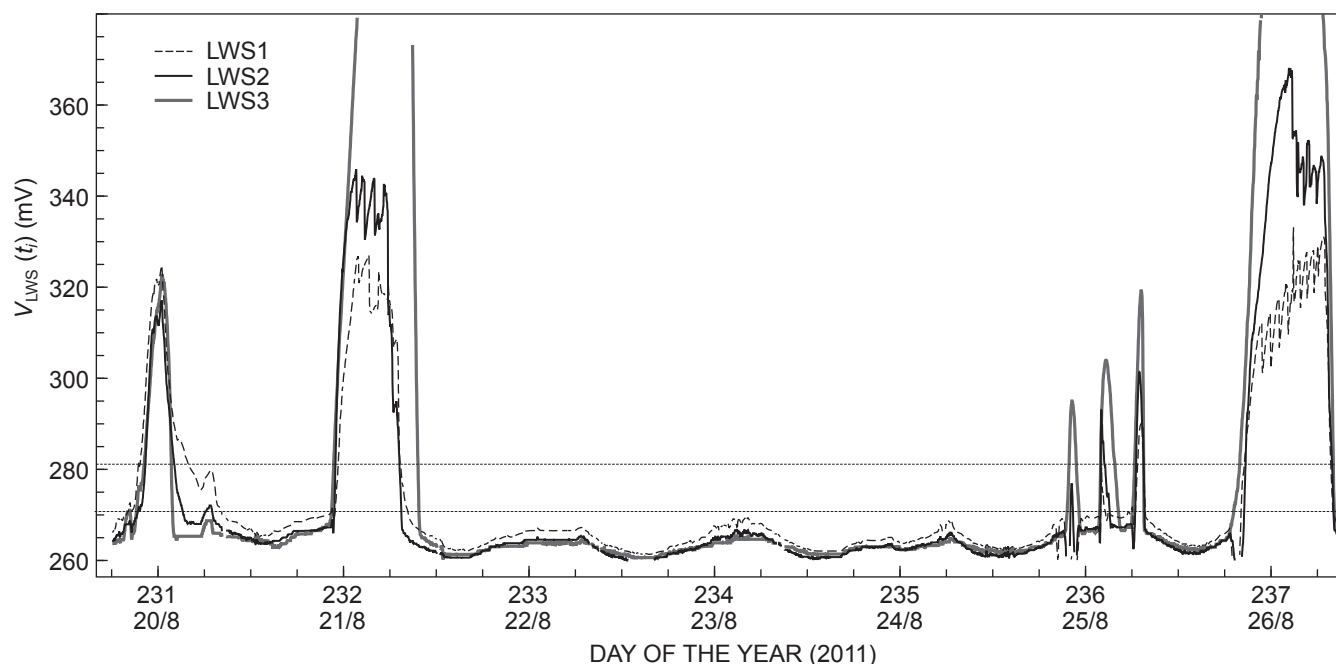


Figure 1: Two-minute voltage traces for three leaf wetness sensor (LWS) units for 20–26 August 2011 with significant leaf wetness on three mornings. The two dotted lines correspond to 274 mV below which the sensor is dry, and 284 mV, above which the sensor is wet. LWS3, when dry, yielded voltages that exceeded 380 mV for some of the time – the y-axis scale has therefore been limited to 380 mV for clarity of the events between 274 and 284 mV

temperatures less than surface temperature with agreement improving for lower (negative) temperatures, consistent with stable conditions. The difference in height between grass and surface temperatures is therefore critical, resulting in many cases with $T_{\text{grass}} > T_{\text{surface}}$. In addition, since leaf

wetness is a surface phenomenon, surface temperature in relation to atmospheric dewpoint (condensation) is critical.

Five methods were used for determining LWD: (1) dielectric LWS, (2) grass temperature in comparison with the dewpoint (either at 0.1 or 2 m), (3) surface temperature in

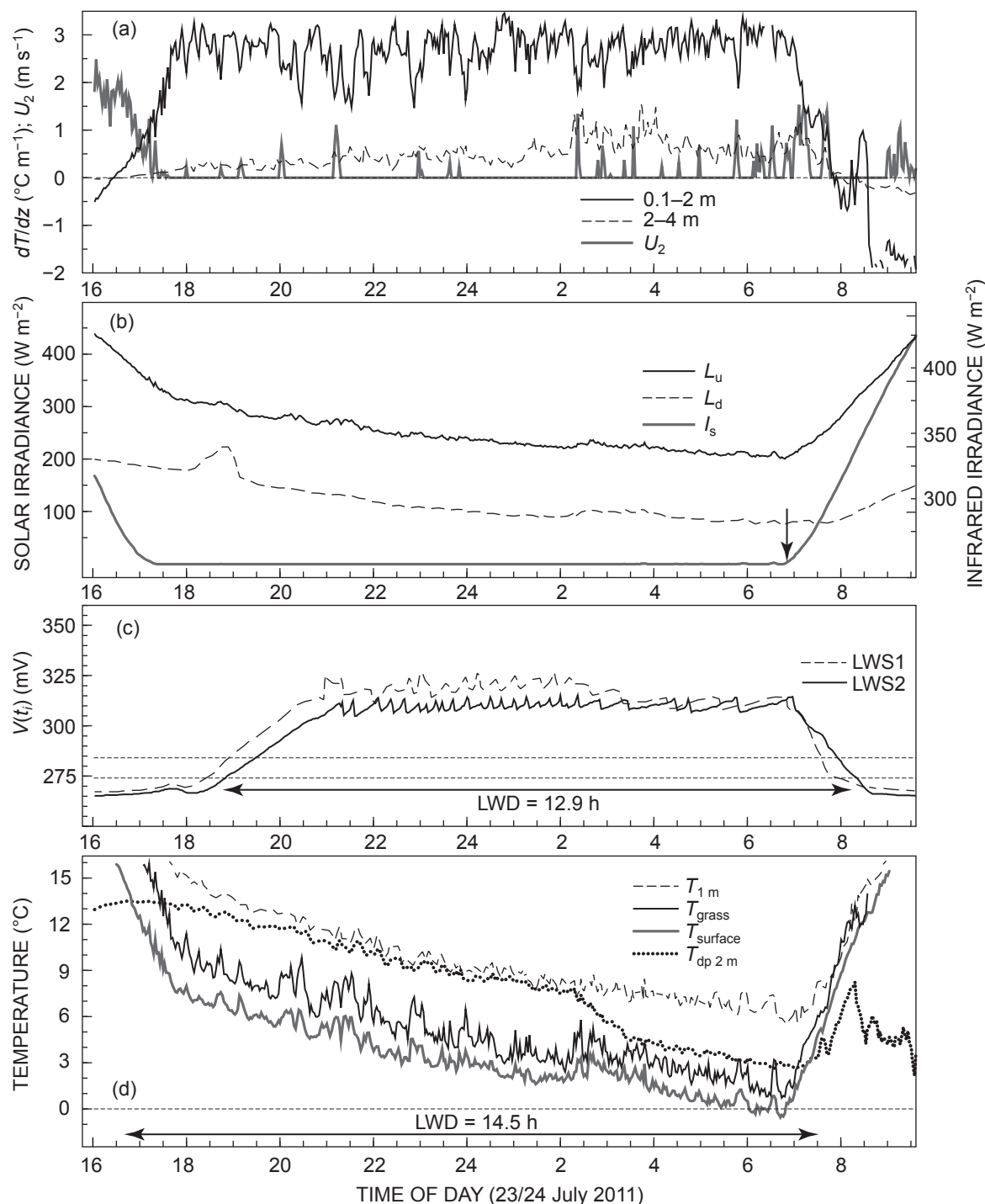


Figure 3: Conditions for a night/day early in winter (23/24 July 2011) with significant leaf wetness. (a) Air temperature profile gradient between 0.1 and 2 m and between 2 and 4 m and wind speed at 2 m (U_2); (b) outgoing (L_u) and downward (L_d) infrared and solar (I_s) irradiances. Sunrise is indicated by the arrow; (c) leaf wetness sensor (LWS) voltage [$V_{\text{LWS}}(t)$] traces for two units including the 274 and 284 mV limits shown by the dotted horizontal line; (d) air temperature at 1 m (T_{1m}), grass temperature (T_{grass}), IRT-measured surface temperature (T_{surface}) and the dewpoint at 2 m ($T_{\text{dp } 2m}$). LWD = Leaf wetness duration

comparison to the dewpoint at 0.1 m, (4) the constant RH method, and (5) the extended threshold RH method (Kruit et al. 2004, Sentelhas et al. 2008).

Voltage traces for three LWS units on winter mornings with surface wetness are shown (Figures 3d and 4d),

together with the corresponding microclimatic conditions (Figures 3a and 4a). The microclimatic conditions for condensing events are fairly similar to those for frost occurrence (Savage 2012) except that for these condensing events, afternoon temperatures are usually

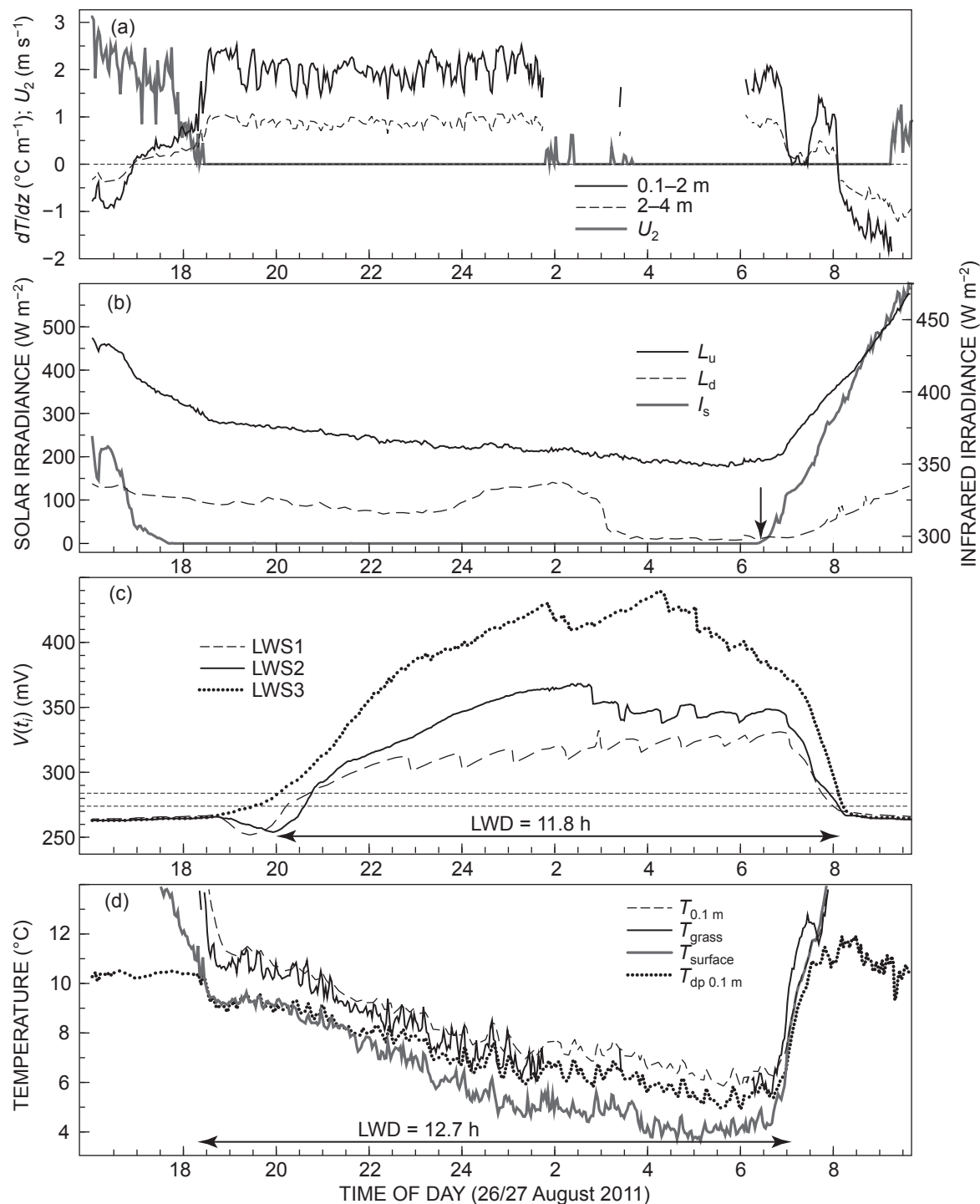


Figure 4: Conditions for a night/day in late winter (26/27 August 2011) with significant leaf wetness. (a) Air temperature profile gradient between 0.1 and 2 m and between 2 and 4 m and wind speed at 2 m (U_2); (b) outgoing (L_u) and downward (L_d) infrared and solar irradiances; (c) leaf wetness sensor (LWS) voltage [$V(t_i)$] traces for three units; (d) air temperature at 0.1 m ($T_{0.1\text{ m}}$), grass temperature (T_{grass}), IRT-measured surface temperature (T_{surface}) and the dewpoint at 0.1 m ($T_{\text{dp } 0.1\text{ m}}$). LWD = Leaf wetness duration

greater and there is often an increased wind speed at night. LWD for LWS units are fairly similar in spite of very different voltages during wetness periods – they showed the same time for transitions from dry-to-wet and wet-to-dry on both nights (Figures 3c and 4c). The LWD estimate using surface temperature in comparison to the dewpoint (Figures 3d and 4d) was in reasonable agreement with that using the LWS units. The estimate of LWD using grass temperature in comparison to dewpoint was in reasonable agreement with the surface temperature method in Figure 3d but not so in Figure 4d – probably because of the increased wind speeds near sunset and increased nocturnal cloud (Figure 3a compared to 4a and 3b compared to 4b).

Daily LWD totals for the five methods for a 31-day period are shown (Table 2). The agreement in daily LWD for three collocated LWS units is very good (Table 2, first five columns). Agreement between the IRT- and grass-temperature methods is reasonable apart from when one method indicated almost no LWD, corresponding

to rain days (underlined in Table 2). The statistics for these comparisons, with rain days excluded, are shown (Table 3). The two RH methods (Sentelhas et al. 2008) generally yielded larger LWD estimates compared to others (Tables 2 and 3). For daily LWD < 5.5 h, the IRT estimates of LWD were less than those using the LWS method and vice versa for LWD > 5.5 h because of the fact that there were days for which LWS units registered no LWD with the IRT temperature method indicating surface wetness and vice versa. In addition, the IRT method, based on surface conditions, generally yielded larger estimates than the grass-temperature method. This result would explain the height differences noted by Sentelhas et al. (2004), and mentioned previously, that LWD measured closer to the surface than at screen height gave better estimates of LWD for use in operational plant disease management.

All three of the LWS units, after more than a year of field use, showed signs of the paint degrading to powder because of high ultraviolet (UV) exposure.

Table 2: Daily leaf wetness duration (LWD; h), starting on 20 August (day 231) and ending on 20 September (day 262) 2011, for three leaf wetness sensor (LWS) units, the infrared thermometer-measured temperature (IRT), grass temperature (T_{grass}) and the two relative humidity (RH) methods, and the daily total rainfall (mm). Underlining indicates days with rain

Day	LWD (h)									Rainfall (mm)
	LWS1	LWS2	LWS3	Mean	SD	IRT	T_{grass}	RH	RH (extended)	
231	4.0	2.9	2.9	3.3	0.6	0	0	10.6	13.1	0.3
232	7.2	7.1	9.6	8.0	1.4	1.6	0.0	9.3	10.9	0.0
233	0.0	0.0	0.0	0.0	0.0	7.7	0.0	6.6	7.5	0.0
234	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	1.2	0.0
235	0.0	0.0	0.8	0.3	0.5	5.8	0.0	0.0	1.7	0.0
236	4.0	4.6	6.7	5.1	1.4	3.6	0.5	2.2	5.6	0.0
237	7.6	7.8	8.0	7.8	0.2	7.0	5.0	11.9	13.4	0.0
238	8.4	9.8	10.4	9.6	1.0	8.6	2.7	8.4	9.5	0.0
239	7.5	8.3	9.7	8.5	1.1	0.0	0.0	8.8	11.2	0.8
240	11.5	10.9	10.7	11.0	0.4	0.2	0.0	18.0	18.1	0.8
241	6.9	7.3	7.9	7.4	0.5	8.6	4.2	14.3	15.7	0.0
242	0.0	1.8	1.4	1.1	0.9	6.9	3.8	5.9	6.7	0.0
243	0.2	0.9	1.4	0.8	0.6	2.0	0.0	5.2	7.0	0.0
244	0.0	0.0	0.0	0.0	0.0	0.3	0.0	7.8	7.8	0.0
245	0.0	0.0	0.0	0.0	0.0	1.8	0.0	0.0	0.0	0.0
246	4.5	5.8	9.1	6.5	2.4	0.0	0.0	6.3	7.1	0.0
247	10.1	10.6	12.3	11.0	1.2	5.9	5.1	10.5	12.7	0.0
248	10.1	10.3	10.8	10.4	0.3	12.4	10.7	12.0	13.5	0.0
249	9.7	10.1	10.0	9.9	0.2	11.7	9.2	10.6	12.3	0.0
250	9.8	12.2	13.8	11.9	2.0	6.8	6.9	14.6	15.7	0.0
251	9.9	10.5	8.2	9.5	1.2	6.2	5.6	13.0	14.7	0.0
252	6.1	6.2	6.3	6.2	0.1	3.5	3.3	10.7	12.2	0.3
253	5.5	5.7	6.7	6.0	0.6	6.4	4.1	11.3	12.7	0.0
254	1.9	1.9	2.3	2.0	0.2	5.5	3.1	4.6	4.6	0.0
255	5.0	5.3	5.9	5.4	0.5	2.0	0.0	6.2	8.2	0.0
256	7.0	8.8	5.9	7.2	1.4	3.0	2.5	6.0	7.7	0.0
257	6.4	7.0	7.3	6.9	0.5	0.0	0.0	17.6	19.4	18.3
258	4.5	4.9	5.4	4.9	0.4	4.7	2.0	7.3	8.4	0.0
259	4.1	3.7	4.7	4.2	0.5	4.3	3.9	5.2	6.4	0.0
260	5.1	5.5	6.4	5.7	0.7	5.8	4.2	7.8	9.1	0.0
261	4.0	3.0	4.2	3.7	0.6	4.6	3.5	4.2	6.5	0.0
262	4.0	3.0	4.2	3.7	0.6	4.6	1.1	2.2	4.9	0.0
Total	165.1	175.9	193.0	178.0		143.6	81.3	258.9	305.2	20.3
Total ¹	129.6	140.5	156.1	142.1		139.9	78.0	193.3	231.3	

¹Excludes days with rain

Table 3: Comparison between daily leaf wetness duration (LWD) measured using the infrared thermometer (IRT) method (x) against the leaf wetness sensor (LWS), grass temperature (T_{grass}) and relative humidity (RH) and RH extended methods for 20 August to 20 September 2011 excluding rain days

	LWD LWS (y) vs LWD IRT (x)	LWD T_{grass} (y) vs LWD IRT (x)	LWD RH (y) vs LWD IRT (x)	LWD RH extended (y) vs LWD IRT (x)
Slope	0.583	0.763	0.710	0.734
Intercept (h)	2.243	-1.065	3.481	4.764
r^2	0.228 ^{ns}	0.654 ^{**}	0.273 ^{ns}	0.287 ^{ns}
RMSE (h)	3.406	1.761	3.674	3.672

^{**} Significant at $p = 0.01$, ns = not significant

Under accelerated exposure, equivalent to five years of high UV exposure, there was no change in sensor function (Campbell Scientific 2009). The manufacturer of the LWS recommends treating the surface of the sensor with a UV blocker every 45 d (Decagon Devices 2010).

Based on the results of this study, the LWS method appears to be accurate and consistent in determining LWD, compared to grass- and IRT-temperature methods. However, according to Savage (2012), the use of the LWS method for determining frost is problematic, with the grass- and/or IRT-temperature methods more desirable for determination of frost duration.

Conclusions

Leaf wetness duration (LWD) measurements using collocated LWS units were consistent. The RH and extended RH methods for estimating LWD yielded the largest LWD estimate for the five methods used. The IRT- and grass-temperature methods for estimating LWD involved comparing these temperatures with the dewpoint at 0.1 or 2 m heights. These two methods showed reasonable agreement with the latter underestimating compared to the LWS estimates. The IRT-temperature method showed reasonable agreement of daily LWD with the grass-temperature method. There was poor agreement between the IRT-temperature LWD estimates and the LWS estimates even if rain days were excluded, underestimating for LWD < 5.5 h, although there were days for which LWS units registered no LWD with the IRT-temperature method indicating surface wetness and vice versa. Theoretically, the IRT-temperature method should yield the correct estimate of LWD and has the advantage of a greater surface-area representation, but the method is more expensive and requires RH data for a sensor adjacent to the surface. To increase the value of AWS measurements, AWS systems should also include grass temperature that could possibly be used to estimate LWD if RH measurements are also available. Furthermore, timeous e-mail and SMS alerts with near real-time data and graphics of LWD for the current day, week and month displayed on the internet, as used in this investigation, would considerably enhance the data product.

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Title **ESTIMATION OF SUNSHINE DURATION FROM SOLAR IRRADIANCE MEASUREMENTS FOR IMPLEMENTATION INTO A WEB-BASED ENVIRONMENTAL MONITORING SYSTEM**

Category **Agrometeorology / Agrometeorologie**

Version **1**

Presented by **Savage (savage@ukzn.ac.za)**

Uploaded on **08 November 2012**

Description

Agrometeorologist, Senior Professor

Content

ESTIMATION OF SUNSHINE DURATION FROM SOLAR IRRADIANCE MEASUREMENTS FOR IMPLEMENTATION INTO A WEB-BASED ENVIRONMENTAL MONITORING SYSTEM

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INTRODUCTION

Sunshine duration data are used as a simple description of the climate of a site and surrounding area which has economic implications on tourism and human health as well as for estimating diffuse irradiance. There is also a long standing tradition of sunshine duration (SD) measurements at weather stations for inclusion in daily weather data. The need to replace the manual method of SD measurement with an accurate estimation using automatic weather station measurements is apparent.

MATERIAL AND METHODS

Three commonly used algorithms for determining SD from 2-minute solar irradiance measurements were used in this study, at the University of KwaZulu-Natal (UKZN) weather station (Pietermaritzburg, KwaZulu-Natal, South Africa), for the period 01/06/2011 to 31/05/2012. Additional data from Cedara were also used for model testing. The accuracy of the Royal Dutch Meteorological Institute (KNMI) and Campbell Scientific (CS) algorithms were compared to an algorithm used by the World Meteorological Organisation (WMO). The near real-time SD data could be viewed or downloaded using the Internet: <http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Sunshine>

RESULTS AND DISCUSSION

Although the WMO and KNMI methods showed good agreement (coefficient of determination of 0.99), the KNMI SD estimation presented a significant daily root mean square error (RMSE) of 0.89 h. This was attributed to incorrect locational correlation coefficients and not to the previously hypothesised miscalculation of the solar elevation angle. Seasonal correlation coefficients were then produced for the UKZN study site to decrease the daily RMSE to 0.32 h. Monthly correction equations were used to increase the accuracy of the CS algorithm for use at the UKZN weather station. The 'corrected' algorithm has been successfully implemented into the web-based environmental monitoring system and has been tested against the WMO results for June, July and August 2012, generating a RMSE of 0.46 h with a coefficient of determination of 0.99.

CONCLUSIONS

All methods for estimating SD showed good correlation although the KNMI algorithm underestimated SD during winter. The WMO algorithm was determined to be the standard although complex. Therefore the CS algorithm was used for the web-based system

ACKNOWLEDGEMENTS

The UKZN Teaching and Learning Office and the NRF funded the web-based system. The WRC funded some of the equipment used in this research.

Keywords: Diffuse radiation, near real-time radiation measurements

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Title **A WEB-BASED MICROCLIMATIC MEASUREMENT AND EVAPORATIVE COOLING CONTROL SYSTEM IN A FORESTRY NURSERY**

Category **Agrometeorology / Agrometeorologie**

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Uploaded on **08 November 2012**

Description

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Content

INTRODUCTION

Protected environment structures such as greenhouses and shadenetting are an option to address the problem of many weather hazards and improve control of the microclimate. Evaporative cooling may be an option to reduce inside temperatures. In this study, that utilises a web-based data and information system for sharing of measurements and display of the shadenet environmental conditions in near real-time, the effectiveness of automated and environmentally-controlled evaporative cooling is investigated.

MATERIAL AND METHODS

Air temperature, atmospheric vapour pressure, solar irradiance, wind speed and leaf wetness duration, measured using a dielectric leaf wetness sensor, were measured every 2 and 60 min. A datalogger was programmed to control evaporative cooling of *Eucalyptus dunni* seedlings. The solenoid valve was controlled based on the measured shadenetting microclimate and leaf wetness. The measured near real-time data was displayed using a web-based system. The data could be viewed or downloaded using the Internet:

http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=ICFR_nursery

The automated evaporative cooling system was compared to timer-based system within the shadenetting.

RESULTS AND DISCUSSION

The automated evaporative cooling (AEC) system was effective at reducing air temperature inside the shadenet. Water savings was also noticed from the system compared to the timer-based system. The AEC system over- and under-irrigated at high and low air temperatures respectively. AEC plants showed poor growth early in the season during system setup, but plants showed significant improvements later in the season. The study showed that AEC can be used with success in evaporatively cooling the seedlings.

CONCLUSIONS

Water wastage was noticed in the timer based system since it was programmed to sprinkle water at fixed time of the day. For example water sprinkling on rainy days or at lower air temperatures. AEC system applied 4 mm of water per day on hot days compared to a timer system that applied a fixed 8 mm of water on daily basis.

ACKNOWLEDGEMENTS

Assistance from ICFR staff Drs S. Dovey, L. Titshall and M. Light, Mr I. Gordon and R. Garner, Ms Z. Ngubane of the ICFR and Mr G. Dewar (UKZN) for construction of the solenoid controller is gratefully acknowledged. Funding from the ICFR is acknowledged. The UKZN Teaching and Learning Office funded the web-based system.

Keywords: Leaf wetness, microclimate control, nursery microenvironment

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Category **Agrometeorology / Agrometeorologie**

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Uploaded on **05 November 2012**

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Senior Professor, Agrometeorologist, UKZN

Content

WEB-BASED NEAR REAL-TIME SURFACE ENERGY BALANCE SYSTEM ABOVE SHORT GRASS

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INTRODUCTION

Increasingly, near real-time evaporation and surface energy fluxes and micrometeorological data using relatively inexpensive methods are required, for example, for comparison with satellite flux estimates or for use when remotely-sensed estimates are compromised by the occurrence of cloud, particularly for summer-rainfall areas. In this work, methodology and results for near real-time estimation of evaporation are reported using temperature-based methods for obtaining sensible heat flux (H) with unattended updates on a web-based system.

MATERIAL AND METHODS

Net irradiance was measured above short grass at Tower 1 using a four-component net radiometer with soil heat flux measured using a self-calibrating heat flux plate. For measurement of H at Tower 2, two unshielded type-E fine-wire thermocouples were positioned at 0.46 m above the soil surface. Measurements were at 10 Hz with calculations of H by surface renewal (H_{SR}), temperature variance (H_{TV}) (including stability-correction using air temperature skewness) and SR-dissipation theory (H_{SRDT}) performed in near real-time and displayed on the Web. For SR and SRDT methods, lag times of 0.4 and 0.8 s were used. An iterative procedure, applied in the logger program, was used to calculate the air temperature ramp amplitude and the (sum of) quiescent and ramping periods from which H_{SR} and H_{SRDT} were calculated. For the TV method, the mean, variance and skewness of air temperature were calculated from high frequency air temperature measurements from which H_{TV} was calculated in near real-time. Dataloggers of Towers 1 and 2 were connected via COM ports. A radio was connected to the datalogger at Tower 1 and another radio on a nearby building which was in turn connected to a server running software for display of near real-time fluxes, including evaporation, and totals for current week/month.

RESULTS AND DISCUSSION

The SRDT method underestimated H compared to SR and TV (with skewness) methods. With adjustment for stability using skewness, the TV method showed good agreement with the SR method.

CONCLUSIONS

A web-based shortened surface energy balance system was used to determine the latent energy (evaporation) from net irradiance, soil heat flux and H, the latter using SR or TV methods. Current daily, weekly and monthly totals, updated frequently, are made available on a web-based system:

<http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Energy%20balance>

ACKNOWLEDGEMENTS

UKZN Teaching and Learning Office, NRF and WRC funded this research.

Keywords: Dissipation theory, surface renewal, temperature variance

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Agrometeorologist, Senior Professor UKZN

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WEB-BASED SYSTEM FOR NEAR REAL-TIME AGROMETEOROLOGICAL APPLICATIONS

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INTRODUCTION

A web-based teaching, learning and research system was developed for near real-time agrometeorological and environmental applications. The system displays data in the form of tables and graphs using field-based measurement systems including: automatic weather station (AWS), carbon dioxide and water vapour concentrations, energy balance, ETo, infrared thermometry, radiation (including diffuse), radiation balance and temperature station, encompassing agricultural, earth and environmental sciences. The main objectives are to present the system details and to use it for various near real-time teaching and research applications in agrometeorology: 1. estimation of leaf wetness duration (LWD) above a short-grass surface; 2. estimation of frost duration; 3. early-prediction of surface, grass and air temperature minima based on sub-daily pre-dawn measurements; 4. surface energy balance using surface renewal, temperature variance and dissipation theory; 5. measurement of forestry nursery microclimate, and control.

MATERIAL AND METHODS

The main station, four inter-connected datalogger stations and two towers formed the basis for the system and was setup at the Agrometeorology site, Pietermaritzburg, KwaZulu-Natal. Shortened surface energy balance components were measured in near real-time using surface renewal (SR), temperature variance (TV), and surface renewal-dissipation theory (SRDT) methods. For SR, a real-time iterative procedure was used. Radiation balance was measured using a four-component net radiometer. Dielectric leaf wetness sensors (LWS) and a grass minimum thermometer were used for frost and LWD.

RESULTS AND DISCUSSION

Measurements, including air temperature profile, water vapour and carbon dioxide concentrations, frost duration, LWD, nursery conditions, and soil water content were displayed in various information screens (<http://agromet.ukzn.ac.za:5255>). The LWS method was

consistent in determining LWD. The LWS method for determining frost is problematic, with the grass- and/or IRT-temperature methods more desirable for frost duration.

CONCLUSIONS

To increase the value of AWS measurements, AWS systems should include grass temperature for frost determination and possibly also to estimate LWD if relative humidity measurements are also available. Furthermore, timeous email and SMS alerts with near real-time data and graphics of LWD for the current day, week and month displayed on the Internet, as used in this investigation, would considerably enhance the data product. The web-based system is useful for demonstrating, to under- and postgraduates, different agrometeorological and environmental applications.

ACKNOWLEDGEMENTS

Support of the UKZN students of 2011 is acknowledged. UKZN Teaching and Learning Office funded this research.

Keywords: Near real-time data and information system

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Air temperature measurement errors

Michael J. Savage¹

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Abstract

Accurate air temperature measurements are required for many different purposes, including global warming impacts. Temperature methods used in this study included: Stevenson screen, 6-plate Gill shield, radiation-shielded and aspirated systems, and unshielded and naturally ventilated 25- and 75- μm fine-wire thermocouples. The 25- μm unshielded thermocouple measurements were most accurate. A web-based near real-time data and information teaching, learning and research system was used to display measurements (<http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Tair%20comparison>). This assisted in establishing the relative magnitude of the air temperature differences between the different systems. Stevenson screen properties are poorly characterised under conditions of varying solar irradiance and low wind speeds.

Keywords

Aspirated air temperature, Gill shield, Near real-time data and information, Stevenson screen, Unshielded fine-wire thermocouple.

Introduction

The Stevenson screen, constructed of wood with a double-louvered design, has been used for the measurement of air temperatures for almost 150 years. More recently, plastic has been used since it is more durable than wood and more maintenance-free (Perry *et al.*, 2007). The standard for the height of the thermometers for air temperature measurements is between 1.25 and 2 m above the ground (World Meteorological Organization, 2010). Most automatic weather station (AWS) systems use Gill radiation shields, usually either six-, ten- or twelve-plate at a 2-m height, for air temperature and relative humidity observations.

Increasingly, international weather services are aspirating their air temperature sensors – also referred to as active systems. Active systems involve the forced movement of air, using a fan or a blower, across a temperature sensor that is also usually radiation shielded. In theory, an active system yields an air temperature representative of a much larger volume of air forced across an air temperature sensor than passive systems such as a Stevenson or a Gill shield. In South Africa, however, there are few instances of routine active air temperature measurement systems.

The aim of the research was to inter-compare passive and active air temperature measurement systems and measurements, including fine-wire thermocouples, using a variety of sensors exposed in different ways. In this study the most common methods of exposure, such as Stevenson screen or 6-plate Gill shield passive systems, are compared with a naturally exposed and naturally ventilated 25- μm fine-wire thermocouple which was used as the reference standard. A secondary objective was the near real-time display of measurement comparisons in an open web-based teaching, learning

and research system so as to assist with the immediate and continuous comparison with the reference standard.

Materials and Methods

Air temperature data using a passive Stevenson screen containing a 30-gauge chromel-constantan (type E) thermocouple (TC), were collected for almost a year. Five meters away, a horizontal pole maintained at a height of 2 m, was used to support a number of air temperature measurement systems and sensors (Table 1). A commercially-available aspirated and radiation-shielded system also included a thermistor. A six-plate Gill radiation shield was used together with a passive Vaisala (Helsinki, Finland) CS500 combination air temperature and relative humidity instrument. Fine-wire thermocouples of various diameters, 25- and 75- μm , were also used in passive mode, without shielding.

The air temperature measurement system was part of the Agrometeorological Instrumentation Mast (AIM) System, a teaching, learning and research system for the

Table 1 Details of some of the air temperature measurement systems and sensors used.

System	Sensors	Mode
Stevenson screen	Thermocouple (TC)	Passive
Six-plate Gill radiation shield (RM Young, model 41303, USA)	Vaisala, model CS500, naturally ventilated	Passive
Aspirated radiation shield system (home-made) [Asp_UKZN]	TC (type-E, model TT-E-30, Omega, USA)	Active
Aspirated radiation shield system (RM Young, model 43502, USA) [Asp_RMY]	TC	Active
Fine-wire thermocouples [TC_25, TC_75]	Unshielded, naturally ventilated 25- and 75- μm diameter	Passive

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near real-time display of data and information for the agricultural and environmental sciences, of the University of KwaZulu-Natal Pietermaritzburg campus.

The AWS measurements were performed every 15 s and averaged, sampled, totalled or wind-vectored every two minutes. Measurements, from sensors attached to a 3-m mast, included solar irradiance, air temperature, relative humidity, wind speed, wind direction and rainfall.

The master datalogger system and its attached radio were connected to an antenna in line-of-sight with another antenna on top of a nearby building. This allowed connection of the receiver radio to a computer server connected to the internet. The master logger was hard-wired to the air temperature station datalogger in a manner that allowed sharing of the same radio for data telecommunication. Commercially-available software was used to schedule the data collection from both dataloggers and to display in near real-time temporal air temperature difference graphs as well as regression graphs.

All sensors were attached to an AM16-32 multiplexer (Campbell Scientific, Logan, USA) which was in turn connected to a Campbell CR1000 datalogger. All measurements were sampled every 30 s and these were averaged and stored in memory every two minutes.

Results and Discussion

If a passive air temperature sensor is inadequately shielded from incoming (direct and diffuse) and reflected solar irradiances and sky and ground infrared irradiances, radiation errors may occur. Radiation error for passive and active air temperature measurement systems is governed by the radiative, solar and infrared irradiances, and convective properties of the radiation shield if used and/or sensor characteristics under conditions of varying solar irradiance, air temperature wind speed and relative humidity. Other influences determining air temperature measurement error include screen/shield/ sensor characteristics that may impact on radiative and wind speed influences experienced by the air temperature sensor, sensor accuracy and the sensor time response. In this study, the sensor influences were eliminated by using the same sensor type (30-gauge thermocouple) except where otherwise indicated.

Determining the extent of any possible radiation error (Harrison, 2010) is difficult, may change the radiative and convective environment of the screen/shield/sensor combination and is also time consuming and was avoided in this work. Instead, initially, the web-based system was used to display in near real-time, in a temporal graph, the air temperature measurements from the different systems. This display system allowed for easy identification of measurements greater than others for a variety of conditions including high solar

irradiances, low wind speed, and less than others during night-times.

Under high solar radiative and low wind speed conditions, systems that resulted in air temperature measurements greater than others were regarded as inadequately radiation shielded. Logically, using the same sensor type, a number of measurements greater than those for a given system can only be due to inadequate radiation shielding of the former and/or reduced air flow imposed by the screen or radiation shield. A consistently lower air temperature, for a given reference system compared to others, is an indication of the correct air temperature for the reference system. In this manner, it was easy to identify which measurement system yielded the lowest air temperatures during high solar irradiance conditions.

The 25- μ m exposed thermocouple usually yielded the lowest air temperature measurements under conditions of high solar irradiance and also when wind speed was low. Confirmation of the best measurement system was demonstrated using temporal difference plots for each system using the 25- μ m unshielded and naturally ventilated fine-wire thermocouple as the standard reference. The difference plots were displayed in near real-time using the web-based system (Fig. 1). All measurement comparisons made were therefore against the corresponding 2-min average 25- μ m air temperature measurement.

For a 30-day period of measurements, the RMSE for the commonly-used Stevenson screen vs. 25- μ m measurements and the 6-plate vs. 25- μ m comparisons were 0.347 and 0.534 °C respectively (Figs. 2a, b respectively). There was a much improved agreement between corresponding measurements from the 25- μ m fine-wire TC and both of the two aspirated and radiation-shielded systems. Typical root mean square errors (RMSE) of 0.156 and 0.175 °C for the UKZN and RMY active systems respectively were noted (Figs. 2c, d respectively). Of all systems used and compared with 25- μ m thermocouple air temperature measurements, the UKZN aspirated system regression data (Table 2) resulted in a slope value closest to 1, an intercept value closest to 0 °C, a coefficient of determination (R^2) closest to 1 and the lowest RMSE. In the case of the 6-plate passive measurements, a different sensor was used – the Vaisala CS500 housed in the 6-plate used a PT1000 sensor class B (within 0.4 °C at 20 °C), yielding increased RMSE (Table 2).

Examination of the daytime air temperature measurements showed that for much of the time, passive measures of air temperature such as in a Stevenson screen generally exceeded those measured using the 25- μ m fine-wire thermocouple by as much as 1.5 °C (Fig. 3, upper). Stevenson screen air temperatures, compared to the other measures, were slow to increase following sun-

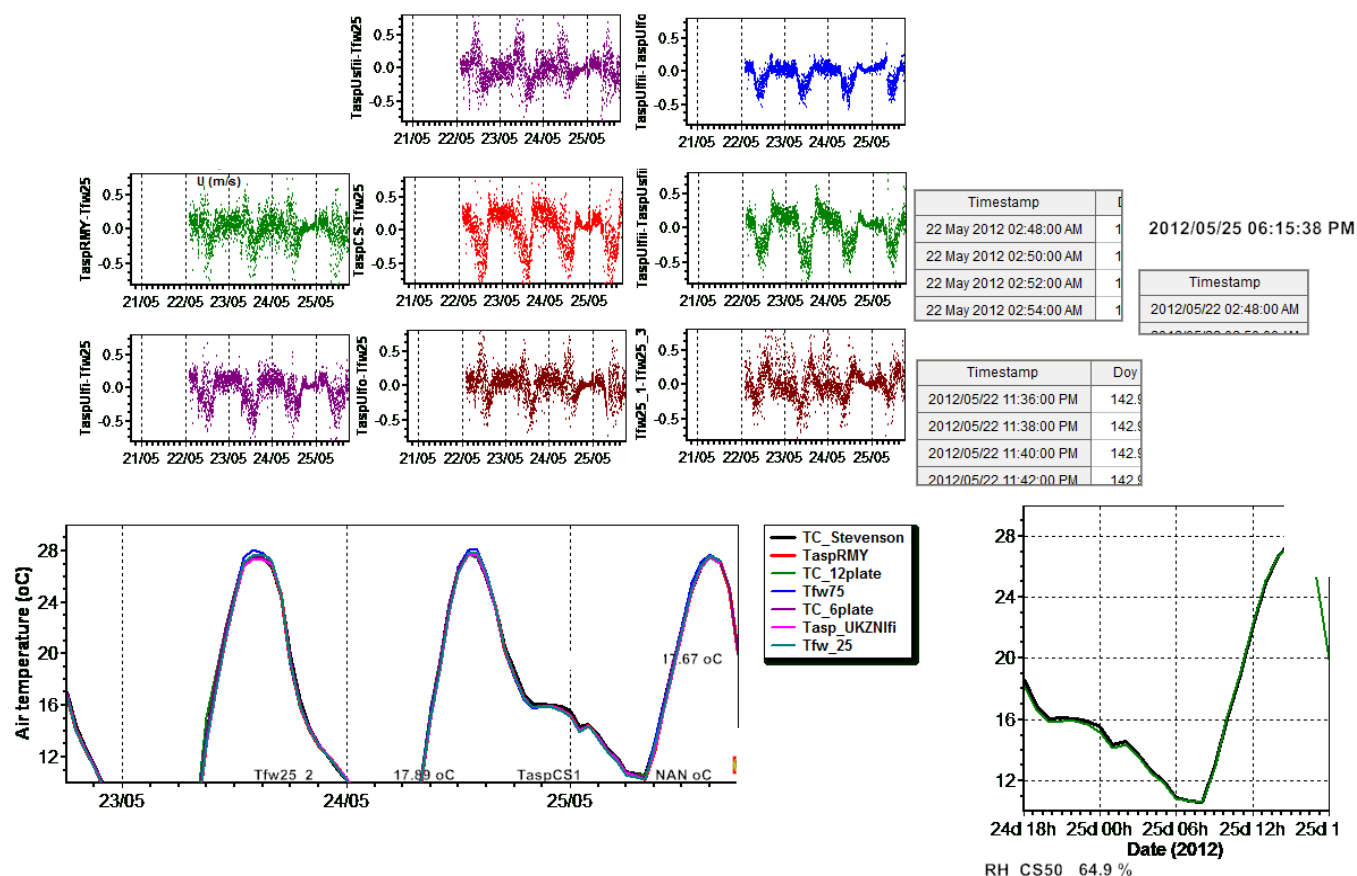


Fig. 1 A screen-shot of the air temperature comparison screen from the AIM system. Air temperature difference graphs displayed in near real-time allowed for easy identification of measurements least affected by radiation and reduced convective influences.

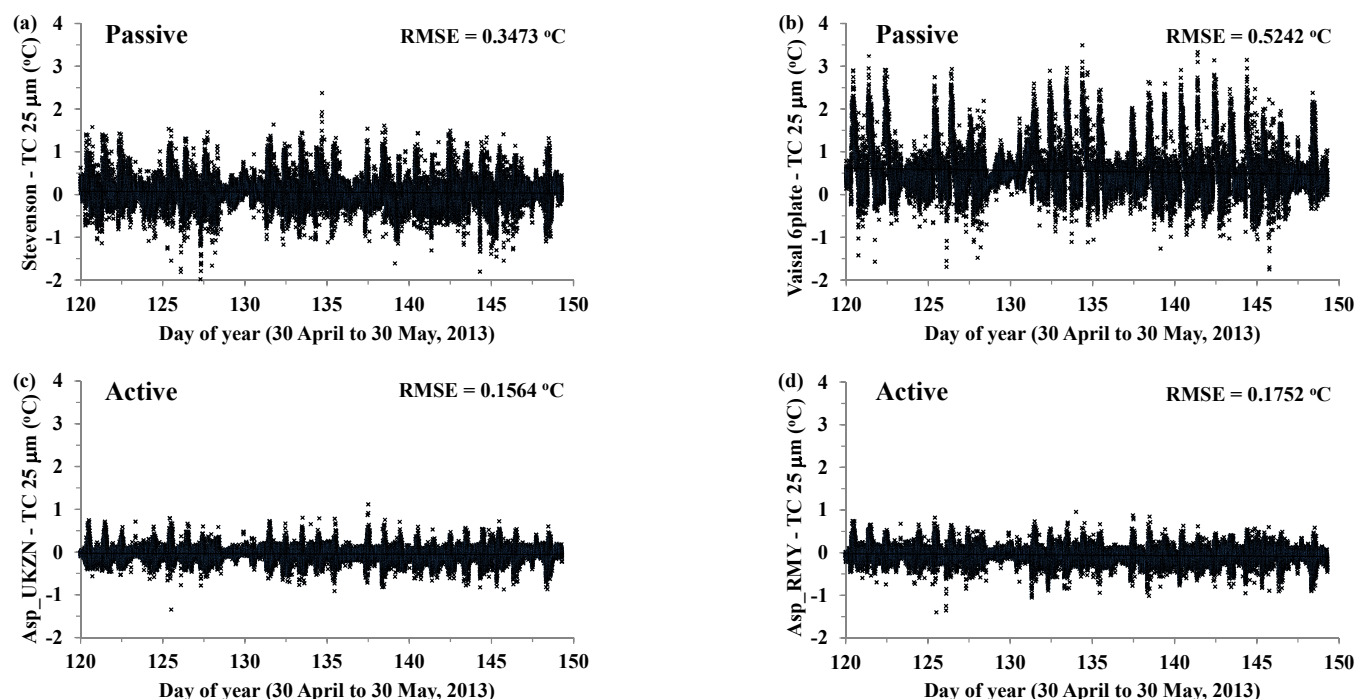


Fig. 2 Temporal plot of the 2-min temperature differences between various passive (P) and active (A) systems and the corresponding thermocouple (25-μm) air temperature (P) 31 days (30th April to 30th May 2013) for (a) Stevenson screen (P); (b) Vaisala in a 6-plate (P); (c) aspirated and radiation shielded UKZN system (A) and (c) aspirated and radiation shielded RM Young system (A).

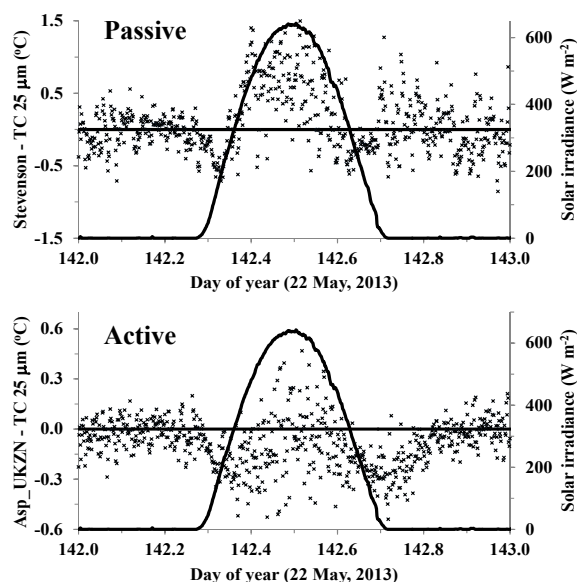


Fig. 3 Temporal plot of the 2-min air temperature differences for a passive (Stevenson screen, upper graph) and an active (UKZN, lower graph) system for 22nd May 2013 relative to the 25- μ m TC air temperature. Note the change in scale for the leaf-hand y-axis for upper and lower graphs.

Table 2 Regression statistics for measurement comparisons from 30th April to 30th May 2013 ($n = 21325$) for various sensors (y) using 25- μ m thermocouple measurements as a standard reference (x).

Sensor	Slope	Inter- cept ($^{\circ}\text{C}$)	R^2	RMSE ($^{\circ}\text{C}$)
Stevenson	1.0101	-0.1046	0.9962	0.347
Vaisala 6- plate	1.0340	0.0161	0.9919	0.524
AspUKZN	0.9971	0.0011	0.9992	0.156
AspRMY	1.0036	-0.1123	0.9990	0.175
TC 75- μ m	1.0101	-0.1252	0.9991	0.173

R^2 : coefficient of determination; RMSE: root mean square error; Asp: aspirated measurement system

rise and slow to decrease after sunset (Fig. 3, upper). Active systems demonstrated much reduced air temperature differences that were almost random during the daytime but with noticeable sunrise and sunset influences (Fig. 3, lower). These influences could be due to the transport of shield-stored heat to the temperature sensor whenever there was a sudden change in the net irradiance. Sunrise and sunset, and scattered cloud, would cause such changes.

The study demonstrates that, compared to passive unshielded fine-wire TC and active systems, passive systems are poorly characterised under conditions of varying solar irradiance, and for low wind speeds. Compared to the 25- μ m fine-wire measurements, the Stevenson screen and 6-plate measurements showed RMSEs much greater than that of the aspirated systems.

It is recommended, that at first-order weather stations, aspirated air temperature measurements be employed instead of using a Stevenson screen or a 6-plate Gill shield.

The correction for radiation error in a spatial network of passive air temperature sensors, as attempted by Mauder *et al.* (2008), requires further research.

Conclusions

Under high solar radiative and low wind speed conditions, unshielded 25- μ m fine-wire thermocouple air temperature (passive) measurements were consistently less than air temperatures from other passive measurement systems that included a Stevenson screen, 6-plate and 75- μ m fine-wire thermocouple. Measurements from the two (active) aspirated and shielded systems used were much closer to the 25- μ m air temperature measurements, with measurement differences within 0.5 $^{\circ}\text{C}$. Of all systems used, with the passive 25- μ m air temperature thermocouple measurements as the reference standard, the UKZN aspirated system regression data resulted in a slope value closest to 1, an intercept value closest to 0 $^{\circ}\text{C}$, an R^2 closest to 1 and the lowest RMSE (0.156 $^{\circ}\text{C}$). The commercially-available aspirated system yielded an RMSE of 0.175 $^{\circ}\text{C}$, 0.347 $^{\circ}\text{C}$ for the passive Stevenson screen measurements, 0.524 $^{\circ}\text{C}$ for the passive Gill 6-plate, and 0.173 $^{\circ}\text{C}$ for 75- μ m measurements. The active systems not only had the lowest RMSE but also yielded by far the least bias in air temperature measured, relative to the 25- μ m exposed and naturally-ventilated thermocouple, compared to the passive systems.

Acknowledgements

Financial support from the University of KwaZulu-Natal Teaching and Learning Office, the National Research Foundation and the Water Research Commission is gratefully acknowledged.

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A near real-time fire danger index measurement system

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Abstract

The objectives of this research included the development of a system for improved monitoring of meteorological conditions conducive to fire. The nomogram and lookup table lowveld fire danger index (FDI) system was replaced by mathematical functions programmed into a datalogger. Near real-time results of FDI were displayed in a web-based teaching, learning and research system (<http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Fire%20danger%20index>). Historic automatic weather station data were used together with a fuzzy logic system for determining Berg wind conditions. This involved use of wind direction and diurnal sinusoidal functions for solar irradiance, air temperature, relative humidity and wind speed, for various locations.

Keywords

Berg winds, Near real-time fire danger index, Fire meteorology, Disaster management

Introduction

Fire plays an important part in nature by providing a number of regulating services and by ensuring the integrity of many earth systems (Keywood *et al.*, 2013). While fires may have certain environmental benefits, fire disasters result in large financial losses and fatalities every year. A good understanding of conditions conducive to fire danger would assist in improving warning systems that would reduce damage and fatalities that fires cause every year.

Currently in South Africa, the National Veld and Forest Fire Act (Act 101 of 1998) specifies the prevention of veld, forest and mountain fires through a National Fire Danger Rating System under the responsibility of the Department of Water Affairs and Forestry.

The main objective included the development of a system in near real-time (hourly) for improved monitoring of meteorological conditions conducive to fire development and developing an improved understanding of the meteorological conditions during periods of fire danger. Near real-time results of the lowveld fire danger index (FDI) for Pietermaritzburg, South Africa were calculated and then displayed in an open web-based teaching, learning and research system. A secondary objective involved determining when conditions were conducive for Berg winds, on an hourly basis, using a fuzzy logic system applied to historic data from four locations in KwaZulu-Natal, South Africa.

Materials and Methods

The lowveld fire danger index (FDI) is based on a nomogram used to convert air temperature and relative humidity to a burning index (BI). The BI is then adjusted upwards, for wind speeds greater than 2.3 m s^{-1} , using a lookup table. The FDI is then calculated from the

adjusted BI, elapsed days since last rainfall and the daily total rainfall. The nomogram for BI was converted into an equation using multi-linear regression analysis and the lookup table replaced by datalogger code eliminating the need for manual calculation of the BI and FDI and allowing for it to be programmed into a near real-time monitoring system.

An automatic weather station (AWS) system, attached to a 3-m mast, was used as the basis for the measurements and the hourly calculation of FDI. The system was part of the Agrometeorological Instrumentation Mast (AIM) System, a teaching, learning and research system for the near real-time display of data and information for the agricultural and environmental sciences, of the University of KwaZulu-Natal Pietermaritzburg campus. The AWS measurements were performed every 15 s and averaged, sampled or totalled every hour. Measurements included solar irradiance, air temperature, relative humidity, wind speed, wind direction, rainfall and atmospheric pressure. Most measurements were at 2 m except for rainfall. The rim of the raingauge was maintained at 1 m.

The datalogger system and its attached radio were connected to an antenna in line-of-sight with another antenna on top of a nearby building. This allowed connection of the receiver radio to a computer server connected to the internet. Commercially-available software was used to schedule the data collection and display the data and temporal graphics of the weather conditions, BI adjusted for wind speed and FDI.

A fuzzy logic system that involved the use of diurnal sinusoidal functions for solar irradiance, air temperature, relative humidity and wind speed as well as information on wind direction and atmospheric pressure, when available, was used to determine conditions favourable for Berg winds. For this purpose a sinusoidal function, centred at noon, was used with a defined value at noon to generate a typical diurnal variation in solar irradiance for Berg wind conditions. air temperature, Similarly, for relative humidity (RH) and wind speed a cosinusoidal function, centred at noon, was used with a defined value

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at noon to generate a typical diurnal curve for RH and wind speed for Berg wind conditions. The defined values at noon were 25 % and 1.5 m s^{-1} respectively. For air temperature, the model of Parton and Logan (1980) was used to generate a diurnal curve with a maximum of 27°C specified. For wind direction, only directions between westerly (270°) and north-easterly (45°) were regarded as applicable for Berg wind conditions. The fuzzy logic system was applied using historic hourly weather data from four locations in KwaZulu-Natal (Pietermaritzburg, Ukulinga, Cedara and Baynesfield).

Results and Discussion

The nomogram of the lowveld FDI system was cross-checked with the multi-linear regression function for BI used and programmed into the AWS datalogger. For a wide range of simulated environmental conditions, with the air temperature between 5 and 35°C and relative humidity between 0 and 55% , the differences between the nomogram values and that calculated BI using the mathematical functions were small: slope of 1.012 , intercept 0.312 BI units, $R^2 = 0.999$ (Fig. 1) and root mean square error of 0.4 BI units.

A similar multi-linear regression method was applied to the rainfall correction factor (RCF) lookup table so as to develop a relationship that could be used in near real-time (Fig. 2). The discrete nature of the tabled RCF data resulted in more than one RCF calculated for a given tabled RCF value.

An example of the near real-time display of the FDI screen of the AIM system is shown (Fig. 3). Two graphs of FDI are shown in the web-based system, one for a week and one for the current day. Threshold FDI values of 95 , 71 , and 36 are shown by horizontal lines. The wind speed adjusted BI, which is always less than FDI, is also shown. The calculations for BI, BI adjusted for wind speed, FDI and FDI adjusted for elapsed days since last rainfall were all performed in the datalogger programme. Hourly plots of FDI and other meteorological measurements allow users to follow in near real-time the

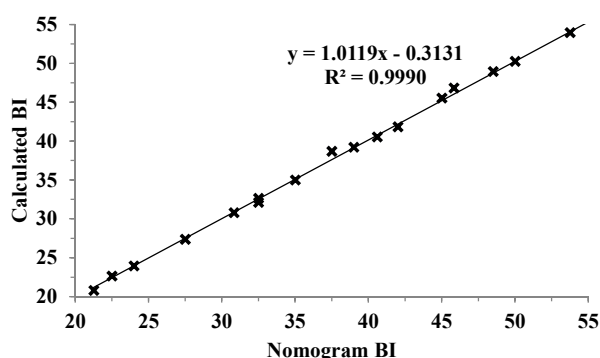


Fig. 1 Regression plot of the burning index (BI) calculated using the nomogram and using a multi-linear regression equation.

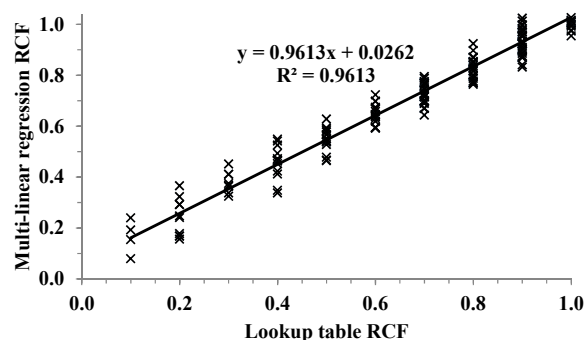


Fig. 2 Regression plot of the rainfall correction factor (RCF) calculated using lookup table and using a multi-linear regression equation.

conditions that would affect fire danger. It would be a simple matter to include alerts, based on the FDI calculated, air temperature, relative humidity, wind speed and the like, that could be emailed to a predefined user list.

Data collected through the web based monitoring system indicated that fire danger was generally higher during late morning and early afternoon periods which is in agreement with the study by Gaffin (2007) on American foehn winds. Prevailing wind speed plays a significant role in fire danger as can be seen by comparing the burning index prior to adjustment for wind speed and after. The adjusted burning index is always greater and the difference appears to peak around midday when the fire danger is greatest.

The fuzzy logic system of identifying Berg wind conditions was applied to (hourly) historic weather data from four locations in KwaZulu-Natal (Table 1). Baynesfield and Ukulinga experienced a greater percentage of Berg wind hours compared to the UKZN AIM and Cedara locations. Cedara experienced the lowest temperature conditions (1.51%) but the greatest percentage of high wind speed conditions. Ukulinga had the greatest number of favourable wind direction events (between west (270°) and north-east (45°) 43% of the time) – a much greater percentage than Baynesfield (34%) and Cedara (29%).

Historical data indicates that Berg winds are not common events in the Pietermaritzburg and Midlands areas – comprising only a small percentage of data duration hours. Between the four historical datasets, the Baynesfield dataset had the greatest duration of Berg winds (1.91% of record) with the Cedara dataset having the lowest duration (0.79%). While windier than the other sites, Cedara was the coolest due to its highest elevation of the four sites.

The lowveld fire danger index (FDI) is determined from air temperature, relative humidity, wind speed and elapsed days since last rainfall (2 mm or more in an hour). A nomogram, converted into an equation, is used for determining the burning index BI and a wind speed adjustment is applied. From the adjusted BI and the elapsed days since last rainfall, FDI is calculated.

An FDI greater than 95 corresponds to extreme fire danger, 71 to 95 to high, 36 to 70 to moderate and less than 35 to low. In the graphs, the wind speed adjusted BI, which is always less than FDI, the FDI and the danger limits are shown.

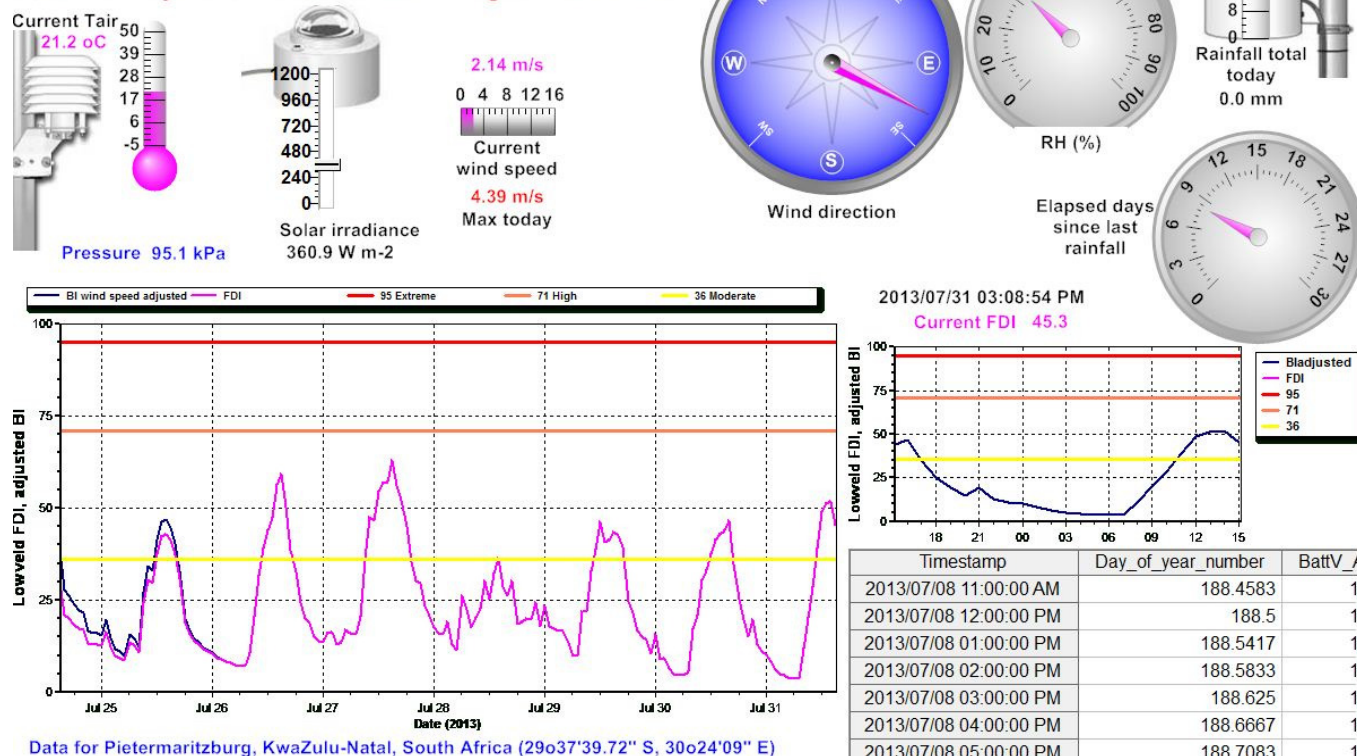


Table 1 The results of the fuzzy logic system for identifying Berg wind conditions, hourly, for various locations in KwaZulu-Natal. The limits of 27 °C and 25 % are set for Berg wind conditions between noon and 2 pm.

UKZN AIM system	May 2011 - present		Baynesfield Estates	April 2008 to May 2010	
	Duration (h)	% of time		Duration (h)	% of time
Berg wind conditions	239	1.57	Berg wind	290	1.91
Air temperature $\geq 27^{\circ}\text{C}$	473	3.12	Air temperature $\geq 27^{\circ}\text{C}$	385	2.53
Wind speed ($> 1.5 \text{ m s}^{-1}$)	5294	34.88	Wind speed ($> 1.5 \text{ m s}^{-1}$)	6406	42.13
Wind direction ≥ 270 or $\leq 45^{\circ}$	3764	24.80	Wind direction ≥ 270 or $\leq 45^{\circ}$	5144	33.83
RH $\leq 25\%$	649	4.28	RH $\leq 25\%$	627	4.12
P $< 94 \text{ kPa}$	8441	55.61			
Record length	15178		Record length	15205	

Cedara	Sept 2002 - May 2010		Ukulinga, Pietermaritzburg	Jan 2001 - May 2010	
	Duration (h)	% of time		Duration (h)	% of time
Berg wind	403	0.79	Berg wind	1415	1.74
Air temperature $\geq 27^{\circ}\text{C}$	769	1.51	Air temperature $\geq 27^{\circ}\text{C}$	1380	1.69
Wind speed ($> 1.5 \text{ m s}^{-1}$)	27707	54.50	Wind speed ($> 1.5 \text{ m s}^{-1}$)	18870	23.16
Wind direction ≥ 270 or $\leq 45^{\circ}$	14860	29.23	Wind direction ≥ 270 or $\leq 45^{\circ}$	35385	43.42
RH $\leq 25\%$	2639	5.19	RH $\leq 25\%$	32120	39.42
Record length	50838		Record length	81490	

Conclusions

Berg winds and fire danger are closely linked and fire danger will be escalated during Berg wind conditions. Using a near real-time web-based monitoring system, the overwhelming financial loss and fatalities may be decreased. The AIM system allowed the near real-time display of hourly FDI, calculated from hourly weather data. The calculations were shown in weekly and daily graphs, together with horizontal lines for the FDI limits for extreme, high, moderate and low fire danger. The fuzzy logic system used allowed historic weather (hourly) data to be assessed for Berg wind conditions for a given location, so as to identify vulnerable sites and therefore fire hazard. Of the four locations chosen in KwaZulu-Natal, Cedara was the least vulnerable due to a lower incidence of high air temperatures. Baynesfield was the most vulnerable due to a combination of air temperature, wind speed and wind direction factors determining Berg wind conditions. Further research should aim at using the system in near real-time and over a large scale utilizing remote sensing data.

Acknowledgements

Financial support from the University of KwaZulu-Natal Teaching and Learning Office, the NRF and the WRC is gratefully acknowledged. Data for Baynesfield, Cedara, and Ukulinga were provided by the Agricultural Research Council. The support and motivation from both the Agrometeorology and Environmental Science disciplines at UKZN, Pietermaritzburg are also gratefully acknowledged.

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Weather warning before KZN fitness test

August 7 2013 at 05:38pm

By SAPA

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Pietermaritzburg - The SA Weather Service issued a warning on the first day of a recruitment fitness test in KwaZulu-Natal, an inquiry in Pietermaritzburg heard on Wednesday.

"The warning they gave was (for) extremely uncomfortable weather," University of KwaZulu-Natal agrometeorologist Michael Savage said.

Savage said when weather conditions were about 26.7 degrees Celsius, and the relative humidity about 40 percent, conditions were uncomfortable for humans.

He was testifying before a commission of inquiry probing the deaths of eight people who took part in a 4km run at the Harry Gwala Stadium in Pietermaritzburg in December.

This formed part of a fitness test for Road Traffic Inspectorate (RTI) job applicants. More than 34,000 people qualified to apply for 90 advertised RTI trainee posts. Of these, 15 600 applicants attended a fitness test on December 27 and a similar number on December 28.

Savage said text messages warning municipalities were sent out.

"The weather service issued a warning the day before. The warning would have gone to online and to public media. All municipalities are part of the sms warning system. When there is a warning one should take precautions."

He said weather conditions on December 27 were adverse. People were advised to be cautious between 9.42am and 6.30pm. Extreme weather conditions were indicated from 1.10pm to 5pm. On December 28 there were only three hours of caution – from 12.04pm to 3pm. There was no extreme caution.

When the temperature goes above 26.7C a caution is issued. Extreme caution is at 32.2C and higher. These are measured with a relative humidity of 40 percent.

Savage said he was shocked that eight people died after participating in the fitness test. He wrote a letter to the Natal Witness newspaper, not blaming anyone, but warning that such incidents should never happen again.

"I still think that for any large event that happens at that time of the year, knowing that it's summer and weather conditions are more humid than in winter, you know you can expect a hot day," he said.

"There should have been water, shade, and medical services."

Sapa

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Aspirant traffic cops wait to run 4km in 30 minutes to pass the fitness test which will qualify them to go into the next round for one of 90 provincial posts. File photo; Supplied

About 200 treated at RTI fitness test

August 8 2013 at 06:30pm

By SAPA

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Pietermaritzburg - Paramedics treated about 200 people on the first day of the KwaZulu-Natal Road Traffic Inspectorate's (RTI) fitness test for job applicants, a commission of inquiry in Pietermaritzburg heard on Thursday.

Thulani Khuzwayo, for the provincial health department, said this excluded participants taken to hospitals.

Participants who took part in the fitness test started collapsing around 10am on December 27, it emerged during his questioning of Prof Michael Savage, an agrometeorologist from the University of KwaZulu-Natal.

The commission is probing the deaths of eight people who took part in a four kilometre run at the Harry Gwala Stadium in Pietermaritzburg. This formed part of a fitness test for RTI job applicants.

More than 34,000 people qualified to apply for 90 advertised RTI trainee posts. Of these, 15,600 attended a fitness test on December 27 and a similar number on December 28.

On Thursday, Savage said weather conditions on December 27 were adverse. People were advised to be cautious between 9.42am and 6.30pm. Extreme weather conditions were indicated from 1.10pm to 5pm.

He said that when people started collapsing at the stadium the organisers should have taken precautions.

"On that day, whether one was a participant or non-participant, the weather became more and more uncomfortable. It became unbearable. At some point someone should have realised a disaster was going to happen."

He said the previous day had been hot. Given that information the organisers should have expected a hot December 27.

Ravenda Padayachee, for the KwaZulu-Natal transport department, told Savage the advertisement for the job had stated that applicants would be subjected to strenuous exercise.

Savage said the advertisement did not mention when this strenuous exercise would take place.

Padayachee said the 90 posts for trainee RTI officers had to be filled in about two months.

He said the advert for the positions ran from November 20 until December 4, and successful applicants had to be ready for admission to the training college on January 14.

Padayachee said the department had frozen posts in November 2009 and it was decided in November 2012 to fill critical positions.

"Trainee officers were categorised as critical posts," he said.

The commission continues on Monday, when a representative of the paramedics is expected to testify.

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SUPPLIED

Aspirant traffic cops wait to run 4km in 30 minutes to pass the fitness test which will qualify them to go into the next round for one of 90 provincial posts. File photo; Supplied

Web-based teaching, learning and research using accessible real-time data obtained from field-based agrometeorological measurement systems

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To enhance teaching and learning in agrometeorology and allied disciplines, a Web-based data and information system was developed. The system uses field-based agrometeorological measurements, from automatic weather, radiation and temperature stations, to collect and display near real-time and previous data in graphs/tables. An important feature is the display of agrometeorological data, information and graphics in the lecture room or laboratory with early-warning capability. Examples include hourly short-grass and tall-crop reference evaporation, sunshine duration, grass-surface radiation and energy balances. The system is applicable to the agricultural, earth and environmental sciences. This study presents the rationale, detail, application and evaluation of the system that is currently used by undergraduate and postgraduate students and staff, to access online data and information for lectures, tutorials, practicals, projects and research. For undergraduates, data can be extracted and manipulated, thereby reinforcing computer literacy, numeracy – including statistical ability – and graphical capabilities. The aim is to ensure that these abilities are improved with users obtaining a deeper understanding of the agroenvironment. More than 75% of respondents of an open questionnaire indicated that the graphical display of data had enabled further understanding of agroenvironmental concepts irrespective of language.

Keywords: seeing data, shared agroenvironmental measurement system, visual literacy

Introduction

Agrometeorology, as an applied technological discipline, is initially challenging to undergraduate students and even postgraduate students. In addition, many of the students have a first language for which the words 'meteorology' and 'agrometeorology' do not exist. The teaching of agrometeorology presents significant challenges due to the use of mathematics, physics, meteorology and technology in agricultural and environmental applications.

Climate change is upon us and yet many, students in particular, have a poor conception of their environment, poor numeracy ability, poor interpretation of the graphical display of data and limited ability of statistically manipulating data. Often, this poor conception is due to a lack of exposure to data associated with important elements making up the environment. Our experience, over many years at many different institutions both locally and internationally, has been that students are not adequately exposed to information and data that directly reflects the state of the environment around them and may therefore leave university with a degree that has not sufficiently equipped them with a first-hand understanding of the environment. They are therefore unable to easily relate to the problems of our uncertain agricultural and environmental future. Students also lack a basic understanding of important agroenvironmental concepts such as temperature (for example, air temperature, temperature gradient, temperature scales and rate of change of temperature) and more complex concepts

such as solar irradiance, surface radiation balance and the graphical display of information in various forms. Often students have difficulty in 'reading' graphs (Lowe 2000; Aoyama and Stephens 2003; Aoyama 2006), and the difference between a temporal graph and a regression graph, for example, is not appreciated. These deficiencies are evident when students start to collect agroenvironmental data for their practicals and projects or are assigned tutorials. Also relevant to the current study and pertinent to South African students is the question: does the use of graphics and data in teaching and learning transcend language differences between students and between student and staff, more than does written text and other resources?

Lowe (2000) and Felten (2008) use the term 'visual literacy', stating that it is an essential component of science and technology education. Arcavi (2003) refers to this lack of interpretation of data as 'seeing the unseen – in data' and that '...seeing..., with the aid of technology... may also sharpen our understanding, or serve as a springboard for questions which we were not able to formulate before'. Using observationally-based climatic data sets and focusing on the (possible) cause(s) of global warming, Schweizer and Kelly (2005) found that students used observationally-based climatic data sets supplied in a variety of ways – such as '(for) supporting their own argument; negating the argument of the opposing side; presenting challenges to the opposing side; and raising new scientific questions'.

This work attempts to link agroenvironmental measurement systems to collected data and to their display via graphs and tables that are easily accessible to the lay public, undergraduate and postgraduate students and staff for a range of disciplines. The implemented system emphasises 'seeing data' and 'visual literacy' through interweaving computer literacy, mathematical manipulation and basic statistical manipulation to near real-time agricultural, earth and environmental sciences data.

Discussing the next decade of environmental science in South Africa, Shackleton et al. (2011) state: 'new graduates will be ill-equipped to deal with the new environmental challenges and thinking as they emerge, and research programmes will be unable to contribute to meaningful knowledge frontiers or solutions. This places a particular responsibility on universities to adopt a dynamic approach to teaching and research around environmental science, as well as the need for frequent stock taking and alignment of environmental science programmes with the latest developments internationally.' The Web-based system reported on here (<http://agromet.ukzn.ac.za:5355>), and largely based on agrometeorological and agroenvironmental applications, is pillared on the approach of 'a dynamic approach to teaching and research' relevant to a range of disciplines. These approaches are in keeping with the recent Council for Higher Education (2013) report that 'The conditions on the ground dictate a fundamental systemic review of the undergraduate curriculum.' The work described in this paper has redefined the teaching and learning approaches, specifically that used for the teaching of agrometeorology at undergraduate level, and redefined the approach used for undergraduate and honours projects.

We describe the implementation, and assessment, of a near real-time Web-based teaching, learning and research system that would allow undergraduates (and postgraduates and academic staff) to view agrometeorological and other agroenvironmental data in table and graphical form, and extract data for downloading. The results of a questionnaire on system usage, friendliness and improvement are presented. The system allows lecture material to be directly accessed using near real-time events and historical data relevant to the following disciplines: agricultural plant sciences (crop science, horticultural science and plant pathology), agricultural engineering, agrometeorology, biological sciences (ecology), environmental sciences, geography, geology, hydrology, irrigation science, soil science and others. The product is a field-based, meteorological, agricultural and environmental sciences system linked via radio telecommunication to a laboratory computer connected to the Internet with regular uploads of data in table form and graphics. Pre-programmed alerts to interested students, based on near real-time measurements and calculations, are in various forms including e-mails, file transfer protocol (FTP) or indicator buttons displayed by the graphical uploads to the Internet.

The main aim of the research was the development, testing and evaluation of use of a Web-based teaching, learning and research early-warning system for selected agrometeorological and environmental applications, data visualisation and visual literacy, so as to provide a near

real-time agricultural, earth and environmental sciences data and information resource system mainly for use by undergraduate and postgraduate Agriculture and Science students. The innovation of the work is the integration of the various applications across many disciplines and accessibility of near real-time agricultural and environmental data and information in a laboratory, LAN laboratory, lecture room or using a cell-phone or Wi-Fi. We are unaware of any similar system in Africa for the purposes described. The system developed at Utah State University (<http://weather.usu.edu/htm/publicity>), the first of its kind on a university campus and also launched in 2011, focuses on the reporting of agroenvironmental measurements but does not allow data downloads by students.

Materials and methods

A three-metre mast with a pole extending to 8 m was used for attachment of sensors, enclosures and antenna. The main mast is used for broadcast of data and information for the Web-based system. A second mast for undergraduate, postgraduate and staff projects contains a second automatic weather station (AWS) system as a backup and as a cross-check of AWS data from the main mast. An air temperature and radiation station were added for teaching and research purposes. At each station, additional dataloggers were added by connection to the input/output or RS232 ports of any of the existing dataloggers (Table 1) using a three-core cross-over cable.

Each datalogger was set to a (unique) proprietary address protocol, similar to the Internet Protocol (IP) for computers, with a baud rate of 38 400. This protocol allowed transparent communication between a base station PC to and/or from different dataloggers. The datalogger at the main mast with connected antenna and radio acts as the 'master' datalogger with all others 'slave' dataloggers. The slaves did not require an antenna or radio but used two control ports configured for RS232 communication for connection of one datalogger to another, saving costs for each added datalogger. For each datalogger, a schedule protocol was defined. Datalogger communication software enabled scheduled downloads with defined timing intervals for primary and secondary retries.

An open-ended questionnaire was used to assess the value and use of the system and to invite comments by students and staff on improvements for the future. Open-ended questions give the respondent the opportunity to express their own thoughts (Sawyer 1992) but since the answers are many and varied, the analysis is usually difficult or at least very time-consuming. Open-ended questions were chosen since they gave the opportunity of varied answers particularly in the case here where the aim was to obtain comment on usage, purpose and access in an unbiased manner. The paper version of the questionnaire had a total of 48 respondents with 15 respondents for the e-mailed version. A two-week period was given for completion with two reminders, the last reminder 4 d before the deadline for return. A similar questionnaire was used the following year (2013) except that additional questions about the role of language were included.

Table 1: Details of the various parts of the Web-based system located in the field

Stations	Mast 1 (main mast) ¹	Mast 2	Temperature station	Radiation station
Sensors	Solar irradiance (CM3 ³), relative humidity and air temperature (combination instrument ³), wind speed and direction instrument ⁴ model 03001, raingauge ⁵ , SDI relative humidity and air temperature placed at 100 mm above soil surface in seven-plate radiation shield (combination instrument model CS215 ⁶), infrared thermometer ⁷ , barometric pressure sensor (model CS106 ⁸), carbon dioxide/water vapour infrared analyser ⁹ , leaf wetness sensor ⁹ , soil water content ¹⁰ , four-component net radiometer (CNR1 ²), 16 differential type-E thermocouples for measuring: grass minimum temperature, air temperature in seven-plate radiation shields at heights of 0.1, 1, 2 to 8 m above soil surface and soil temperatures at 0.01, 0.02, 0.05, 0.1 and 0.2 m as well as the average soil temperature between 0.02 and 0.06 m depths	Solar irradiance (CM3 ³), relative humidity and air temperature (combination instrument ³), wind speed and direction instrument ⁴ (connected to CR1000 ⁶)	Relative humidity and air temperature (combination instrument ³), aspirated and radiation-shielded air temperature thermocouples (models 43502 ⁴ (one) and two of ASPTC ⁶), in-house constructed thermocouple and aspirated and radiation shielded air temperature thermocouples (30-gauge) also placed in seven plate and 12-plate Gill shields ⁴ and unshielded and naturally ventilated sensors ¹¹ including fine-wire type-E thermocouples (12.5, 25 and 75 µm diameter). Thermocouples placed in a Stevenson screen and in the various aspirated radiation shields	Radiation instruments for measurement of solar irradiance (CM11 ¹² secondary radiation standard) and diffuse irradiance using a CM3 shaded by an in-house radiation band requiring adjustment every 10 d
Logging equipment and power details	CR1000 (101) and AM16-32 multiplexer ⁶ connected to two 14 A h batteries and a 40 W solar panel	CR1000 (102) and multiplexer CR3000 (301)	CR1000 (103) connected to two 120 A h deep-cycle batteries, one 14 A h battery, a 40 W solar panel and a mains battery charger	CR800 ⁶ (801) connected to a 14 A h battery and a mains battery charge
Communication method	RF416 ⁶ (broad-spectrum base station radio, 2.4 GHz) with attached panel antenna ¹² in line-of-sight with base station antenna	Hardwired to Mast 1 and the Temperature station	Hardwired to Mast 2 and the Radiation station	Hardwired to the Temperature station
Software ¹³	The base station software included (1) Loggernet ⁶ for scheduled connection to all loggers and download of data at 11 min intervals, and (2) RTMC Pro ⁶ development version to create the graphics and data tables used for the Web-based system			

¹ Located at the Agrometeorology site (29.6277° S latitude, 30.4025° E longitude, 671.3 m altitude) near the Rabie Saunders Building of the University of KwaZulu-Natal, Pietermaritzburg, South Africa. The other mast and stations were in close proximity

² Kipp & Zonen B.V., Delft, The Netherlands

³ Vaisala Oyj, Helsinki, Finland

⁴ RM Young Company, Traverse City, Michigan, USA

⁵ Pronamic RAIN-O-MATIC consumer raingauge with attachment that results in 0.254 mm resolution (www.pronamic.com)

⁶ Campbell Scientific, Inc., Logan, Utah, USA

⁷ Apogee IRT model IRR-P with a half angle of 22°, Apogee Instruments, Inc., Logan, Utah, USA

⁸ Model LI-840A, LI-COR, Inc., Lincoln, Nebraska, USA

⁹ Model LWS, Decagon Devices, Inc., Pullman, Washington State, USA

¹⁰ Stevens HydraProbe – SDI model, Stevens Water Monitoring Systems, Inc., Beaverton, Oregon, USA

¹¹ The thermocouples, thermistors and PT 1000 sensors were constructed in-house with the thermistors and PT1000 sensors sealed in metal tubes

¹² Poynting panel antenna 2.4 GHz 14 dBi (model) POY-A-PANL-0005 with 10 -m cable (HDF-195); Poynting Direct (Pty), Johannesburg, Gauteng, South Africa

¹³ Other software with the same functionality was not tested. However, Loggernet is required for communication with the field stations

Results and discussion

System design, whatever its form, should allow for expansion in time and space and for a variety of uses and users. The core of the Web-based system used is an AWS system. Data from such a system, unless made freely and easily accessible via a number of different forms – including the Internet, e-mail, FTP, Wi-Fi, cell-phone and public display – may be of limited use. The data from traditional AWS systems often have limited scope and hence the system includes a whole host of sensors, measurements and calculations rarely found at a standard AWS station (Table 1, Sensors row). This significantly increased the purposes and uses of the current system and applicability to other disciplines. Although the system is based on a local AWS in Pietermaritzburg, South Africa, other remote systems may be added using the proprietary datalogger communication software (Table 1, Software row). Such systems would usually have a GSM (Global System for Mobile Communications) modem attached to the datalogger to be added with the software scheduled to dial in for data downloads.

Selected themes that encompass the agricultural, earth and environmental sciences as far as possible were developed to construct the screens used in the development of the system for which a selection is shown in Table 2.

Web-based teaching and learning example: re-evaluation of Brunt's equation

As an example of stressing the need to critically examine data, and directly relate it to climate change, the surface radiation balance for short grass is depicted in a single screen shot of the **radiation balance** screen (Figure 1; Table 2, Radiation balance row) for a week. This need is illustrated using the equation of Brunt (1934) for which the use of the original coefficients underestimates the returned infrared irradiance L_d for cloudless night-times, from the measured air temperature T_z (°C) and water vapour pressure e_z (kPa) at height z , using:

$$Ld_Brunt = \sigma(T_z + 273.15)^4(0.44 + 0.08\sqrt{10 \cdot e_z})$$

where $\sigma = 5.6704 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ is the Stefan–Boltzmann constant. Through the display of Ld_Brunt and the measured L_d (Figure 1) using a four-component net radiometer (Table 1, Sensors row; Figure 1), it is immediately obvious that the Ld_Brunt estimate consistently underestimates measured L_d . Through a guided tutorial, students explore why and also explore the

Table 2: A selected list of the various screens (themes) displayed on the Internet via the Web-based data and information system

Screen name, theme	Details of theme
Air temperature comparison: A comparison of various air temperature measurement methods	The air temperature station consists of 24 different methods for measuring air temperature ranging from unshielded fine-wire thermocouples (Table 1) to shielded and aspirated and radiation-shielded sensors and sensors placed in 6-plate and 12-plate radiation shields and in a Stevenson screen. Air temperature data are displayed as temporal plots and temperature difference plots for easy identification of differences using the various methods
AWS current: Current AWS measurements	Display of temperatures (air, grass, surface using infrared thermometer), wind speed, wind direction, relative humidity, solar irradiance, rainfall, leaf wetness duration and grass reference evaporation (ETo) (Allen et al. 2006). Screen also contains an hourly data table
AWS yesterday: AWS measurements for yesterday	Display of yesterday's maximum and minimum temperatures (air, grass and surface using infrared thermometer), wind speed, wind direction, relative humidity and total solar irradiance, rainfall, leaf wetness duration and ETo. Screen also contains a daily data table
Berg winds: Micrometeorological factors during and after Berg winds	This screen presents six simultaneous criteria for the occurrence of Berg winds and the micrometeorological conditions for a typical Berg wind are displayed. A table of data of 2 min AWS data is also displayed
Energy balance	The shortened energy balance is discussed, including a definition of closure. Temperature-based methods are used to determine sensible heat flux density – including surface renewal, temperature variance and dissipation theory-surface renewal combination method
ETo: Grass reference evaporation	Figure 3. Definition of Penman-Monteith ETo (Allen et al. 1999) and display of latest hourly ETo and and display of ETo totals for yesterday and today. Table of hourly data available for downloading the AWS data and short-grass and tall-crop ETo
Radiation balance: Grass-surface radiation balance	Figure 1. A temporal plot of the four components of the grass-surface radiation balance as well as the estimated downward infrared flux calculated using Brunt's equation (Ld_Brunt). The corrected Brunt downward infrared flux, Ld_Brunt_today is also shown. The 2 min data table of the various components is shown at the bottom
Solar radiation comparisons: Calibration facility for various solarimeters	Scatter plots, temporal plots, difference and percentage difference plots are used to highlight measurement differences in solar irradiance measured using a number of different thermopile solarimeters including a secondary standard and two second-order solarimeters
Temperature: Graphical display of temperature from surface to 8 m and sky temperature	Figure 2. The temporal record of air temperature profile in graphical and table form are displayed as well as soil temperature in table form

linear relationship that Brunt proposed between L_d/σ ($T_z + 273.15$)⁴ and $\sqrt{10 \cdot e_z}$ for night-times to develop new coefficients that express the significantly increased [CO₂] between 1934 and today. The revised version, Ld_Brunt_today , was also added to the system for students to visually compare with the measured L_d and Ld_Brunt (Figure 1) on an ongoing basis.

Web-based system as a multidisciplinary teaching and research tool

Evaporation estimation is a multidisciplinary topic. Grass reference evaporation, ETo , is discussed in the **ETo** screen (Figure 2; Table 2, ETo row) with the relevant hourly data table at the bottom of the screen containing both short-grass and tall-crop reference evaporation (Allen et al. 2006). Through a guided worksheet, students are asked to plot both hourly short-grass and tall-crop ETo for a week and comment on their differences and their variation for days with different environmental conditions – for example, cloudless and cloudy days and inside a misted greenhouse.

Visual reinforcement of concepts

Atmospheric stability is a concept central to agrometeorology, micrometeorology and meteorology. The diurnal heating of the earth's surface during daytime and night-time cooling is demonstrated using 5 d of infrared thermometer measurements of the short-grass surface (Figure 3; Table 1, Sensors row) and air temperature measurements between 0.1 and 8 m. Around midday on cloudless days, the surface is the hottest with cooler air temperatures away from the surface. During the night-time, the surface is the coolest with an increase in air temperature away from the surface. The table of data shown at the bottom of Figure 3 are used to calculate the air temperature gradient for each layer from 0.1 to 8 m. These

gradients, plotted as a function of time of day, demonstrate the change in atmospheric stability for each hour of the day for each layer. The magnitude of the air temperature gradients probes the extent of atmospheric stability at particular times and the impact of these gradients on atmospheric pollution.

Web-based system as an innovative research tool

The continual and automatic graphical display of research data allows for a dynamic and visual interrogation of measurements which can assist in developing ideas for more detailed displays or developing further ideas. This process can be aided by temporal graphs, scatter plots and/or temporal plots of differences between two sensors/methods say, of the data (Table 2, Solar radiation comparisons). Our experience is that the system is very useful for examining collected data with little intervention. Graphical plots assist in developing new ideas, easily comparing instruments and also identifying sensor or data problems.

Web-based early-warning system

An alert via e-mail or FTP can be automatically sent to students and/or staff by the system based on a test of any measurement compared to a fixed value or calculated value. Examples include application to Berg winds, frost (Savage 2012a), leaf wetness (Savage 2012b) and also to the human comfort indices of heat index and wind chill (Table 2). However, use of SMS is a more direct way of alerting and it is possible to use an incoming e-mail to set up a rule to e-mail or SMS others of an adverse weather or environmental event.

An aspect that is part of the learning process that has not been explored in detail is the use of the Web-based system as a fuzzy-logic system to alert students of, for example, Berg winds, fire danger, floods or frost. For example, rules

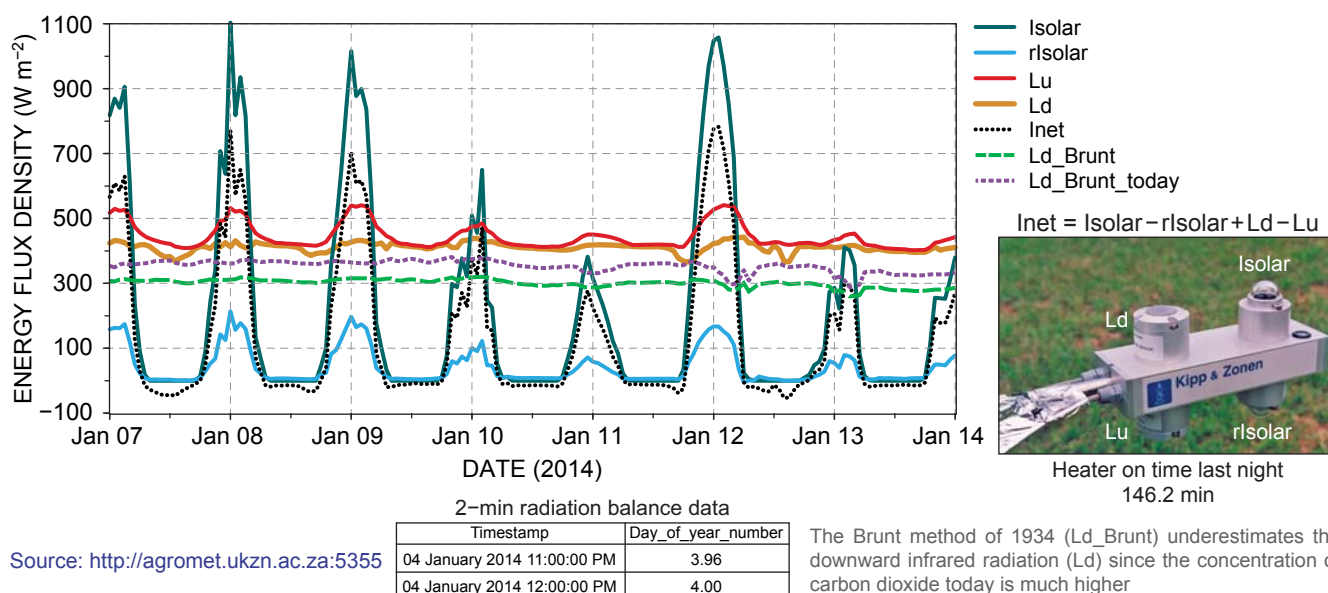


Figure 1: Temporal plots for hourly data of the four components of the grass-surface radiation balance in August 2013 as well as the estimated downward infrared flux calculated using Brunt's equation (Ld_Brunt). The corrected Brunt downward infrared flux, Ld_Brunt_today is also shown. The 2-min data table of the various components is shown at the bottom

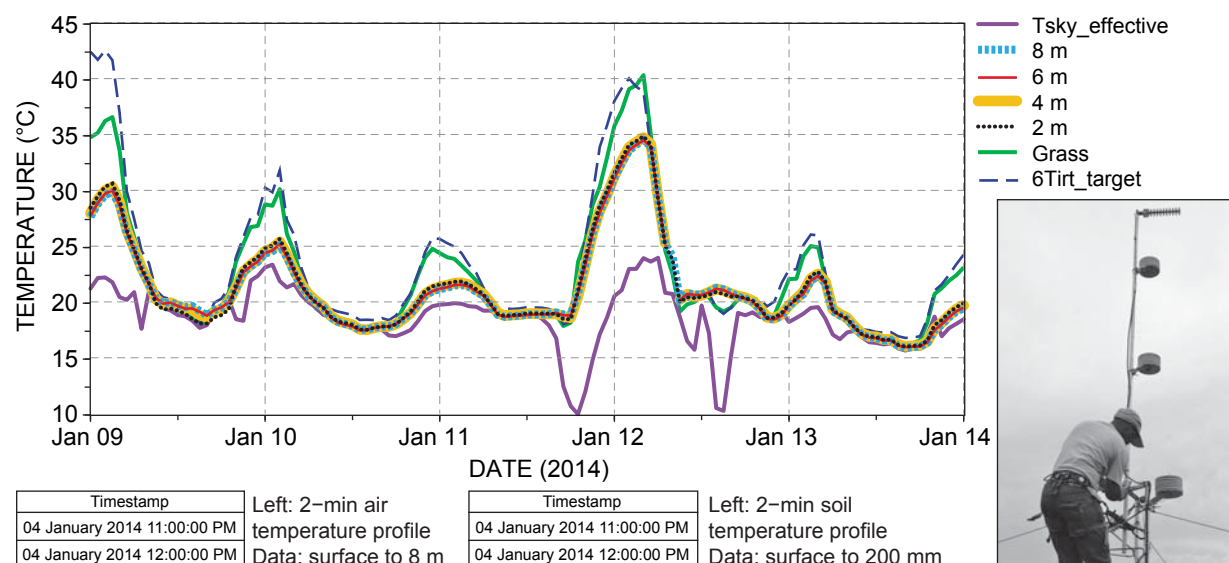


Figure 2: Temporal plots for August 2013 of various hourly temperatures from surface temperature using an infrared thermometer, unshielded temperature of grass and air temperature at 0.1, 1, 2, to 8 m and sky temperature. The data tables at the bottom include 2 min air temperature profile data as well as soil temperature

for floods could be based on the measured rainfall intensity and the soil water content at two depths (Table 1, Sensor row) in relation to the saturation soil water content. Such rules could be included in the datalogger program or the server software used (Table 1, Software row).

Provision of timely student project data

The provision of timely project data in the agricultural, biological and environmental sciences is a daunting task for a lecturer responsible for large classes. The Web-based system allows easy creation of data tables (and hotspots for easy navigation from the system to other parts of the Internet and back again) that could be used by groups of students for group projects, postgraduates and staff for lecturing aids, practical and/or tutorial material. Besides using the data as a basis for their projects, the students could regularly maintain the sensors that require cleaning or calibration and provide evidence of such visits through photographs using their cell-phones.

Use of the system for planners and information to lay public about adverse weather

An example of the use of the system in providing timely and crucial data and information to planners of activities involving strenuous activity is given. On the day on which a fitness exercise in Pietermaritzburg was conducted and eight young people died, the heat index was 33.7 °C, in the category of extreme caution for which strenuous activity is not recommended, with regular water intake and shade protection recommended (Environmental Protection Agency 2006). Two articles on adverse weather were published in a local newspaper (*The Witness*, 2 and 10 January 2013). These communications were to provide real applications to students and to provide information to the lay public via an open data and information resource.

Analysis of open questionnaires on use of the Web-based data and information system

A paper version of the first questionnaire was handed to 65 respondents and an electronic version emailed to 30 staff, postgraduates and researchers known to have used or enquired about the system (Table 3). In all in 2012 and 2013, there were 63 and 76 respondents, representing a return percentage of 68.4% and 97.4%, respectively. The electronic returns were printed and combined with the paper versions for analysis. All questionnaires were archived electronically and are available on request.

The questionnaires were analysed manually. For each question, the number of responses for three to five categories was determined. The categories chosen were dictated by the responses for that question. This meant having to read through all responses to define a category, for a given question, that captured most of the responses. The second category was defined by the remainder of the responses that captured most of the balance of the responses, and so on.

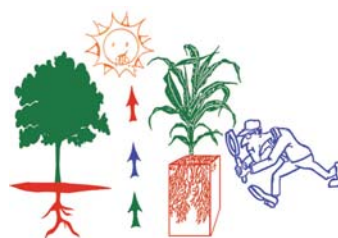
For each question, no more than five categories were used with most (eight out of 18) of the questions having three categories. Six of the questions were easy to analyse, requiring only a yes or no response with some respondents giving no response.

The responses in general were good, if not very good, for different questions. The vast majority of users – nearly 90% – found that the system was user-friendly (Table 3, Question 2) in spite of only 9.5% shown how to use the system. In terms of system use (Question 3), 39% of users accessed the system for their projects, 32% for a specific module, 15% for study and 9% for data. Most users accessed the system from on-site (71%, Question 4) with 21% of users accessing it both on- and off-site, with 8% accessing the system off-site.

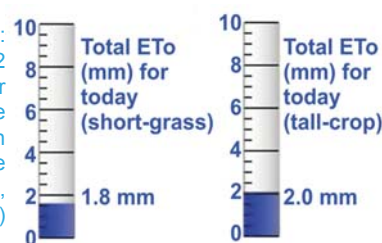
Most users accessed more than two of the data/information screens (Question 5) with 22% accessing the AWS

ETo is referred to as short-grass reference evaporation. It represents the evaporation from short green grass not limited by water or nutrients

Four factors that quantify the microclimate include solar irradiance (W/m^2), air temperature ($^{\circ}\text{C}$), atmospheric water vapour pressure and wind speed. These are usually measured at an automatic weather station. Often, the dominant factor affecting evaporation is the solar irradiance. Historically, the crop factor approach has been used for estimating evaporation based on class-A pan (or Symon's tank) evaporation and a crop factor determined using simultaneous pan and lysimeter evaporation measurements. Recently, Allen et al. (2006) showed how to estimate hourly reference evaporation (for short grass and a so-called tall-crop, the later corresponding to lucerne) from hourly data from an AWS.

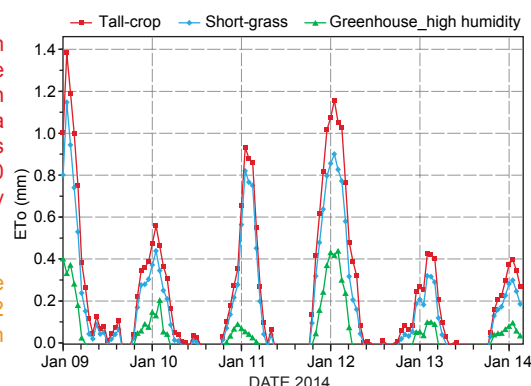


Commonly, crop evaporation (LE) is estimated from grass reference evaporation (Allen et al., 1998; FAO 56; Allen et al., 2006) based on point atmospheric measurements at a single level, usually at 2 m, at an automatic weather station from measurements of solar irradiance, air temperature, water vapour pressure and wind speed. In addition, a crop factor is used as a multiplying factor for reference evaporation to obtain LE, the crop factor effectively distinguishing the vegetation under consideration from a grass reference crop. The dual crop factor approach uses one crop factor for the soil surface and another for the basal crop cover. The extension of reference evaporation from daily (Allen et al., 1998) to hourly estimates has been recommended (Allen et al., 2006) for both grass (0.1-m tall) reference evaporation and tall vegetation (0.5-m lucerne).



Allen et al. (2006) recommend that for application of the FAO-PM ETo method from FAO56 applied for hourly or shorter time intervals for short grass, a surface resistance $r_s = 50 \text{ s/m}$ is recommended for daytime and $r_s = 200 \text{ s/m}$ for nighttime periods and an aerodynamic resistance of $208/U_2$ is used, where U_2 is the horizontal wind speed at a height of 2 m. These adjustments are based on best agreements with computations made on a 24-h time step basis lysimeter measurements. The daytime value of $r_s = 50 \text{ s/m}$ recommended by Allen et al. (2006) is also in agreement with that found by Savage et al. (1997) for a short grass surface.

Also for hourly or shorter time intervals for a 0.5-m tall canopy, $r_s = 30 \text{ s/m}$ for daytime and $r_s = 200 \text{ s/m}$ for nighttime periods and an aerodynamic resistance given by $118/U_2$ is recommended. Allen et al. (2006) based these adjustments on best agreement with 24-h time-step lysimeter measurements.



The partitioning of the available energy flux density, $R_{\text{net}} + S$ where R_{net} is the net irradiance and S the soil heat flux density, is slightly different for short grass reference evaporation than that for tall-crop reference evaporation. For short grass, $S = 0.1 R_{\text{net}}$ when R_{net} is positive (daytime) and $S = 0.5 R_{\text{net}}$ for the nighttime. For tall-crop reference evaporation, it is assumed that $S = 0.04 R_{\text{net}}$ when $R_{\text{net}} > 0$ (daytime) and $S = 0.2 R_{\text{net}}$ for nighttime.

Totals for periods indicated (or datalogger reset)

Total ETo (mm) for current week	9.9 mm	Total ETo tall (mm) for current week	13.3 mm
Total ETo (mm) for current month	78.3 mm	Total ETo tall (mm) for current month	100.1 mm

References

- Allen, R.G., L.S. Pereira, D. Raes, M. Smith, 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. United Nations Food & Agriculture Organisation, Irrigation & Drainage Paper 56. Rome, Italy, 300 pp.
- Allen R.G. et al. 2006. A recommendation on standardized surface resistance for hourly calculation of reference ETo by the FAO56 Penman-Monteith method. Agric. Water Mgt. 81: 1-22.
- Savage, M.J., C.S. Everson and B.R. Metelerkamp, 1997. Evaporation measurement above vegetated surfaces using micrometeorological techniques. Water Research Commission Report No. 349/1/97, p248, ISBN 1-86845-363-4.

Hourly ETo (mm/h) for Mast 1 (and AWS data)

Timestamp	Day_of_year_number
04 January 2014 11:00:00 PM	3.96
04 January 2014 12:00:00 PM	4.00

Hourly ETo (mm/h) for high humidity greenhouse

Timestamp	Day_of_year_number	ETo_mm	Rso0
15 September 2013 09:00:00 AM	257.38	0.09	1.78
15 September 2013 10:00:00 AM	257.42	0.17	2.48

Figure 2: The ETo screen for hourly and daily short-grass and tall-crop reference evaporation for August 2013. Detailed information is given about the calculation of daily and hourly ETo, and gauges for ETo for Mast 1 as well as a temporal plot of hourly ETo. The hourly data used for calculating ETo is given

Table 3: Summary results of the open questionnaire used to gauge use and feedback to improve the Web-based teaching, learning and research system. The percentage for each category within a given question is shown as well as the total number of responses *n*

1 Respondent status (e.g. undergraduate or postgraduate postgraduate student, etc.)	AMET212	49.2	Yes	80.6
	Yes	23.8	No response	16.1
	No response	12.7	No	3.2
	Hydrology	7.9	<i>n</i>	62
	Other modules	6.3		
	<i>n</i>	63		
2 Have you been shown how to use the Web-based data and information system (http://agromet.ukzn.ac.za:5355) and if so by whom and for which module? If you were not shown how to use the system, how user-friendly did you find it?	Undergraduate	73.0	16 Has the Web-based system improved your ability to manipulate data in a spread sheet and/or display data in a graphic or table form? Please elaborate.	
	Postgraduate	11.1	Yes	65.1
	Staff	11.1	No response	20.6
	Honours	4.8	No	14.3
	Friendly	87.3	<i>n</i>	63
	Shown use	9.5		
3 Please give the reason(s) for your use of the system. If you are a student, please indicate which module(s) you are registered for required your use of the system. Otherwise, where necessary, please elaborate.	Not friendly	3.2	17 Has the Web-based system improved your appreciation/awareness of global climate change and/or global warming aspects? Please elaborate	
	<i>n</i>	63	Yes	60.3
	Project	39.1	No	28.6
	Specific module	31.9	No response	11.1
	Study	14.5	<i>n</i>	63
	Data	8.7	18 Has the Web-based system improved your appreciation/awareness of the graphical display, and trends, of agroenvironmental and environmental data? Please elaborate.	
4 Please indicate how you accessed/viewed the system – e.g. on-campus LAN connection, Wi-Fi, off-campus, corridor display.	Interest	5.8	Yes	66.7
	<i>n</i>	69	No	20.6
	On	71.0	No response	12.7
	On off	21.0	<i>n</i>	63
	Off	8.0	19 Are you aware of any similar system(s) used elsewhere? If so, please give details.	
	<i>n</i>	62	No	76.2
5 Were you ever unable to connect to the system? If yes, how many times?	AWS current/ AWS yesterday	63.0	Yes	15.9
	Various	24.7	No response	7.9
	No response	12.3	<i>n</i>	63
	<i>n</i>	73	20 Do you have any suggestions for improvement or specific requirements that could be incorporated as part of the Web-based system? If so, please elaborate.	
	12 Have you made use of the AWS_today and AWS_yesterday screens? Please elaborate		• Add dewpoint temperature graph to AWS current screen	
	Yes	51.6	• Advertise	
6 What event/screen did you monitor/use and why? Where necessary, please elaborate.	No	28.1	• Complicated, pse simplify	
	Other screens	20.3	• Data only on a static background	
	<i>n</i>	64	• Frontal weather	
	13 Have you ever downloaded data or graphics from the system? If so, please state the purpose for downloading and the relevant module – e.g. for use for a tutorial, a project, an assignment, a practical, research, personal use. Please elaborate.		• Future weather (x2)	
	Yes	61.9	• Improve visuals	
	No	31.7	• Info separate from data; email notifications; mobile app; link to forecasting	
7 What was the purpose for your use of the system – e.g., for interest, personal, study, data download, practical(s), tutorial(s), lecture(s), project? If you used the system for academic work, please indicate the purpose(s) and in each case the corresponding module. Please elaborate.	No response	6.3	• Make it easier to download data	
	<i>n</i>	63	• Monthly averages, totals	
	Personal interest	31.9	• More info needed on use of Website	
	Project	29.8	• More interactivity	
	Practicals	26.6	• Overview screen, better graphics, mobile version	
	AMET212	11.7	• Screen should be available all over campus	
8 Is the content of the system related to the lecture content of modules you are taking and if so, state which modules and which lecture content? Please elaborate.	Did not download	6.3	• Suggestion box	
	<i>n</i>	63	• Well demonstrated	
	14 If you did download data or graphics from the system, how easy was it to do? Please elaborate.			
	Easy	50.8		
	No response	23.8		
	Not	19.0		
9 Have you used the system for observing any particular near real-time event(s)? If so, please indicate which event(s).	15 Has the Web-based system improved your appreciation of the ranges of the various weather elements – e.g. range in air temperature, relative humidity, rainfall, wind speed, etc.? Please elaborate.			
	Yes	26.4		
	No response	8.3		
	<i>n</i>	72		
	10 Please describe your frequency of use of the system – e.g. casual, monthly, weekly, regular.			
	Casual	52.4		
10 Please describe your frequency of use of the system – e.g. casual, monthly, weekly, regular.	Regular	22.2		
	Weekly	14.3		
	Monthly	6.3		
	Daily	3.2		
	<i>n</i>	63		
	11 Which event/screen did you use the most? If more than one screen, please say which ones. To answer this question you may wish to refer to: http://agromet.ukzn.ac.za:5355			
11 Which event/screen did you use the most? If more than one screen, please say which ones. To answer this question you may wish to refer to: http://agromet.ukzn.ac.za:5355	AWS current/ AWS yesterday	63.0		
	Various	24.7		
	No response	12.3		
	<i>n</i>	73		
	12 Have you made use of the AWS_today and AWS_yesterday screens? Please elaborate			
	Yes	51.6		
12 Have you made use of the AWS_today and AWS_yesterday screens? Please elaborate	No	28.1		
	Other screens	20.3		
	<i>n</i>	64		
	13 Have you ever downloaded data or graphics from the system? If so, please state the purpose for downloading and the relevant module – e.g. for use for a tutorial, a project, an assignment, a practical, research, personal use. Please elaborate.			
	Yes	61.9		
	No	31.7		
13 Have you ever downloaded data or graphics from the system? If so, please state the purpose for downloading and the relevant module – e.g. for use for a tutorial, a project, an assignment, a practical, research, personal use. Please elaborate.	No response	6.3		
	<i>n</i>	63		
	14 If you did download data or graphics from the system, how easy was it to do? Please elaborate.			
	Easy	50.8		
	No response	23.8		
	Not	19.0		
14 If you did download data or graphics from the system, how easy was it to do? Please elaborate.	Did not download	6.3		
	<i>n</i>	63		
	15 Has the Web-based system improved your appreciation of the ranges of the various weather elements – e.g. range in air temperature, relative humidity, rainfall, wind speed, etc.? Please elaborate.			

Table 3: (cont.)

Further general comments/considerations: Please add further comments relevant to this questionnaire.

- Berg wind forecasting very interesting
- Demonstration
- Great tool
- Helpful, helped with research significantly
- Impressive, comprehensive
- More interactivity and flexibility
- Thanks for service
- Thanks to MGA, Nico, Steve
- Try to have further prediction for air temp
- Useful tool
- Very useful, enjoyable and interesting resource

current screen. The AWS current screen (<http://agromet.ukzn.ac.za:5355/>) displays the current air temperature, relative humidity, rainfall, wind speed, wind direction and sunshine duration as well as the current minimum and maximum air temperature for the day.

Surprisingly, there was a high percentage of respondents indicating personal use of the system (32%, Question 7). From a teaching and learning standpoint, this has benefit for the undergraduate student since personal use is the one usage that would probably continue even after the student has completed the current semester.

Almost 25% of respondents found that system content was related to their current modules (Question 8), with almost 50% finding the content related to their agrometeorology modules.

About 26% of respondents observed near real-time weather events at some time during the semester (Question 9) with 31% viewing a specific weather event. Most users (52%) indicated that their use was casual, 22% regular, 14% weekly and 6% monthly (Question 10). Most users (62%) downloaded data (32% did not) from the system (Question 13) with 51% of users indicating that this was easy to do (Question 14).

Gratifying is that more than 60% of the respondents indicated that they benefited from use of the system (Questions 15 to 18), that their appreciation of the ranges of the various weather elements had improved, that system use had improved their ability to manipulate data in a spreadsheet and/or display data in graphic or table form, improved their appreciation/awareness of global climate change and/or global warming aspects and that system use had improved their appreciation/awareness of the graphical display, and trends, of agroenvironmental and environmental data.

What is also particularly gratifying, however, is the high percentage of 80% (93% for 2013) of respondents indicating that use of the system had improved their appreciation of the ranges of the various weather elements (Question 15). It does mean, however, that early exposure to the system could assist in the understanding of physical concepts of the agroenvironment.

More than 75% of respondents were not aware of a similar system elsewhere (Question 19) with one respondent indicating that the South African Weather Service (SAWS) system is similar and another that the South African Sugar Research Institute (SASRI) system is similar. An

examination of both systems mentioned showed that they are not similar with the only commonality being that they all display weather data. The SAWS and SASRI systems are regional/national systems that focus on fewer weather elements with data downloads not available (SAWS) or focus on sugar-growing areas (SASRI).

The questionnaire responses also highlighted some of the weaknesses of the software used for displaying the graphics, in particular text enhancements, resolution and system interactivity. These issues have now been addressed with the latest software release and implemented.

Role of language

Even for the teaching of children, a teaching strategy is 'As you conduct a science lesson, include visuals that illustrate the subject matter' (Buck 2000). According to Herr (2007): 'Regardless of linguistic background, people around the world can interpret mathematical equations and musical scores. In addition, they can also interpret pictures, and with minimal linguistic skills, can interpret charts and graphs. Visual literacy, or the ability to evaluate, apply, or create conceptual visual representation, is relatively independent of language, and is therefore invaluable to learning science...'. In the second questionnaire (May 2013), in addition to the questions asked previously, the role of language was also surveyed. The results showed (Table 4) that more than 75% of the respondents indicated that the graphical display of data had enabled further understanding of the agroenvironmental concepts irrespective of language compared to 6% of the respondents indicating that it had not. Most of the respondents were isiZulu and 72% indicated 'yes' to this question compared to 80% for main-language English speakers. A relatively small percentage (13%) of all respondents did not give an answer to this question. More than 80% of respondents indicated that the Web-based system improved their appreciation of the ranges of the various weather elements – e.g. diurnal range in air temperature, relative humidity, rainfall and wind speed – and therefore they have improved their first-hand understanding of the environment, irrespective of their home language.

A third similar survey, conducted in November 2013, included the question: What language(s) are you comfortable with? Surprisingly, nearly 78.2% of the respondents (55) indicated English in spite of the fact that 27 out of 41 that replied to this question are isiZulu mother tongue. This high response may be due to the fact that many of the technical English terms, for the agroenvironmental sciences, do not have a corresponding term in isiZulu. Further research is necessary in this regard.

Conclusions

The Web-based system described has shown to be versatile in terms of allowing the connection of a wide range of sensors and is easily upgradable in terms of additional dataloggers, sensors and environments, even for remote locations. The various graphics screens support the concept of visual literacy by displaying the graphics and data tables of near real-time Web-based data. There is easy and open access to such data and information through a range of media, including the Internet, FTP, Wi-Fi and Web-enabled

Table 4: Results of the second open questionnaire (May 2013) used to gauge the role of the graphical display of data in enabling further understanding of the agroenvironmental concepts irrespective of language (79 respondents). The percentage for each language and category of answer and the total number of responses n are shown

17 Do you think that the graphical display of data has enabled your further understanding of the agroenvironmental concepts irrespective of language? Please elaborate.						
Home language	Yes	No	No answer	Not really	Neutral	Not absolutely
isiZulu	31 (72%) ^a	4 (9%)	7 (16%)	1 (2%)	0	0
English	20 (80%)	1 (4%)	2 (8%)	1 (4%)	0	1 (4%)
isiXhosa	3 (100%)	0	0	0	0	0
Other languages ^b	6 (75%)	0	1 (13 %)	0	1 (13%)	0
Total ($n = 79$)	60 (76.0%)	5 (6.3%)	10 (12.7%)	2 (2.5%)	1 (1.3%)	1 (1.3%)

^a The percentage in brackets represents the percentage for the particular language (row)

^b Other home languages included Chichowa, French, Setswana, Sotho, Tshivenda, Venda and Xitsonga

cell-phone for use by the lay public and in the laboratory or lecture room for a wide range of disciplines in the agricultural, earth and environmental sciences, as well as early-warning of a topical event such as Berg winds, flood or frost. Our experience has been that students learn more quickly and have increased interest when using real and very recent data relevant to their chosen discipline. The Web-based system has been used as a tool in teaching, learning and research. Hundreds of students have been made more aware of the current weather and other agroenvironmental conditions via the frequently updated current data. In addition, through tutorials and projects, they handle large data sets, and plot and interpret data graphically – thereby enhancing visual literacy. In a questionnaire for which there were 63 respondents out of a potential total of 95, representing a return percentage of 68.4%, more than 80% indicated that use of the system had improved their appreciation of the ranges of the various weather elements. More than 60% of the respondents indicated that they benefited from use of the system, that they had improved their ability to manipulate data in a spreadsheet and/or display data in graphic or table form, improved their appreciation/awareness of global climate change and/or global warming aspects, and improved their appreciation/awareness of the graphical display, and trends, of agroenvironmental and environmental concepts irrespective of language.

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