INVESTIGATION OF MICROCLIMATE FOR HUMAN COMFORT IN THE NATURAL ENVIRONMENT AND IN A CAR PARKED IN THE OPEN

by

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the 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 University of KwaZulu-Natal Teaching and Learning Office 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: Professor M.J. Savage

Date: 02 June 2016

DECLARATION

I, Sithandiwe Ignatia Luthuli, 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;

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a) their words have been re-written but the general information attributed to them has been referenced;

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(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;

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ABSTRACT

Hot weather extremes have a greater impact on human comfort, human health and mortality compared to episodes of cold waves. With current trends in global climate, deaths and hospital admissions following heat waves as well as deaths of children left unattended in cars parked in direct sunshine on days with clear skies for extended periods of time have been well documented in many parts of the world. However, these receive far less attention in other countries such as South Africa when compared to deaths due to other causes. With the anticipated increase in the global temperatures, increased demand for public health, energy generation for cooling systems and loss of productivity will become a burden on society due to hot weather. Understanding current weather systems and their impacts on society is necessary to generate prompt future warning systems and preparedness. The communication gap between society and meteorology will continue to cause adverse weather a human tragedy. The study investigated microclimates for human comfort in an enclosed car, parked in the open and in a natural environment, for both working individuals and the general public in Pietermaritzburg, South Africa.

Microclimatic data of the natural environment were collected from the Agrometeorology Instrumentation Mast (AIM) situated at the University of KwaZulu-Natal (UKZN) in Pietermaritzburg (PMB). Additionally, the microclimate of a car was measured periodically for more than a year, inside a golden-brown Audi A3 parked adjacent the AIM. Inside the car, various meteorological sensors were used for the radiation balance, while automatic weather station (AWS) data, microclimate measurements and calculations of different indices were used to quantify the level of apparent temperature of human beings inside and outside the car. A web-based system was used to display near real-time data which allowed timely decisions to be made about what should be measured, and where inside the car, as well as the current apparent temperatures and precautionary measures for individuals exposed to heat outdoors. The car was subjected to different treatments on different days, i.e. changes in orientation, levels of ventilation and changes in the seat colour. Lastly, historic data from Cedara, Ukulinga and Baynesfield in KwaZulu-Natal were used for determining which areas were vulnerable to heat from a human comfort perspective.

The results show that the car was much hotter when facing north on cloudless days, even when the ambient air temperature was as cool as 20 ^{o}C in winter. In summer, the maximum passenger's seat temperature recorded inside the car was 75 ^{o}C when the air temperature outside the car was 33 ^{o}C. On cloudless days, the seat and inside-cabin roof temperatures measured using infrared radiometers were similar to each other. Additionally, the reflected solar

irradiance was low due to shaded areas inside the car. Therefore, the transmitted solar irradiance was the dominant term of the radiation balance. In the absence of wind and evaporative cooling inside the car, the transmitted solar irradiance that is absorbed significantly heats the interior surfaces. The air in contact with the interior surfaces is then heated, rises and free convection occurs. This process causes dangerously high air temperatures inside cars kept in the sun even in winter when the outside air temperature was as low as 18 ºC. Current legislation does not obligate the drivers to be responsible for their passengers when their vehicle is in an unattended parked position. Also, the car manufacturing industry has not used available technology to prevent automobile fatalities by installing motion detectors in the front and rear seats to warn of interior passenger motion if all car doors are locked and conditions are adverse.

Ukulinga and Pietermaritzburg had 534 and 693 hours of extreme caution heat index category respectively, setting them to be the most vulnerable locations. Cedara had 95% of the time in the no caution category and was therefore regarded as the least vulnerable site in terms of the extreme heat events. The high vulnerability to extreme heat events in Ukulinga and Pietermaritzburg can be attributed to their lower altitude and the urban heat island effect, while the low prevalence of extreme heat events at Cedara can be associated with its higher elevation and therefore lower temperatures.

Use of the wet bulb globe temperature (WBGT) human comfort index requires globe temperature measurements which are measured using a globe thermometer that is often not used at the typical AWS. The study compared globe temperature measurements taken at different heights (1.1 and 2 m) and painted different colours (matt-black and grey). Also, different methods of estimating the WBGT were compared to one another. The results showed that there is little difference between the globe temperature values in terms of height and colour. The calculated globe temperature (T_g) was highly associated with the measured globe temperature with the R^2 value of 0.94 and a RMSE of 1.1 ºC. Additionally, WBGT calculated using black globe temperature measurements and that calculated using the routinely measured AWS data showed a discrepancy of up to 5.3 ºC, with the calculated WBGT higher than that calculated using the black globe temperature measurements. The heat index is highly affected by the changes in relative humidity even though in its calculation it assumes fixed values of wind speed and solar irradiance. On the other hand, the mean radiant temperature (T_{mrt}) and the WBGT may not be the best indicator of human comfort. The T_{mrt} yields measurements as high as 87 ºC when the surrounding air temperature is 34 ºC, and the globe temperature is 43 ºC. The WBGT tended to underestimate the level of heat discomfort compared to the heat index. In Pietermaritzburg, there were 7.55 days from February 2014 to November 2015 in which work of any intensity (200 to 600 W) was compromised due to taking breaks as recommended

by the WBGT. Adding 2 ºC to the air temperature between February 2014 and November 2015 would increase the number of days compromised, due to taking breaks, from 7.55 days to 26.6 days. This study has highlighted the role of the environment and its impact on human comfort. Increasingly in the future, this aspect should receive more attention.

KEYWORDS: Car cabin temperature, heat index, car-seat emissivity, near real-time data, web-based temperature display, mean radiant temperature, globe temperature, society, climate change, mortality, health, self-pacing

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

For a number of decades, climate change and its subsequent impact on society continues to remain a concern. Several studies have been conducted to provide evidence that the global climates are changing (Houghton *et al.* 2001, Solomon 2007). Based on these studies, human beings are expected to be negatively impacted directly and indirectly by these changes. Africa is one of the most vulnerable continents to climate change (Russo *et al.* 2016). Kjellstrom (2009) illustrates that until recently, very little attention has been paid to climate change and its impact on human health. Much emphasis, however, has been focused on the impacts of climate change on environmental change and the ecosystem.

Hot weather extremes are said to have a greater impact on human health and mortality compared to episodes of cold waves. Extensive research has been done in many subtropical countries to assess the impact of extreme heat events on general public (Robinson 2001, Gosling *et al*. 2007, Matsueda 2011), workers (Kjellstrom *et al.* 2009) and on children and pets that are left in cars parked in full sun (e.g., Guard and Gallagher 2005, Grundstein *et al.* 2009, Booth *et al.* 2010).

According to Henson (2008), about 35 000 deaths were recorded across European countries as a result of heat waves in the summer of 2003. During those heat waves, the maximum air temperature in France was as high as 37 ºC (Fouillet *et al.* 2006), which is the normal maximum air temperature for some provinces in South Africa. Notable recent events in South Africa include a fitness test for KwaZulu-Natal Road Traffic Inspectorate (RTI) job applicants, which took place in Pietermaritzburg in December 2012 and claimed the lives of eight participants, while about 200 people were treated for various heat related illnesses (SAPA 2013), as well as the heat waves experienced during the 2015 El Niño event which claimed the lives of eleven in North West province (SABC 2016).

While extreme heat events are not common for South Africa, the anticipated impact is substantial in the face of human induced climate change. Meehl and Tebaldi (2004) and Kjellstrom *et al.* (2014) state that the direct impact of climate change heat extremes are expected to be more frequent, more intense and to last longer. According to Kjellstrom *et al.* (2014), in South Africa, heat waves will be the most common and inevitable impact of climate change.

It is important to monitor excessive heat events since they are normally accompanied by other adverse weather events such as Berg winds and droughts causing great economic demand for managing their damage. Secondly, in South Africa it is reported that every summer at least one child loses its life and suffers from heat stroke from automobile hyperthermia (Rose-Innes 2012). Since heat impacts everyone, a timely and cost efficient monitoring system is desirable to avoid the adverse consequences of hot weather as well as to save lives.

1.1.1 Monitoring heat stress on humans

Studies on the effect of heat stress on human beings in South Africa have been historically done in the mining industry (e.g., Wyndham *et al*. 1965) and little has been done involving the general public, manual workers or individuals carrying out strenuous activities, or on passengers in parked cars.

Most weather forecasts available to the general public consider air temperature as the only variable to assess human heat burden. Even though environmental temperature is essential to determine the extent of heat impact on organisms, it cannot be used as the only indicator since wind speed and atmospheric humidity are also important elements. Secondly, environmental air temperature is measured in shade and therefore it cannot be a true representation of how a human exposed to the sunlight feels.

Atmospheric conditions that impact on human comfort or discomfort include air temperature, air moisture (relative humidity), wind speed and solar radiation and two behavioral factors, clothing and physical activity (Kjellstrom *et al.* 2009). An appropriate monitoring tool or heat burden assessment of humans is the one that considers the impact of all these parameters. Several indices that consider the combined impact of air temperature (Steadman 1979, Rothfusz and Headquarters 1990) wind speed, solar load (Thorsson *et al*. 2007, Kantor and Unger 2011) on humans have been formulated and used extensively to assess the heat burden on the general public, at sporting events and in work places.

1.2 MOTIVATION FOR THE STUDY

Hot weather extremes have both direct and indirect negative impacts on human beings and cannot be prevented. Apart from the increased direct mortality and morbidity that they cause, they normally set the scene for other life threatening and costly disasters such as wild fires, and they escalate droughts. As a result, economic losses are incurred every summer due to decreased labour productivity caused by self-pacing, increased hospital admissions and fatalities, and immense need is placed on resources to provide strategies such as power (for air-conditioning) and adequate water supply.

There is a great need for research on heat extreme events to understand their characteristics, so as to provide prompt warning systems that can be used to determine current and future heat extreme events and their consequences. The system can be useful to schools, planners of events including strenuous activities, outdoor workers and parents who forget or intentionally leave their children or pets in cars parked directly in the sun in spite of impending dangers. Secondly, there is a need to provide awareness of heat extreme events dangers as well as to understand their influence on communities and families that they impact.

1.3 AIMS AND OBJECTIVES

1.3.1 Aims

The aims of this study are as follows:

1. To quantify the level of human heat discomfort outdoors and in parked cars to both the general public and to those involved in strenuous activities.
2. To determine heat wave prone locations through the use of the heat index and the mean radiant temperature (T_{mrt}).
3. To determine the occupational heat exposure through the use of the wet bulb globe temperature (WBGT) index.

1.3.2 Objectives

Specific objectives for the study include:

1. Use an Agrometeorology Instrumentation Mast (AIM) system to guide the research decisions through the near real-time display of the conditions inside a car and outdoor conditions that impact human comfort.
2. An investigation of the microclimate and radiation balance inside a parked car.
3. To apply the Heat Index method using a cost efficient method, i.e. through measuring the wet- and dry-bulb temperatures and measuring the mean radiant temperature (T_{mrt}) using the method explained by Kantor and Unger (2011).

1.4 STRUCTURE OF THE DISSERTATION

This dissertation consists of six chapters. Chapter 1 provides an introduction and the rationale for the study, outlining the motivation behind it, the aim, objectives and lastly, it provides the road map of the dissertation.

Chapter 2 provides a review of the related literature. It looks at the role of climate change on heat extremes and it provides an interplay between the meteorological factors and the factors that influence the human energy balance and the indices that are used to assess the environment. It also looks at the impact of excessive heat events on health, mortality and the individual's factors that promote susceptibility to heat.

Chapter 3 is the first experimental chapter. It determines the radiation balance and the microclimate of a closed parked car, using various measurement sensors and different indices that are used to quantify the level of apparent temperature in human beings.

Chapter 4 is the second experimental chapter. It investigates how prone the region is to heat waves using the heat index and other meteorological data from three areas (Cedara, Ukulinga, Baynesfield and Pietermaritzburg) and T_{mrt} as the alternative index. It also looks at the social impacts of heat extreme using the RTI fitness test as a case study. It also proposes the simple method of obtaining timely data to calculate the heat index in resource poor areas and schools.

Chapter 5 is the last experimental chapter. It looks at the occupational heat exposure using the WBGT index. It considers the impact of heat on working population and sporting events.

Chapter 6, the final chapter, contains the conclusions and recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

Extreme heat events have a number of profound impacts on any country (Omonijo *et al.* 2013). These impacts include increased death tolls, increased levels of heart related diseases and a decrease in the number of days in which outdoor leisure and work can be enjoyed and performed respectively. Hot weather extremes have a greater impact on mortality compared to episodes of cold weather (Kalkstein and Valimont, 1987).

Morbidity and mortality caused by hot weather events have been well studied in the field of biometeorology in many countries. Omonijo *et al.* (2013) states that extreme weather events such as heat waves are a global issue and are not restricted to a particular region. Among most of the extreme heat fatalities, there is a positive link between the observed and projected global climates, regardless of whether they are natural or human induced. Role of climate change on human comfort

For a number of decades, climate change and its subsequent impact on society continues to be of environmental concern. Several studies have been conducted on a global scale (Houghton *et al.* 2001, Solomon 2007, Stocker *et al*. 2013) and on a national scale (Kruger and Shongwe 2004, Deressa *et al*. 2005, Kruger and Sekele 2013) to provide evidence that climates are changing. According to Ziervogel *et al*. (2014), over the past 50 years South Africa has seen an increase in the average annual temperatures which is 1.5 times higher than the observed 0.65 ^{o}C for the entire globe. Kruger and Shongwe (2004) investigated temporal and spatial trends in air temperature from 1960 to 2003 using 26 weather stations across South africa. The authors found that the average annual temperatures from 1960-2003 increased by 0.13 ^{o}C per decade.

The mean global temperatures are expected to increase even further than the observed trend. Stocker *et al*. (2013) project a warming relative to 1986-2005 of 0.3 ^{o}C to 0.7 ^{o}C by 2016-2035. According to these projections, warming in sub-Saharan Africa is expected to be higher than the global average and rainfall could decline in some parts of the region (Kruger and Shongwe 2004, Mathee *et al.* 2010). Future climate projections not only reveal an increase in the near surface air temperature, but also the frequency, intensity and the extended duration of heat waves is expected. The increase in the global temperature is said to increase the relative humidity in the lower troposphere with consequential impact on human thermal comfort.

Based on these studies, humans are expected to be negatively impacted directly and indirectly by these changes. Kjellstrom (2009) illustrates that until recently there has been very little attention paid to climate change and its impact on human health. Greater emphasis, however, has been placed on the impacts of climate change on environmental change and the ecosystem. With the rise in the average global surface temperatures, organisms have already been exposed to a variety of extreme weather conditions, as predicted. These weather conditions include high air temperatures, severe rains and flooding, droughts, and storms. These adverse weather conditions pose a serious threat to human health (Kjellstrom *et al*. 2009), by increasing the rate of illnesses such as asthma, heart-related illnesses and infectious diseases (Johnson *et al*. 2009) as well as increasing human discomfort.

Heart related illnesses such as heat stroke, heat exhaustion and even deaths have been said to increase on days that are characterized by high relative humidity and high air temperatures, amongst other factors (Luber and McGeehin, 2008). According to Maloney and Forbes (2011), the increase in average annual temperature will affect human health by negatively impacting the human energy balance as well as decreasing the number of days in which leisure and work is possible. The effect of harsh weather conditions cannot be prevented from occurring in the future. However, if daily weather is measured and predicted with reasonable accuracy, then adverse weather response plans can be developed and precautions can be taken.

In South Africa, most attention on heat stress has been within the mining industry (Wyndham *et al*. 1965), because of the apparent fatalities that are attributed to heat related illnesses due to exposure to heat. Additionally, the weather forecast that is accessible to the majority of the general public hardly shows the impact of combined meteorological aspects that are detrimental to human comfort. The following section outlines the connections that occur between the surrounding environment and the human body in order to create discomfort or comfort.

2.1.1 Factors influencing human comfort

Human comfort can be determined by six factors: four microclimatic factors and two behavioural factors. The microclimatic factors include: relative humidity, air temperature, solar radiation and wind speed (Lin *et al.* 2010). The behavioural factors include metabolic rate and the level of clothing (Lundgren *et al*. 2013). Some researchers, e.g., Stathopoulos *et al.* (2004), add other factors such as air quality, gender and age.

When a person is exposed to excess solar radiation, it is not only the heat from the sun that causes discomfort, but also the heat from adjacent objects that are exposed to the same level of radiation. A combination of high air temperature, high solar radiation, high relative humidity and low wind speed significantly impacts on the human energy balance and therefore can increase the human body temperature after prolonged exposure. This can lead to heat stroke.

Relative humidity is regarded as the factor that mostly creates heat discomfort. It influences human comfort in that it determines the rate of cooling effect for human beings by determining the rate at which sweat will evaporate. Relative humidity can be estimated through the use of the natural wet bulb temperature, which is obtained by a thermometer with a wetted wick, or through the use of the wet bulb temperature which is obtained by means of a sling psychrometer. In addition, air temperature is required for the determination of relative humidity.

2.2 FACTORS GOVERNING BODY ENERGY BALANCE

Under ideal conditions, the human body energy (both stored and generated energy) and the energy transferred into the human body must balance. The balance is said to occur when the core body temperature is 37 ^{o}C. This means that there is a balance between the body and the surrounding environment. Heat exchange between the human body and the surrounding environment can be defined through the energy balance equation. According to Parsons (2010), when the energy generated and the energy received by the body is greater than the energy dissipated by the body, the body temperature increases. Also, when the energy dissipated by the body is greater than the energy generated and the received energy, the body temperature decreases. An equation that defines the balance of energy in humans for a given environment is given by:

$$M - W = E + R + C + K + S \qquad [2.1]$$

where *M* is the metabolic flux, *W* is the mechanical work performed by the body per unit area, *E* is the evaporative heat flux gain or loss, *R* is the radiant energy exchange, *C* is the convective energy flux transfer, *S* is a stored energy flux and *K* is the conductive energy flux transfer. All terms are in W m^{-2}.

2.2.1 Metabolic flux

Metabolic flux is the sum of energy production in a human per unit area. Metabolic activity is the primary source of internal heat flux generation in humans in order for physical and mental activities to be performed.

2.2.2 Conduction

Conduction is one of the modes of energy transfer in which energy flux is transferred as a result of direct contact and temperature difference from one object to another (Grubenhoff *et al.* 2007). Since it depends on physical contact between objects, it usually has a low impact in the case of body heat flux transfer.

2.2.3 Convection

Convection is the mode of energy flux transfer that occurs when the skin is in direct contact with air or water. There are two types of convection: free convection and forced convection. According to Gosling *et al*. (2014) free convection is a result of thermal gradients between air temperature and skin temperature. Free convection energy flux loss occurs when skin temperature is greater than air temperature, and convective energy flux gain occurs when air temperature is greater than skin temperature. Forced convection occurs as a result of external features such as fans, body movement or natural features like air movement.

2.2.4 Radiation

Radiation refers to the energy flux transfer by certain electromagnetic waves and includes solar and infrared irradiances. Radiant energy flux exchange includes the transmission of thermal radiation between the human body and the surrounding environment (Gosling *et al*. 2014). It accounts for most of the energy flux transfer to humans. Positive values of radiant energy flux exchange shows energy flux transfer to the environment while the negative values shows energy loss by the body.

2.2.5 Evaporation

Evaporation is the primary mechanism that the body uses to lose excessive heat through sweating. Sweat is triggered when the surrounding air temperature is greater than body temperature. It is mainly governed by the surrounding air temperature, wind speed and mostly, relative humidity. When the environmental relative humidity is greater, the rate of evaporation is reduced in humans. Furthermore, the presence of wind speed over the human skin aids evaporation to occur.

2.2.6 Stored heat flux

According to Parsons (2014) the stored energy flux *S* is the total of energy production and energy loss parameters. Therefore, when the energy flux stored is equal to zero, the body is in energy flux balance:

$$M - W - E - R - C - K = 0 \qquad [2.2]$$

When *S* is greater than zero (Equation 2.1), there is a net energy gain and the body temperature will increase. When *S* is less than zero, the net energy flux loss will be achieved and therefore body temperature will decrease.

2.3 BODY HEAT GAINS AND BODY HEAT LOSSES

The body gains heat primarily through metabolism and in lesser quantities through radiation, convection and conduction. Heat is lost from the human skin either by sensible heat transfer or latent heat transfer to the surrounding environment (Arens and Zhang 2006). The rate of heat generation needs to balance the rate of heat loss in order to avoid adverse effects.

When the temperature of the surrounding environment is cooler, body energy is lost through radiation and conduction, as a result of the temperature difference between the environment and the body. On the other hand, in the presence of extreme solar radiation, the body gains a large amount of energy by radiation (Maia and Loureiro 2005). In this form the capacity of humans to survive is related to their ability to dissipate heat by evaporation through sweating as well as conduction, convection and infrared radiation loss within. Therefore, the human body temperature does not vary with the temperature of the surrounding environment. The following section explains the process by which the body dissipates excess heat and how it gains heat in a cold environment in order to maintain a constant body temperature through thermoregulation.

2.3.1 Thermoregulation

The human thermoregulatory system seeks to preserve the core body temperature within a narrow range around 37 ºC. Regulation of the internal body temperature for humans is achieved by both behavioural and physiological factors that affect the balance of energy loss and energy gain. According to Schlader *et al*. (2010), behavioural factors are often intentionally applied by individuals in order to alter the surrounding environment so as to assist the body's thermoregulatory control. These factors include sitting in the shade or using air-conditioning in hot weather, and putting on thicker clothing in cold weather. Behavioural factors are triggered by the changes in skin temperature. If skin temperature changes significantly in such a manner that behavioural responses are not efficient, physiological responses occur. Physiological responses are automatically produced by the body following exposure to changes in temperature of the surrounding environment.

According to Epstein and Moran (2004), when the body temperature rises above 41 ºC, the body cells and tissues encounter irreversible damage. Additionally, a core body temperature of 43 ºC is lethal for humans. Therefore, for normal functioning of the body, humans have the ability to maintain a fairly constant core body temperature irrespective of environmental conditions. In hot weather, thermoreceptors in the hypothalamus and the receptors in the skin are activated to notify the hypothalamic regulatory centre, which then increases the delivery of heated blood to the surface of the body as a response (Bouchama and Knochel 2002). According to Bouchama and Knochel (2002), when this occurs, the sympathetic nervous system triggers heat loss by dilation of blood vessels in the skin and also generates sweating. Bouchama and Knochel (2002) elaborate that if the surrounding air is dry, sweat will vaporize and cool the body surface. However, if the surrounding air is saturated with water, cooling the body surface becomes difficult. The enlargement of blood vessels allows an increased flow blood to the skin and thus energy is lost through radiation and conduction. This process places more pressure on the heart to generate more blood, and can be very difficult to achieve in people with heart disease.

2.4 IMPACTS OF HEAT EXTREMES ON HEALTH

When the heat load on the human body increases due to exposure to hot weather or due to the creation of metabolic heat, the thermoregulatory mechanisms take over to alleviate or moderate heat load. Epstein and Moran (2004) illustrate that sometimes heat becomes so intense that these mechanisms fail or simply becomes insufficient to keep the body temperature in the desired range. In the event of failure of thermoregulatory mechanisms, the body experiences heat related illnesses which may lead to mortality.

Heat related illnesses are not only a threat due to fatalities that may result, but also to the economic consequences. Kjellstrom *et al*. (2014) indicate that worker productivity decreases in days that are characterized by high ambient temperatures, which in turn leads to health issues such as food insecurity and malnutrition. Haines *et al*. (2006) illustrate that the poorest population groups are expected to be most exposed to harmful health effects of climate change. Furthermore, vulnerability is determined by other factors such as age, socio-economic status (such as the state of housing, income and access to air conditioning) and pre-existing cardiovascular and respiratory disease. Mathee *et al*. (2010) explained that the elderly and the young, also chronically sick patients, socially isolated people, urban residents, and people without access to air conditioning are more at risk to the illnesses caused by heat extreme events.

2.4.1 Heat related illnesses

Heat related illnesses result when the heat gained by the human body cannot be dissipated through behavioural or physiological thermoregulatory processes. Even though these illnesses are of concern with respect to public and occupational health, little is known of their impacts on the former in the population of this country. Kjellstrom *et al.* (2014) illustrates that in South Africa, increasing heat exposure in the workplace will be the most common and likely occupational health impact of climate change.

According to Howe and Boden (2007), various heat related illnesses extend from fatal illnesses like heat stroke, to less critical illnesses such as heat oedema. All heat related illnesses are dependent on the rate of exposure to heat and the individuals pre-existing health conditions. Severe heat related illnesses may cause severe permanent damage to the kidneys, liver, heart and lungs.

2.4.1.1 Heat oedema

Heat oedema is regarded as a minor heat disorder which is characterized by the swelling of the limbs as a result of dilation of blood vessels from exposure to high temperatures. Grubenhoff *et al*. (2007) states that heat oedema is self-limited and hardly lasts more than a few weeks. Treatment consists of moving the patient to a cooler environment and elevating the affected body parts.

2.4.1.2 Heat syncope

Heat syncope, is known as fainting, occurs as a result of insufficient flow of blood to the brain and dehydration (Grubenhoff *et al*. 2007). It may be caused by standing for a long time. The elderly and poorly acclimatized individuals are highly susceptible to it. Howe and Boden (2007) illustrate that it is also self-limiting following a supine positioning of the patient, cooling and rehydration.

2.4.1.3 Heat cramps

According to Grubenhoff *et al*. (2007) Heat cramps are irregular, painful contractions of skeletal muscles occurring mostly in the limbs and abdomen. Grubenhoff *et al*. (2007) points out that heat cramps occur after carrying out strenuous activity and are a result of liquid replacement but not sodium replacement following sweat. They last for a few minutes and usually disappear spontaneously. Treatment involves resting and adequate intake of water and salt.

2.4.1.4 Heat exhaustion

Heat exhaustion is a moderate heat disorder that can occur when the core body temperature is elevated but less than 40 ^{o}C. It may be a warning of an awaiting serious heat disorder, heat stroke. Common symptoms of heat exhaustion include headache, dizziness, irritability, nausea, vomiting and muscle cramps (Howe and Boden 2007). According to Grubenhoff *et al*. (2007), heat exhaustion can be divided into two categories depending on its course. Inadequate liquid replacement results in what is termed hypernatremia heat exhaustion while prolonged water replacement with inadequate sodium intake results in hyponatremia (Grubenhoff *et al*. 2007). Treatment of heat exhaustion is replacement of sodium and water and rest in a cool environment. If untreated, it can progress to heat stroke.

2.4.1.5 Heat stroke

Heat stroke is a much more serious heat disorder. It occurs firstly when the core body temperature is at 40.6 ºC or greater; secondly, when the central nervous system is disturbed; lastly when the there is a lack of sweating as a result of the failure of the sweat glands (Bouchama and Knochel 2002). Grubenhoff *et al*. (2007) illustrate that fatalities due to heat stroke are common amongst the elderly, children and those trapped in cars. Symptoms of heat stroke include headache and confusion, dizziness, nausea and possible unconsciousness. It is advisable to move the individual to cooler environments and remove excess clothing.

2.4.2 Extreme heat events fatalities

Mortalities are said to increase in extreme hot weather events such as heat waves. Kovats and Hajat (2008) and Amengual *et al.* (2014) explain that fatalities during these events are mainly due to cardiovascular, cerebrovascular and respiratory disease along with the vulnerability factors indicated by Mathee *et al*. (2010). Hales *et al*. (2003) indicate that there is uncertainty with hot weather fatalities as to whether hot weather events increase the rate of sicknesses which increase mortality, or whether the pre-existing sickness increases vulnerability to hot weather events thus increasing the rate of sicknesses, then mortality.

Studies conducted in different temperate regions have sought to analyze the hot weather-mortality relationship by simply observing the increased rate of deaths following extreme weather events (Curriero *et al.* 2002, Hajat *et al.* 2002) and by analyzing the historic daily weather data and mortality data of people who died from respiratory disease, cardiovascular disease and the like (Michelozzi *et al*. 2005).

According to Johnson *et al.* (2009), extreme heat events are the number one cause of weather related death for many countries. However, it is difficult to prove because there is a lack of health observation data. In the summer of 2003, across European countries, about 35 000 deaths were recorded as a result of heat waves. During that heat wave, the maximum air temperature in France increased from the normal 25 ºC to an alarming 37 ºC (Fouillet *et al.* 2006). Furthermore in 2010, Russia experienced a severe summer heat wave which resulted in approximately 15 000 deaths (Matsueda. 2011).

In South Africa, there exist no records of the impacts of extreme heat events and mortality, except for in the mining industry (Kjellstrom *et al.* 2014). Therefore, little is known about deaths related to extreme heat events. However, one notable recent event includes a fitness test for Road Traffic Inspectorate job applicants which took place in Pietermaritzburg (PMB) in December 2012 and claimed the lives of eight (Peters 2015b) while hundreds were treated for heat related illness of various degrees.

2.5 CATEGORIES OF HUMAN VULNERABILITY

2.5.1 Demographic factors

Numerous studies done on heat morbidity and mortality indicate that age is the significant demographic factor that determines susceptibility of individuals to extreme heat events (e.g., Harlan *et al*. 2006, Luber and McGeehin 2008, Basu 2009). Buscail *et al*. (2012) state that the elderly (65 years and above) and the young (children younger than five years) are at risk. This is due to the diminishing and immature thermoregulatory and physiologic heat adaptation capacity respectively. Age becomes a contributing factor for other behavioural factors such as social isolation and demographic factors such as health status. For example, elderly people are more likely to live alone and have poor health. In addition to these factors, vulnerability to heat mortality and morbidity is reported to vary in terms of gender, race (e.g., Basu 2009), level of education and socio-economic status (Harlan *et al.* 2006, Mathee *et al*. 2010).

2.5.2 Behavioural factors

Individuals' choice of activity such as engaging in strenuous activities or standing outdoors in hot weather as well as the choice of clothing makes them more prone to heat related illnesses. Basu and Samet (2002) state that other behavioural factors that were associated with high heat mortality include living alone, not having access to air conditioning and being an alcoholic.

2.5.3 Regional factors

Regional factors that determine an individual's risk to extreme heat events include the geographic location, residential location and the type of residence (EPA 2006). Because of the impact of the urban heat island effect, people who reside in urban areas are more at risk compared to those in rural areas. The EPA (2006) state that because of tall buildings, urban areas have a reduced air flow. Lastly Harlan *et al*. (2006) states that in urban areas, summer temperatures are more extreme than in suburban and rural areas.

2.6 HEAT ACCLIMATIZATION

Heat acclimatization is individuals' physiological adaptation to hot environments through repeated exposure to heat. Sufficient duration of heat-acclimatization enhances physiologic function, heat tolerance, and exercise performance. It usually takes about 7 to 14 days for individuals to be acclimatized (Maughan and Shirreffs 2004). According to Maughan and Shirreffs (2004), acclimatization to hot and humid environments is primarily determined by the rise in body temperature and induced sweating response. When people who are not acclimatized perform strenuous work in heat, their evaporative heat loss mechanism becomes inadequate to lower their elevated body temperature. According to Tian *et al*. (2011), acclimatization can be encouraged through introducing humans to extreme heat environments regularly.

Maughan and Shirreffs (2004) illustrate two ways of achieving adaptation for competitions such as long-distance running in heat. The first way is to relocate and train in the place of the competition. The second way is referred to as acclimation, which involves creating artificial but similar climatic conditions as the venue of the competition.

Research done on heat acclimatization has primarily focused on athletes (e.g., Luo *et al.* 1999, Yeargin *et al.* 2006), military (e.g., Radakovic *at al*. 2007), and secondary school athletes (e.g., Casa and Csillan 2009) and recently on average humans working in excessively hot environments (e.g., Tian *et al*. 2011). Kalkstein and Valimont (1987) illustrate that a number of studies have evaluated acclimatization as a factor contributing to heat related deaths. The authors elaborate that the use of temperature-humidity indices by meteorologists do not accommodate acclimatization for human activities as they are based on absolute values only.

2.7 MONITORING HEAT STRESS

Over the past century, numerous bioclimatic indices have been developed and used in different regions to assess heat burden on human beings and animals. Epstein and Moran (2006) list about 40 of these indices. They divided these indices into three distinct groups, according to their purpose. They referred to the first group as ‘rational indices’. These are based on calculations that include the heat balance equation. The second group they referred to as ‘empirical indices’. These indices are based on the measured and the individual’s vote of heat strain such as the physiological strain index by Moran *et al*. (1998). The last group termed ‘direct indices’ are based on direct measurements of environmental factors such as the Steadman’s apparent temperature, heat index and the wet bulb globe temperature (WBGT). The direct indices are easy to apply and are more user friendly (Blazejczyk *et al*. 2012). Epstein and Moran (2006) argue that the first two groups are hard to apply on a daily basis, as they depend on numerous variables, of which some are unavailable. The following section reviews selected heat stress indices from the ‘direct indices’ group.

2.7.1 The wet bulb globe temperature index (WBGT)

The WBGT is one of the indices used worldwide to present the level of heat sensed by people who are conducting strenuous activities. It is the index of preference by the South African Occupational Health and Safety Act 85 of 1993. According to Blazejczyk *et al*. (2012), it was developed by Yaglou and Minard (1957) as part of the research on heat related injuries in the US Navy military training.

Hyatt *et al*. (2010) state that it is a composite temperature used to estimate the influence of temperature, humidity, wind speed and solar radiation on humans. WBGT is the weighted average of the black globe temperature (T_g), natural wet bulb temperature (T_w) and dry bulb temperature (T_a), using:

$$\text{WBGT} = 0.7\ T_w + 0.3\ T_g \qquad [2.3]$$

for indoor and outdoor conditions without solar radiation and

$$\text{WBGT} = 0.7\ T_w + 0.2\ T_g + 0.1\ T_a \qquad [2.4]$$

for outdoor conditions.

The use of the two WBGT equations requires the measurement of black globe temperature, which can be obtained from a copper sphere painted black with a thermometer placed at the centre of the globe (Dimiceli *et al*. 2011). According to Ongoma and Muthama (2014), the use of the WBGT to assess the heat stress is limited since it requires the use of the black globe which is usually not available at weather stations. This has led researchers to either estimate the black globe measurements (e.g., Hunter and Minyard 1999, Tonouchi *et al*. 2006, Liljegren *et al.* 2008, Dimiceli *et al*. 2011), or WBGT (e.g., Australian Government Bureau of Meteorology (BOM) 2010) measurements from the routinely measured automatic weather station (AWS) data.

Tonouchi *et al*. (2006) presented an equation based on the heat balance on a flat surface that only requires the measurements of the solar radiation, air temperature and wind speed to calculate the globe temperature. Their globe temperature (°C) equation is as follows:

$$T_g = T_a + 0.0175\ I_s - 0.208\ u \qquad [2.5]$$

where T_a is the air temperature (°C), I_s is the solar irradiance (W m^{-2}) and u is the wind speed (m s^{-1}).

The BOM (2010) estimates the WBGT from an equation that does not take changes in solar irradiance and wind speed into consideration. The BOM WBGT equation is given by:

$$\text{WBGT} = 0.567\ T_a + 0.393\ e + 3.94 \qquad [2.6]$$

where T_a is the dry bulb temperature (°C) and e is the water vapour pressure (kPa).

As is the case of other heat stress indices, the WBGT has detailed precautions recommended for a person exposed to direct sunlight. Table 2.1 provides the work, rest and water intake recommendations for a certain WBGT category.

The recommendations provided in Table 2.1 are mainly for acclimatized army recruits since the WBGT was primarily developed for soldiers exposed to extremely hot weather. For any other personnel that will be exposed to sunlight the Occupational Safety and Health Administration (OSHA) (1999) provides similar work/rest duration but specifies easy work as 250 W, moderate work as 425 W and hard work as 600 W. Blazejczyk *et al.* (2012) provided different recommendations (Table 2.2) for sporting activities which do not include the water replacement guide.

2.7.2 Heat index

Heat index (HI) is one of the examples of the direct indices. The commonly used heat index equation is the National Oceanic and Atmospheric Administration's (NOAA) (2009) heat index which was the original work of Steadman (1979) given by:

$$HI = (-42.379 + 2.04901523 \times (9 \times T_a/5 + 32) + 10.14333127 \times RH - 0.22475541 \times (9 \times T_a/5 + 32) \times RH - 6.83783 \times 10^{-3} \times (9 \times T_a/5 + 32)^2 - 5.481717 \times 10^{-2} RH^2 + 1.22874 \times 10^{-3} \times (9 \times T_a/5 + 32)^2 \times RH + 8.5282 \times 10^{-4} \times (9 \times T_a/5 + 32) \times RH^2 - 1.99 \times 10^{-6} \times (9 \times T_a/5 + 32)^2 \times RH^2) - 32 \times 5/9 \qquad [2.7]$$

where T_a is the ambient dry bulb temperature in (°C) and *RH* is the relative humidity (%).

The NOAA heat index is based on the Steadman (1979) heat index, which was originally termed the Apparent Temperature. The HI calculation is based on the human model with the measured values of air temperature and relative humidity and assumed values of the assumed magnitudes of water vapour pressure, skin's surface area, significant diameter of human, clothing cover, core temperature, core water vapour pressure, activity, effective wind speed, clothing resistance to heat transfer, radiation to and from the skin's surface, sweating rate, ventilation rate, skin resistance to heat transfer, and surface resistance to water vapour transfer in order to determine the air temperature perceived by humans. The magnitude of the assumed values are given by Rothfusz and Headquarters (1990) and are shown in Table 2.3. Even though the heat index was initially developed to study thermal comfort, it has gained extensive attention from researchers in environmental health to assess the impacts of air quality on cardiovascular diseases (e.g., Zanobetti and Schwartz 2005), impacts of elevated outdoor temperatures on mortality (Barnett *et al*. 2010) and for the design of the synoptic-scale heat awareness systems (Sheridan and Kalkstein 2004).

Table 2.1: Work-rest/water intake schedule for specific WBGT (Spitz *et al.* 2012)

WBGT flag category	WBGT index (°C)	Easy work		Moderate work		Hard work	
		Work/Rest (min)	Water intake (L h^{-1})	Work/Rest (min)	Water intake (L h^{-1})	Work/Rest (min)	Water intake (L h^{-1})
1	25.6 – 27.7	No Limit	1/2	No Limit	3/4	40/20	3/4
2	27.7 – 29.4	No Limit	1/2	50/10	3/4	30/30	1
3	29.4 – 31.1	No Limit	3/4	40/20	3/4	30/30	1
4	31.1 – 32.2	No Limit	3/4	30/30	3/4	20/40	1
5	>32.2	50/10	1	20/40	1	10/50	1

Easy work	Moderate work	Hard work
• Weapon maintenance • Walking: hard surface at 4.0 km h^{-1}, <15 kg load • Manual of arms • Marksmanship training • Drill and ceremony	• Walking: loose sand at 4.0 km h^{-1}, no load • Walking: hard surface at 5.6 km h^{-1}, < 18 kg load • Patrolling • Individual movement techniques (low crawl, high crawl) • Defensive position construction	• Walking: hard surface at 5.6 km h^{-1} (3.5 mph), <18 kg load • Walking: loose sand at 4.0 km h^{-1} with load • Field assaults

According to Savage (2014), HI exceeds the air temperature for relative humidity values greater than 40% and the air temperature values greater than 26.7 °C. The heat index is set apart from other indices by the heat index chart, which categorizes the heat index values with possible health illnesses. For example, HI values within 26.7 to 32.2 °C, the caution category is associated with the development of fatigue. Other different categories of HI are shown in Table 2.4.

Table 2.2: Recommendations for outdoor activity on different categories of WBGT (Blazejczyk *et al*. 2012)

WBGT category (ºC)	Recommendations
< 18	Unlimited
18-23	Symptoms of heat stress may develop if the temperature advances
23-28	Active exercise for an unacclimatized person should be shortened
28-30	Active exercise for all but well-acclimatized person should be shortened
>30	All training should be stopped

2.7.3 Humidex

Humidex is a Canadian index used by meteorologists to determine the thermal burden on an average human. According to Blazejczyk *et al.* (2012) it was developed in 1965 and it is still used by the Canadian Weather Services in weather forecasts. Humidex (ºC) was initially developed to assess the perceived outdoor conditions. However, some researchers (e.g., Rana *et al*. 2013) have proposed its use indoors as well. It combines water vapour pressure and air temperature to determine how hot or cold it feels. It is calculated using:

$$Humidex\ = T_a + 0.555\ [\ 6.11 \times e^{5417.753} \times (\frac{1}{273.16} - \frac{1}{T_{dp}}) - 10] \qquad [2.8]$$

where T_a is the air temperature (ºC) T_{dp} is the dew point temperature (K). Humidex also provides the categories of comfort for particular degree of humidex as shown in Table 2.5.

2.7.4 Discomfort index

Discomfort index (DI) is the human heat stress index used by the South African Weather Services (SAWS). It is calculated using:

$$Discomfort\ index\ = (2 \times T_a) + (RH/100 \times\ T_a) + 24 \qquad [2.9]$$

where T is the air temperature (ºC), and RH is the relative humidity (%). There is no clear guidelines of when the discomfort index yields conditions that are harmful to individuals. Banitz (2001) states that a warning is issued if the discomfort index is equal to 42 ºC or greater. However, the SAWS (2016) indicates that the warning is given according to the certain discomfort level given in Table 2.6.

Table 2.3: Parameters assumed by Steadman (1979) in the heat index calculation

Parameter	Magnitude
Surrounding water vapour pressure	1.6 kPa
Skin's surface area	1.7 m tall person weighing 66.7 kg
Ratio of effective radiation area of skin	0.80
Significant diameter of human	153 mm
Clothing cover	0.84 (84% coverage)
Core body temperature	37 ^oC
Core body water vapour pressure	5.65 kPa
Metabolic rate	Body heat production of 180 Wm^{-2} for a person walking at 1.4 $m\ s^{-1}$
Effective wind speed	2.5 $m\ s^{-1}$
Ventilation rate	Amount of heat lost through exhaling (2 to 12% depending on the relative humidity)
Skin resistance to heat transfer	0.0387 $m^2\ K\ W^{-1}$
Skin resistance to moisture transfer	A function of the water vapour-pressure difference through the skin and relative humidity (= 0.0521 $m^2\ kPa\ W^{-1}$)
Clothing resistance to heat transfer	Clothing fabric with a volume of 20% fiber and 80% air
Clothing resistance to moisture transfer	0.021 kPa $m^2\ kPa\ W^{-1}\ cm^{-1}$
Emissivity	0.97
Surface convection	17.4 (exposed parts), 11.6 (clothed parts) and 12.3 (for entire body at ≥ 26 ^oC
Surface resistance to moisture transfer	Ranges from 16.5 to 16.7 at sea level depending on air temperature and water vapour pressure
Sweat rate	640 $g\ h^{-1}$

2.7.5 Mean radiant temperature

Mean radiant temperature (T_{mrt}) is defined as the 'uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure' (ASHRAE 2001). It sums up all shortwave and longwave radiation fluxes to which the human body is subjected. Therefore, it has an important impact on human thermal comfort and plays a significant role in governing the energy balance of the human body (Lin *et al*. 2010). Auliciems and Szokolay (1997) state that the numerous thermal models that are available for use today include T_{mrt}.

Table 2.4: Categories of heat index with different health risks (NOAA 2009)

Heat index (ºC)	Category	Possible heat disorders for people in high risk group
26.7-32.2	Caution	Fatigue possible with prolonged exposure and/or physical activity
32.2-40.6	Extreme caution	Sunstroke, muscle cramps, and/or heat exhaustion possible with prolonged exposure and/or physical activity
40.6-54.4	Danger	Sunstroke, muscle cramps, and/or heat exhaustion likely. Heatstroke possible with prolonged exposure and/or physical activity
≥ 54.4	Extreme danger	Heat stroke or sunstroke likely

Table 2.5: Degrees of comfort level for different categories humidex (Blazejczyk *et al.* 2012)

Humidex (ºC)	Degree of comfort
20-29	No discomfort
30-39	Some discomfort
40-45	Great discomfort; avoid exertion
≥ 46	Dangerous; possible heat stroke

There are various ways of estimating the T_{mrt}, ranging from simple and expensive methods to different software models such as the RayMan model, ENVI-met and SOLWEIG. An easy way of estimating T_{mrt} is outlined by Nikolopoulou *et al*. (1999) and Kantor and Unger (2011), which estimates the T_{mrt} by taking air temperature (T_a), wind speed and globe temperature (T_g) into account. The method was initially developed for indoor conditions by Vernon (1932) (cited by Lindberg *et al*. 2008) but was later applied to outdoor conditions by Nikolopoulou *et al*. (2001) and Thorsson *et al*. (2007). According to Kantor and Unger (2011), T_{mrt} (ºC) based on this method is calculated using the following equation:

$$T_{mrt} = \sqrt[4]{(T_g + 273.15)^4 + \frac{1.1\times10^8 . V_a^{0.6}}{\epsilon . D_g^{0.4}}\left(T_g - T_a\right)} - 273.15 \qquad [2.10]$$

where ϵ is the emissivity of the sphere (0.95 for a black globe), D_g is the diameter of the sphere (mm) and v_a is the wind speed in (m s^{-1}).

Table 2.6: Degrees of discomfort level for different categories DI

Discomfort index (ºC)	Degree of discomfort
32.2-37.7	Very uncomfortable
37.7-43.3	Extremely uncomfortable
≥ 43.3	Hazardous to health

For this method, the globe temperature was traditionally obtained from the black hollow copper sphere of 150 mm-diameter, 0.4 mm thick, with a thermometer placed at the centre of the globe. However, the use of such globes has been criticized mainly for their shape, colour and size. Kantor and Unger (2011) illustrate that because of the spherical shape, absorbed radiation is equally averaged from all directions allowing a good estimate for a seated person but not for the standing person. Owing to the findings of earlier studies (Benton *et al.* 1990), recent researchers (Thorsson *et al*. 2007, Huang *et al*. 2012) have used globes of smaller diameter (38 mm or 40 mm) because the smaller globes have the advantage of a reduced response time (Nikolopoulou *et al*. 1999). Nikolopoulou and Lykoudis (2006) criticises the use of the black globe for outdoor comfort studies because black globe thermometer without correction for humans' solar thermal reflectivity presumes that everyone in the sun is wearing black clothing and thus a higher value of T_{mrt} is determined. Instead they suggests that a grey sphere may be used to avoid overestimating T_{mrt} in such conditions

Hoppe *et al*. (1992), Thorsson *et al*. (2007) and Kantor and Unger (2011) illustrate the most accurate method of measuring T_{mrt}. This method calculates the T_{mrt} from the three-dimensional measured short-wave and long-wave radiation fields. Comparing this method and the one that uses the 38 mm globe, Thorsson *et al*. (2007) found little discrepancy for a cloudy day. This method has been criticized for being costly as it requires three net-radiometers arranged in different directions so that each measures four radiation components separately. This method requires the knowledge of the mean radiant flux density (S_{str}) of the human body. According to Thorsson *et al*. (2007), S_{str} (W m^{-2}) is calculated as:

$$S_{str} = \alpha_k \sum_{i=1}^{6} K_i F_i + \mathcal{E}_p \sum_{i=1}^{6} L_i F_i \qquad [2.11]$$

where, K_i (W m^{-2}) is the shortwave irradiances, L_i (W m^{-2}) is the infrared irradiances, F_i is the angular factor between the adjacent surface and a person corresponding to direction of measurements given by i = 1 to 6. The shortwave radiation absorption coefficients α_k have a standard value of 0.7 and $\mathcal{E}_p$ the emissivity of the human body with a standard value of 0.97.

The T_{mrt} is then calculated according to Stefan-Boltzmann's law from S_{str} using the following formula:

$$T_{mrt} = \sqrt[4]{\frac{S_{str}}{\varepsilon_p . \sigma}} - 273.15 \qquad [2.12]$$

where, σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}).

2.8 CONCLUSIONS

While excessive heat events have a profoundly negative impact on human comfort and health, they cannot be attributed to a single aspect. This review has outlined the interactions that occur in the environment which are the determinants of an individual's comfort or discomfort. Understanding the interactions that occur between the human body, environment and social and individual's preferences can lead to the development of a sound and appropriate tool to avoid the damages that can be caused by excessive heat events and provide preventative measures.

Several tools for assessment of heat stress have been developed across the world, ranging from cheap and simple methods to expensive and complex. However, none of these tools encompasses all the aspects that are crucial for determining human vulnerability to excessive heat events. Present heat stress assessment methods cater for human body aspects and meteorological aspects and neglect the social, economic and regional aspects that increase human vulnerability.

CHAPTER 3: INVESTIGATION OF THE MICROCLIMATE AND RADIATION BALANCE OF A CAR PARKED IN THE OPEN

ABSTRACT

The microclimate of a car parked in direct sunshine on days with clear skies can be lethal to humans as well as to animals and may damage valuable items. Deaths of children left unattended in stationary cars for extended periods of time under these conditions have been well documented in the United States of America. However, these deaths receive far less attention in other countries such as South Africa when compared to child deaths due to other causes. The microclimate of a car was measured periodically for more than a year, inside a golden-brown Audi A3 parked adjacent to an automatic weather station in Pietermaritzburg, South Africa. Various meteorological sensors were used for the radiation balance inside the car and microclimate measurements and calculations of different indices were used to quantify the level of apparent temperature of human beings. These indices included the heat index and the mean radiant temperature to quantify the microclimate of a parked car. A web-based system was used to display near real-time data which allowed timely decisions to be made about what should be measured and where. The temperatures measured in the passenger's seat, boot, under the driver's seat and at the back seat were compared with the outside air temperature and were displayed on a website. The car was subjected to different treatments on different days, i.e. changes in orientation, levels of ventilation and changes in the seat colour. The results showed that the car was much hotter when facing north. On cloudless days, even when the ambient air temperature is as cool as 20 °C in winter, the cabin temperatures can reach 49 °C at the back seat where children and pets are normally placed. In summer, the maximum passenger's seat temperature recorded inside the car was 75 °C when the air temperature outside the car was 33 °C. On cloudless days, the seat and inside-cabin roof temperatures measured using infrared radiometers may be similar. Additionally, the reflected solar irradiance is low due to shaded areas inside the car. Therefore, the transmitted solar irradiance is the dominant term of the radiation balance. In the absence of forced convection (wind), and evaporative cooling, the transmitted solar irradiance that is absorbed, significantly heats the interior surfaces. The air in contact with the interior surfaces is then heated, rises and free convection occurs. This process causes dangerously high air temperatures inside cars kept in the sun even in winter when the outside air temperature is as low as 18 °C. Changes in legislation are required to ensure that drivers have a responsibility to their passengers even when their vehicle is in a parked position. Legislation should also require car manufactures to install motion detectors in the front and rear seats to warn of interior passenger motion if all car doors are locked.

KEYWORDS: car cabin temperature, car-seat emissivity, infrared radiometer, globe thermometer, near real-time data, web-based temperature display, automobile hyperthermia

3.1 INTRODUCTION

The microclimate of a car can be lethal to humans as well as to animals and may damage valuable items such as computers and cameras that are left inside the car for periods of time. Deaths of children left unattended in stationary cars for extended periods of time have been well documented in the United States of America. However, these deaths receive far less attention in other countries such as South Africa when compared to child deaths due to other causes. In 2015 alone, 24 children died in the USA from vehicle-related hyperthermia, and a total of 670 children died from vehicle-related hyperthermia between 1998 and 2016 (Null 2016).

Grundstein *et al*. (2009) reported that vehicle-related hyperthermia deaths in children in the USA have been constructed from news accounts. In South Africa it is reported that every summer at least one child loses its life and suffers heat stroke from automobile hyperthermia (Rose-Innes 2012). One notable event took place at Mafikeng on the 30th of April 2014 when hyperthermia claimed the lives of three siblings (aged 4, 6 and 10 years). The siblings had been left inside the car for almost 20 minutes by their parents (IOL News 2014). Several other cases in this country have been reported when children suffered from heat stress and were rescued by a bystander or paramedics (Rose-Innes 2012). For example, two recent cases were reported in Pietermaritzburg in July 2015 when parents in a shopping mall had left their children inside their car. In both instances, the children were rescued by paramedics.

Parents often leave their children in parked vehicles to avoid the inconvenience of taking them to work, inside shopping malls and to other events. Many parents are unaware of the impending dangers of leaving their children unattended in a parked vehicle even for short periods and some are delayed or forget their children in their car. Although forgetting children in cars rarely occurs, it is reported to be the highest contributing factor to the mortality of children (Null 2016). According to McLaren *et al*. (2005), other than the actual loss of life, every year hundreds of children suffer from heat-related sicknesses of various degrees as a direct result of being left unattended in parked cars.

Various studies have been done in different meteorological conditions (Marty *et al.* 2001, McLaren *et al.* 2005), different types of vehicle (King *et al*. 1981, Marty *et al.* 2001), and with different levels of ventilation (McLaren *et al.* 2005, Dadour *et al.* 2011) to quantify the increase in cabin temperature and the dangers associated with it. Grundstein *et al*. (2010) revealed that the temperatures inside a car can increase drastically within 5 min, especially when the vehicle is fully exposed to the sun with the windows closed. Marty *et al.* (2001) and Grundstein *et al*. (2009) state that under these conditions, temperatures inside the car can increase by 22 to 27 ºC within an hour and can reach a maximum cabin temperature of 89 °C. McLaren *et al.* (2005) observed that the temperatures inside a car can increase by similar degrees, regardless of whether the windows are closed or open – the latter referred to as a "crack".

Children are more susceptible to heat-related sicknesses such as heat strokes and heat exhaustion than adults for two reasons. Firstly, their thermoregulation is less efficient when compared to that of an adult (McLaren *et al.* 2005, Booth *et al*. 2010). Secondly, they have a larger surface area to body mass ratio than adults (Booth *et al.* 2010, Ferrara *et al.* 2013). This means that they absorb heat more quickly than they can dissipate compared to adults. Therefore, children left inside a car are at a higher risk because their small body size means they are quick to heat up. Furthermore, their sweating mechanism and skin temperature response is insufficient to withstand these increases in air temperature inside the car. More importantly though, small children are often left strapped in a baby chair with layers of clothing or thick clothing that cannot be removed by the infant.

Solar irradiance plays a crucial role in the increase of cabin temperatures. There are two kinds of radiation that govern the human radiation balance namely, net solar irradiance (incoming solar irradiance minus the reflected solar irradiance) and net infrared irradiance (outgoing minus returned infrared irradiance). The difference in the total of all incoming and outgoing irradiance is referred to as the net irradiances (I_{net}). Net irradiance is given by the equation:

$$I_{net} = I_s - rI_s + L_d - L_u \qquad [3.1]$$

where I_s is the incident solar irradiance, rI_s is the reflected solar irradiance, L_d is the downward infrared irradiance and L_u is outgoing infrared irradiance. All terms are in W m^{-2}.

The causes of the drastic increase in the car cabin temperature are however vague. Some researchers suggest that it is caused by a greenhouse effect, whereby the car windows allow the shortwave irradiances to enter the car but are opaque to the infrared irradiances inside the car (Grundstein *et al.* 2009). Others have suggested that it is due to the radiation imbalance (Grundstein *et al.* 2011), minimum ventilation and no evaporative cooling (Savage 2015) among other things. The greenhouse effect theory suggests that shortwave radiation passes into the car through the windows and warms the objects that it encounters. The heat absorbed by these objects is then transmitted into the surrounding air through conduction and convection as infrared radiation that is trapped inside the car. Positive net irradiance results. However, minimal evaporative, conductive and convective losses would also cause the interior of a car to heat up considerably under conditions of a significant positive net irradiance.

Net irradiance is normally measured using a net radiometer with a single measurement output. It can also be determined using four component instruments: one for incoming solar irradiance, another for reflected solar irradiance and two infrared radiometers for the infrared components. Two component net radiometers are used to determine net solar and net infrared irradiances.

Many studies done on car microclimates use air temperature as the only meteorological parameter that poses risk to humans and animals left inside the car. However, this study included some of the substitute estimates of heat exposure to humans. These measures include the mean radiant temperature (T_{mrt}) and the heat index. The T_{mrt} is defined as the 'uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure' (ASHRAE 2001). It sums the shortwave and infrared irradiances that the human body is subjected to. Since it uses the measurement of the black globe (T_g) for its calculation, it takes into consideration a number of environmental factors to determine the heat stress level on humans. These factors include air temperature, wind speed, relative humidity, solar and infrared irradiances. According to Kantor and Unger (2011), T_{mrt} (ºC) based on this method is calculated using the following equation:

$$T_{mrt} = \left[\left(T_g + 273\right)^4 + \frac{1.10\times10^8 V_a^{0.6}}{\varepsilon D^{0.4}}\left(T_g - T_a\right)\right]^{\frac{1}{4}} - 273 \qquad [3.2]$$

where T_{mrt} is mean radiant temperature (°C), T_g is the globe temperature, T_a is air temperature (°C), v_a is wind speed (m s^{-1}), D is globe diameter (m), and ε is the emissivity of the black globe. In the absence of wind speed, as would be expected for an enclosed car, $T_{mrt} = T_g$.

Heat index, also referred to as the apparent temperature, is an index used to measure the influence of different environmental factors which include air temperature, relative humidity, wind and radiation on the ability of the human body to dissipate heat (Delworth *et al.* 1999).

Determination of the radiation balance inside a parked car has, to our knowledge, not previously been investigated. Also, the role of the colour of the seats appears not to have been investigated in previous studies. While the role of car orientation and cracking of windows has been investigated, there have been very few that have performed determination of the T_g and heat index inside vehicles. Furthermore, there have been no studies that have reported conditions inside a car over an extended period of time.

The main aim of the study was therefore to determine the radiation balance and the microclimate of a closed parked car, using various measurement sensors and different indices that are used to quantify the level of apparent temperature of human beings such as the T_{mrt} and the heat index. The study also investigates the impact of changing seat colour, changing orientation of the car and opening or closing the windows on the increase in cabin temperatures and on the radiation balance. The study was also aimed at creating an awareness about leaving children or pets inside a car for extended periods of time.

To achieve this, the study made use of an Agrometeorology Instrumentation Mast (AIM) system (Savage *et al*. 2014), and car in regular use, to guide the research decisions through the near real-time display of the inside car conditions. This made the study different from other studies that have been conducted. Also this mimics a ‘real life scenario’ where children might be left in a car that was previously mobile unlike other studies that have used results from a car that was parked in one area for days. The exclusivity of the study also emerges from the fact that it included measurements of different meteorological parameters that contribute to human discomfort within the car. These parameters included the solar irradiance, infrared irradiance and net irradiance among other measurements.

3.2 MATERIALS AND METHODS

3.2.1 Site detail

The study was conducted over two periods, using two different cars (Table 3.1): for 167 days (23rd of April to 7th October 2010) for car 1 and 17 months for car 2 (25th of February 2014 to 6th August 2015). The cars were in close proximity to an automatic weather station (AWS) most of the time. The AWS is situated in Pietermaritzburg, KwaZulu-Natal, South Africa (altitude 684 m, 29.628º S, 30.403º E). In addition, the measurements for car 2 were taken at different locations in Pietermaritzburg because the car in the study was regularly used. The cars were subjected to different treatments on different days, i.e. changes in orientation, levels of ventilation and changes in the seat colour for car 2.

Table 3.1: Details of measurements and sensors used

Details of measurements	Apparatus used
Car 1 (earlier study) 2010	1993 Toyota Camry, silver in colour with black seats and dim windows. Hobo TEMP loggers[1] placed in a 6-plate Gill radiation shield were used for air temperature measurements.
Car 2 (recent study) 2014/15	2006 Audi A3 (sport back), golden-brown in colour with black seats and dim windows
Sensors	RH and air temperature combination instrument (CS500[2]) in a 6-plate Gill radiation shield; three 24 gauge type-E thermocouples, two unshielded (in the boot and under the front seat), and one placed in a 6-plate Gill radiation shield; two fine wire thermocouples (gauge 30) stitched into the fabric of the passenger's seat; solar irradiance and reflected solar radiation were obtained using two thermopile pyranometers (CM3[3]); one globe temperature measured with a 150 mm-diameter copper sphere, painted matt-black with the thermistor inserted at the centre; NR Lite 2[3] for net irradiance and two IRTs[4], the latter for measuring cabin roof and seat temperatures (models SI-111 and SI-121 respectively)
Calculations	Calculations of the heat index and T_{mrt} using the equation given by Kantor and Unger (2011) using $v_a = 0$ m s^{-1}
Field data loggers	CR1000[2] datalogger - all measurements were averaged/sampled every 2 min and every 60 min
Field-to-base station communication	Datalogger connected to an antenna[5] in line-of-sight with the receiver

[1] Onset Computer Corporation, MacArthur Boulevard, USA
[2] Campbell Scientific Inc., Logan, Utah, USA
[3] Kipp and Zonen B. V., Delft, The Netherlands
[4] Apogee, Apogee instruments Inc., Logan Utah, USA
[5] Poynting antenna, Pointing Direct (Pty), Johannesburg, Gauteng, South Africa

3.2.2 Instrumentation details

3.2.2.1 Car microclimate

For car 1, only inside measurements of relative humidity and air temperature were obtained. The measurements were taken every 5 min using three HOBO data loggers (Table 3.1). The HOBO's were placed at different positions inside the car, i.e. at the front seat and at the back seat, both in 6-plate Gill radiation shields, and one unshielded HOBO was placed in the boot.

For car 2, a CR1000 data logger at a scan rate of ten seconds was used to store the data at an interval of 2 minutes and 60 minutes. Air temperature and relative humidity were measured using a CS500 sensor, placed in a 6-plate Gill radiation shield, and located at the head rest on the front seat 0.34 m away from the roof of the car (Figure 3.1). A 24-gauge type E thermocouple placed in a 6-plate radiation shield was used to measure the air temperature at the back seat, where children or pets would normally sit. Two freely exposed thermocouples were used to measure the air temperature in the boot and that under the front seat of the car. Often, valuable items such as laptops and cameras are left inside the car or in the boot, with the owner being unaware of the temperature range at such positions.

An investigation of the time taken for temperatures inside the car to reach an intolerable level was done in winter on the 6th of August 2015. The investigation was performed with a volunteer inside the car to experience the conditions inside an enclosed car that is parked directly in the sun for an hour and 15 minutes. The investigation was done in the presence of paramedics to supervise the situation.

3.2.2.2 Radiation balance

Radiation balances were performed in car 2. Solar irradiance and reflected solar irradiance were measured using two CM3 thermopile pyranometers (Table 3.1) placed between the front seat and the dashboard. The net irradiance was measured using a NR Lite 2 net radiometer (Table 3.1) without wind speed correction. The upward and downward infrared irradiance components of the radiation balance were measured using two infrared radiometers placed in front of the dashboard targeting 0.06 m^2 of the front seat (placed 0.615 m away from the passenger's seat) and 0.07 m^2 of the cabin roof (placed 0.23 m away from the roof). The pyranometers and net radiometers were positioned so as not to impair their measurements by their shadows. It was therefore not possible to obtain shortwave reflection pyranometer measurements above the passenger seat as this was the location for the net radiometer and infrared measurements.

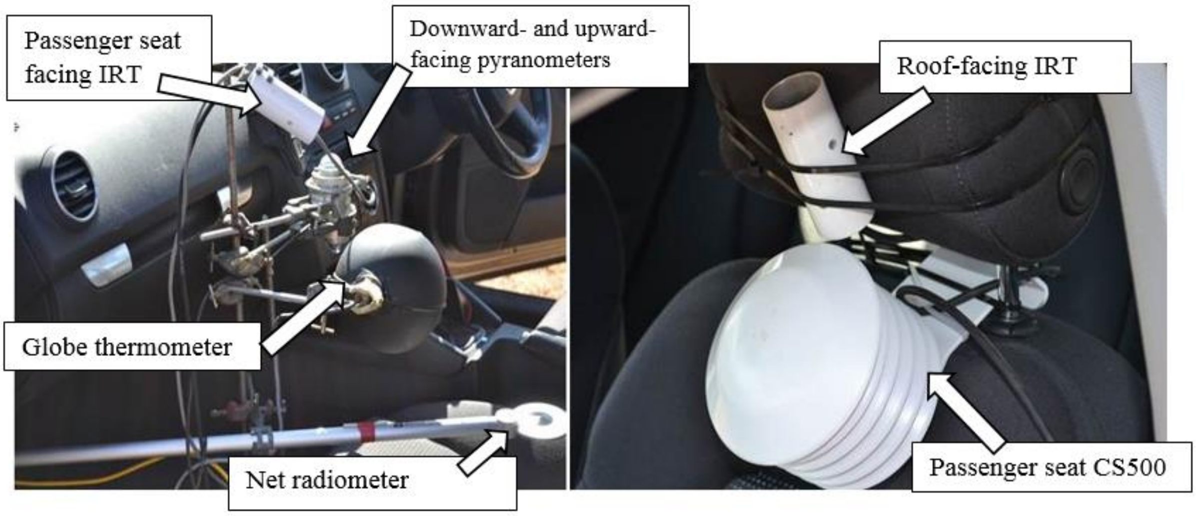

Figure 3.1: Arrangement of sensors inside car 2 for the 2014/15 study. Left: sensors used between the dashboard and the passenger's seat. Right: is the infrared radiometer measuring the temperature of the roof of the car and the CS500 air temperature sensor placed in a 6-plate Gill radiation shield and both attached to the passenger's seat head rest.

The upward infrared irradiance L_u (W m^{-2}) from a surface with an emissivity ε and surface temperature T (K) is given by:

$$L_u = \varepsilon\, \sigma T^4 \qquad [3.3]$$

where σ is the Stefan-Boltzmann constant (W m^{-2} K^{-4}).

Determining the surface temperature from measured infrared irradiance requires knowledge of the emissivity of that surface. Therefore, ε was determined independently. Two 30-gauge type E fine-wire thermocouples were embedded in the passenger seat of the car within the area which the infrared radiometer was targeting. Both the infrared radiometer and the fine-wire thermocouples were used to measure the seat temperature. Each of these methods has its own disadvantages. The seat emissivity (ε_{seat}) was determined using:

$$\sigma T_{IRT}^4 = \varepsilon_{seat}\ \sigma T_{seat}^4 + (1-\varepsilon_{seat})\varepsilon_{roof}\, \sigma T_{roof}^4 \qquad [3.4]$$

where T_{IRT} is the temperature (K) of the seat measured using the infrared radiometer, T_{seat} (K) the seat temperature measured using the thermocouple and T_{roof} (K) the temperature of the surroundings of the target surface where the roof temperature measured using a second infrared radiometer. Assuming that ε_{roof} =1, a plot of σT^4_{IRT} versus σT^4_{seat} would yield a slope of ε_{seat} and an intercept of (1- ε_{seat}) σT^4_{roof}. Alternatively, by rearrangement:

$$\varepsilon_{seat} = (T^4_{IRT} - \sigma T^4_{roof})/(T^4_{seat} - \sigma T^4_{roof}) \qquad [3.5]$$

The assumption that ε_{roof} =1, even if it is not the case, is justified by the fact that it is expected that 1 - ε_{seat} << 1.

3.2.2.3 Apparent indices

The globe temperature was measured using a hollow copper sphere, with a diameter of 150 mm, painted matt-black with a thermistor inserted at the centre. The black globe and the net radiometer were placed 0.6 m above the floor of the car at the front seat. From these measurements, T_{mrt} and the heat index were calculated. The heat index was calculated using the USA National Oceanic and Atmospheric Administration equation for heat index and is given by Kim *et al*. (2006) while T_{mrt} was calculated using Equation 3.2 with v_a = 0 m s^{-1}. All measurements were compared to the measurements obtained from the surrounding weather station. The near real-time data of daily microclimate of a confined car were displayed using a web-based data and information system. During the day, the car was parked in a place such that the antenna was in line-of-sight with the receiver of the AIM system for data transmission. This allowed near real-time plots of the data and timeous decision-making.

3.3 RESULTS AND DISCUSSION

The web-based system was used to provide near real-time data of the interior of the car without disturbance of the inside environment. This allowed timely decisions to be made about what should be measured and where. In order to summarize the large set of data collected, the inside and outside air temperature for a common time and car orientation were averaged according to car orientation, seat colour and the level of ventilation. Selected data, typical of the time of year discussed, are presented.

3.3.1 Seat emissivity and inside car temperatures

3.3.1.1 Seat emissivity

Car-seat temperatures were measured as the average of a pair of 30-gauge type E fine-wire thermocouples (TC) which were embedded in the passenger-seat fabric. Car seat temperature was also measured using the infrared radiometer. In the case of the TC method, radiation error may occur when the thermocouple is exposed to high solar irradiance. On the contrary, the infrared radiometer method assumes a seat emissivity of unity. The seat surface emissivity was determined using Equation 3.5, for which the numerator of the right hand side was plotted on the y axis and the denominator on the x axis (Figure 3.2). Thermocouple radiation error was minimised by using data for car 2 when facing south and included some night time data.

Figure 3.2 shows a positive relationship between the two temperatures, with an R^2 value of 0.99 which shows that the two temperatures are highly correlated. Seat emissivity is determined by the slope of the graph which is 0.96. The result shows that the car seat is almost a perfect radiator since it has an emissivity close to 1. Therefore, for this study, the seat temperature measurements were obtained from radiation emitted with the emissivity equal to 1.

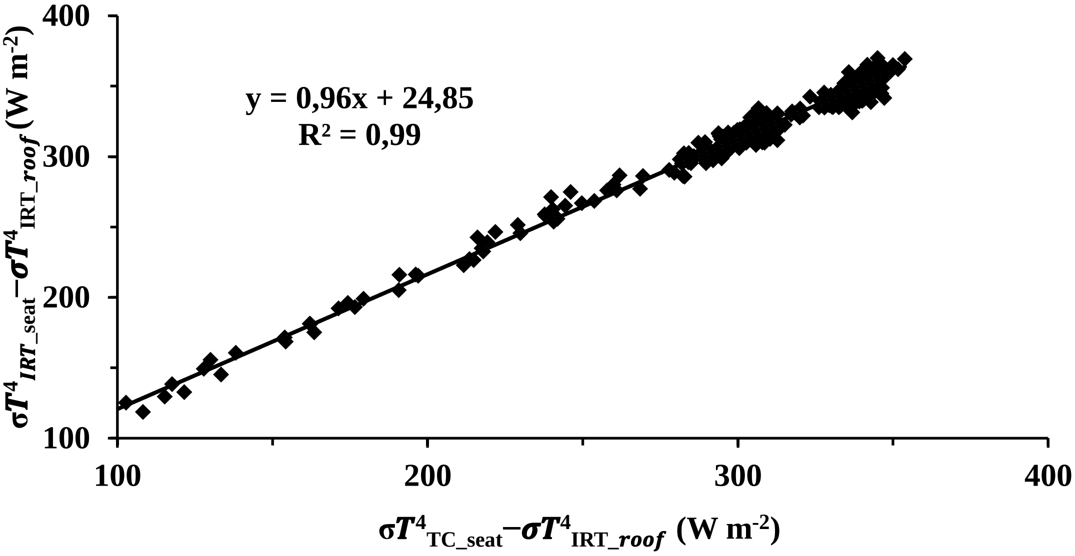

Figure 3.2: Regression plot of the infrared irradiances using seat temperature minus that using the roof temperature when car 2 was parked facing south during the day and parked in a garage during the night on the 4th of July 2014.

3.3.1.2 Maximum cabin temperatures

Summary measurements of three temperatures inside car 2 and the surrounding air temperature for two warm days and two cool days were used to determine the maximum cabin temperature. Measurements taken from the common time on the 23rd of March 2014 and the 30th of October 2014 were summarized into one warm day, while measurements taken from the common time on the 28th July 2014 and the 22nd of August 2014 were summarized into one cool cloudless day and measurements from the 12th of June and the 11th of July 2014 were summarized into one frost day. The summary days are shown in Figure 3.3.

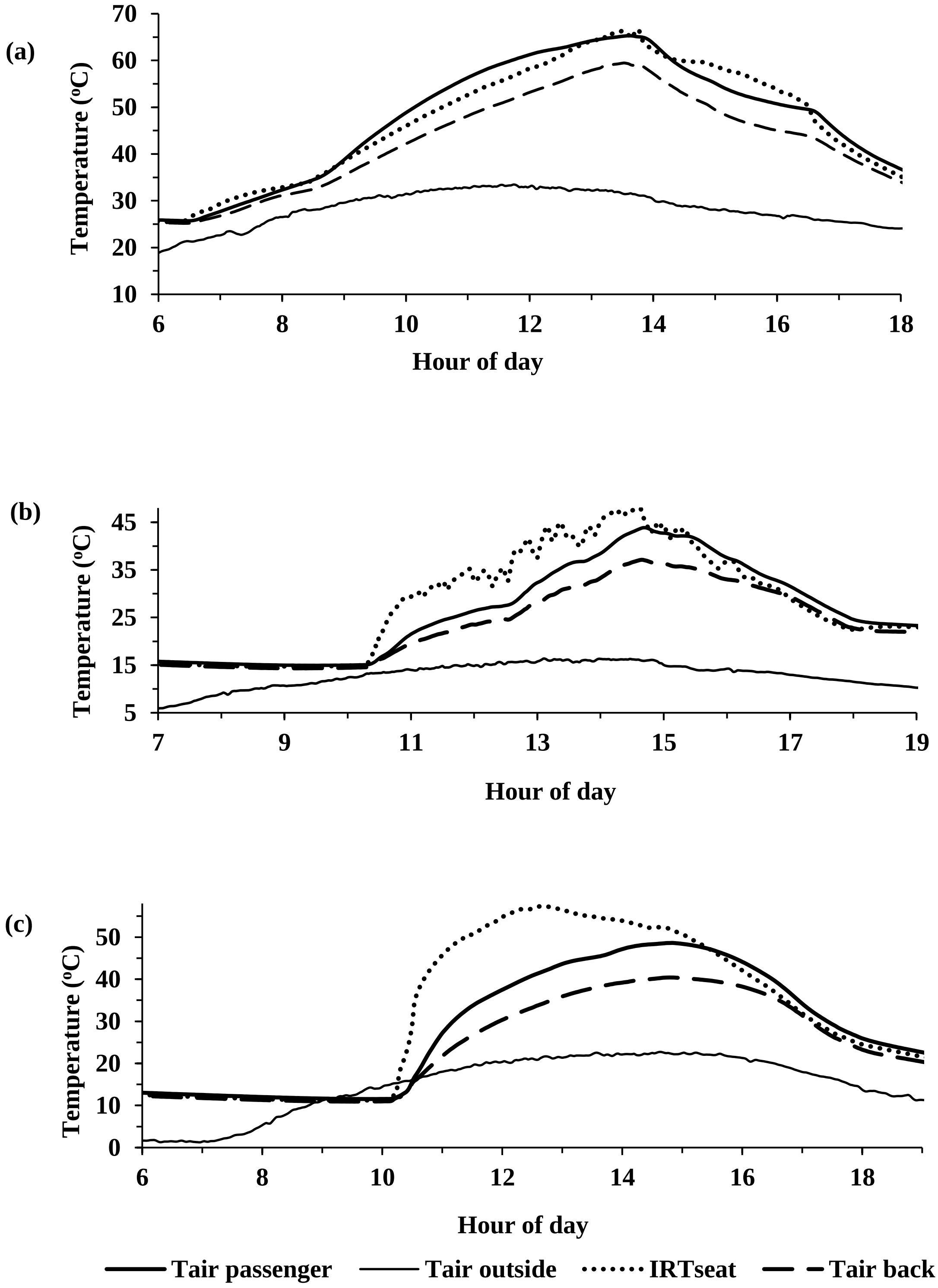

Figure 3.3: Diurnal air temperature, passenger seat temperature inside car 2 and the surrounding temperature: (a) on a warm-cloudless day (23rd March and 30th October 2014), (b) on a cool-cloudless day (28th July and 22nd August 2014) and (c) on a day with frost (12th June and 11th July 2014).

Figure 3.3a shows diurnal measurements of a warm-cloudless day. It shows that the cabin temperatures went 33 °C higher than the ambient temperature. On the same day around midday, the seat temperature rose shockingly to a maximum temperature of 67 °C when the outside air temperature was 31 °C. These car temperatures would be lethal to humans and animals and would cause damage to electronic equipment such as laptops, tablets, cameras and cell phones.

Figure 3.3b shows the cabin temperatures and the outside air temperature for a cool-cloudless day. The cabin temperature, specifically the seat temperature reached the maximum temperature of 46 °C even when the surrounding air temperature was as cool as less than 16 °C. These findings have demonstrated that the outside-car air temperature is not the only factor responsible for the increase in the cabin temperatures. These results are similar to that demonstrated by McLaren *et al*. (2005). They found that even when the surrounding air temperature is fairly cool, the interior of the car heats up drastically when it is sunny.

On all days reported in Figure 3.3, the air temperature at the back seat was cooler than the other cabin temperatures, but still lethal to humans and animals and damaging to electronic equipment on a warm day as it reached the maximum of 59 °C and was 20 °C higher that the outside air temperature on a cool day. These findings agree with those of Grundstein *et al*. (2009), whereby the lowest cabin temperature was high enough to pose substantial risk.

3.3.1.3 Impact of changing orientation of the car and response time

Table 3.2 shows the daily average temperatures for 39 days in 2014 when car 2 was parked facing different orientations. The results show that the seat temperature and the temperature at the passenger's seat were greater when the car was facing north and when it was facing west and were cooler when facing south. This is because when the car is facing north, a greater proportion of the car allows greater transmission of solar irradiance through the windscreen and the two front windows and reduced transmission when facing south.

Table 3.2 shows that regardless of the orientation of the car, the boot temperature is the coolest of all temperatures inside the car. However, even though it is cooler it can still be detrimental. For example on day 138 and day 201 when the car was facing north and south respectively, the outside temperature was as cool as 21 °C while in the boot they were 40 °C and 32 °C respectively.

Table 3.2: Changes in daily average cabin temperatures for different days when car 2 was parked facing four different directions during 2014

Day	Tair out (ºC)	Tair passanger (ºC)	IRT seat (ºC)	Tair boot (ºC)	Tair back seat (ºC)
East					
108	29.94	61.06	66.17	42.11	54.41
141	27.85	50.75	59.98	35.87	43.93
143	28.55	54.93	65.42	36.86	47.85
166	31.07	49.16	52.47	42.09	43.16
174	28.74	48.72	59.14	28.98	40.15
202	22.47	48.24	58.95	32.76	41.82
206	30.94	56.79	63.80	35.43	49.93
214	29.56	50.42	65.65	37.68	45.00
238	29.34	55.58	58.82	37.36	49.47
North					
109	31.22	61.06	66.17	51.84	54.41
138	21.57	53.52	64.09	40.53	46.96
171	20.72	45.88	55.58	26.45	38.63
179	19.98	41.87	44.86	23.12	32.53
191	18.35	46.30	56.55	22.76	38.27
195	20.68	46.22	53.80	23.74	38.59
211	26.45	51.32	66.79	54.21	44.57
279	30.08	61.24	63.02	45.05	62.43
280	36.43	61.24	60.06	45.05	62.43
302	33.91	65.80	67.89	50.67	58.91
South					
110	31.22	54.72	53.78	51.84	51.31
133	25.40	46.93	47.17	36.46	44.75
154	23.72	50.83	64.47	32.45	43.45
163	22.29	48.64	60.16	30.30	40.42
175	28.74	45.60	50.54	33.55	39.91
181	27.87	52.44	59.86	32.25	45.43
185	27.78	41.80	38.60	35.15	38.97
200	21.39	39.48	47.04	23.74	34.03
204	24.22	48.23	57.24	35.44	41.80
205	27.30	48.23	57.24	35.43	41.22
West					
100	27.96	55.06	65.83	52.58	53.63
103	31.62	59.34	70.72	57.23	56.28
122	30.99	51.26	60.34	34.23	46.13
135	24.83	54.58	64.14	40.21	47.66
140	27.85	52.63	59.98	36.11	45.97
149	31.19	46.04	51.83	33.39	39.06
151	30.27	53.70	60.93	35.83	46.93
164	24.08	48.64	60.16	41.50	40.42
168	21.81	36.18	31.74	33.64	30.81
201	21.40	36.46	34.13	32.76	34.45

Overall, the car was hottest when it was facing north, since even at an average outside air temperature as cool as 18 °C (day 191), the seat temperature was a shocking 56 °C while the back seat was double the outside air temperature. Following north is west then east, while south is the coolest. However, changing the orientation does not make any difference in saving lives and in avoiding electronic appliances being damaged, since even cooler orientations are still dangerous enough to kill children and pets left inside the car for extended periods.

Figure 3.4, for a cool winter day (6th August 2015), shows the time at which the temperatures start to increase inside the north-facing car. The results show that temperatures inside the car had already started to increase even before the door of the car was shut at 10h45. At 11h05, 10 minutes after the doors were shut, both the air temperature inside and the heat index had reached 26.7 °C which is the caution category while the air temperature outside the car was 17 °C.

It took only five minutes for the globe temperature inside, which is the composite temperature that represents what one would feel in hot weather, and 25 min for the air temperature and heat index inside to reach 32.2 °C while the air temperature outside was 17 °C. These results agree with the findings of McLaren *et al*. (2005), whereby they found that drastic increase in the air temperature inside the car occurs within the first 30 min after shutting the door of the car.

At 32.2 °C extreme precautions should be taken since prolonged exposure may lead to heat related illnesses such as sunstroke, muscle cramps, or even deadly disorders such as heat exhaustion. It is common for children under the age of 10 to be left in hot cars (Null 2016). Buscail *et al*. (2012) state that children at this age are considered as the high risk group for heat related illnesses and therefore their susceptibility is very high compared to the average person. After 45 min, which could be an average time for doing the groceries with the child left in a car, the air temperature inside the car could have doubled the outside air temperature and reached the danger category (40.6 °C).

Interestingly is that at about 11.6h (11h36), the heat index increased above the air temperature due to the fact that the *RH* increased above 40%. Since the car was enclosed, the increase in *RH* could only have been due to the volunteer sweating although the volunteer did admit to hyperventilation.

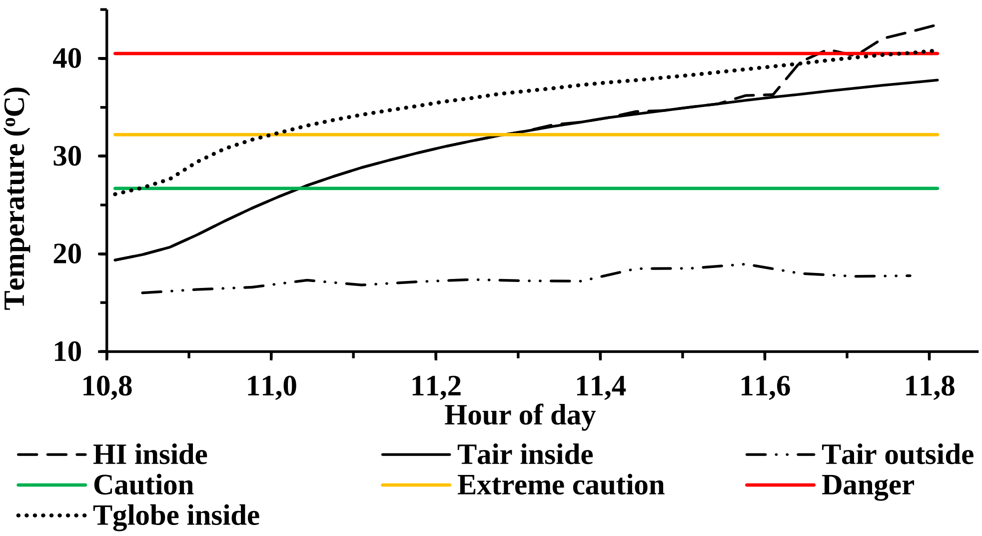

Figure 3.4: Heat index, globe temperature and air temperature inside and outside the car over time with respect to the various heat index precaution for the 6th August 2015 for car 2.

At 11.6 h the volunteer commented that her lungs burnt as the air inside the car became too hot and stuffy. At this time a sudden increase in the heat index curve is notable. This suggests that the volunteer must have been hyperventilating increasing the cabin relative humidity. This means that because of their large lung volume, adults left in hot cars generate more humid air when they are trying to breathe. This in turn has a knock on effect on thermoregulation as humid air prevents sweat from evaporating, reducing evaporative cooling.

3.3.1.4 Impact of wind speed and level of ventilation

Table 3.3 shows the average wind speed and solar irradiance outside car 2 and cabin temperatures on two different days over a specific period of time after the car was parked directly in sun facing west. On the 3rd May 2014 (day 1), the car was parked with the front passenger window left cracked open while on the 9th June 2014 (day 2) the car windows were closed. The car was parked at 09h46 and at 11h30 on the 3rd of May and on the 9th June respectively. Table 3.3 shows that the initial cabin temperatures were lower than the surrounding air temperature and subsequently increased.

A distinguishable increase in the cabin temperature on the 3rd May 2014 was observed after an hour after the car was parked in the sun. During this time the average wind speed was 1.2 m s^{-1}, while temperatures inside the car were 3 ^{o}C higher than the outside air temperature and the solar irradiance was 62 W m^{-2} higher than the initial solar irradiance. Table 3.3 shows that on the 9th June 2014 at sunset, 6 hours after the car was parked (at 17h30), the cabin temperatures decreased due to decreased solar irradiance.

The results show that opening a crack in the front passenger window of the car does not have an impact on cooling the cabin temperatures. This is evident in Table 3.3 when the average wind speed was at its peak after five hours and the cabin temperatures were still increasing, with the interior air temperature of 45.1 ^{o}C and the seat temperature of 46.4 ^{o}C, both up to 18.3 ^{o}C higher than the outside air temperature. A similar trend of increasing cabin temperatures regardless of the increasing wind speed was also observed on the 9th June 2014 when all car windows were closed. Similar effects were observed with car 1 when there was no change in the car cabin air temperature when the driver and the front passenger windows were left open 25 mm. However, opening all the doors and windows of the car instead of opening a crack in a window could allow more cooling by forced convection but with increased security concerns.

3.3.1.5 Impact of changing the seat colour

For this investigation, a white sheet was placed on the seat with the infrared radiometer directed towards the seat when car 2 was orientated north and south. The seat temperatures inside the car when the white sheet was used were cooler than when there was no sheet (data not shown). However, the other temperatures such as the passenger cabin air temperature and the air temperature at the back seat remained the same. Even though there was a slight difference in the seat temperature, it was still lethal to children left inside. This means that a car with a light coloured interior can be a bit cooler than one with a dark interior.

3.3.2 Radiation balance of an enclosed parked car

3.3.2.1 Infrared irradiances inside a parked car

The infrared irradiances measured at the AWS and those measured inside the car on the 3rd August 2014 when the car was parked facing north were compared. The car was parked in direct sun from 08h00 in the morning until 16h30 in the afternoon.

Figure 3.5a shows that the infrared irradiances inside the car (L_u_car and L_d_car) are greater than those measured at the AWS due to the elevated temperatures inside. The maximum infrared irradiances occurred around 12h30. During this time the difference between the incoming infrared radiation measured at the AWS (L_d AWS) and that measured inside the car was 267.3 W m^{-2} while L_u inside was 170 W m^{-2} greater than L_u at the AWS. During the day, when the car was exposed to sunlight, the infrared irradiance emitted by the seat of the car is greater than that emitted by the cabin roof and they are equal at sunset and sunrise, when there is no shortwave irradiance.

Table 3.3: Impact of wind speed and level of ventilation. Car 2 faced west on both days with cracked open window on the 3rd of May 2014 and closed windows for the 9th of June 2014

Elapsed time	Wind speed outside ($m\ s^{-1}$)	Air temperature outside (ºC)	Solar irradiance outside ($W\ m^{-2}$)	Front passenger's seat temperature (ºC)	Seat temperature (ºC)	Back seat temperature (ºC)	Boot temperature (ºC)
Windows cracked open (3rd May 2014)							
0	1.2	22.3	590.1	20.3	20.0	19.5	19.4
10 min	1.0	22.8	600.2	20.5	22.0	20.2	20.3
15 min	1.0	22.8	603.9	21.0	22.4	20.6	20.7
20 min	1.1	23.0	610.7	21.7	23.0	21.1	21.4
30 min	1.1	23.3	621.1	23.2	24.0	22.2	22.7
1 hour	1.2	24.2	652.5	27.4	27.0	25.6	26.3
2 hours	1.3	25.5	698.9	34.1	32.2	31.1	31.8
3 hours	1.3	26.6	700.7	38.7	36.3	35.3	34.7
4 hours	1.3	27.5	710.6	42.3	41.0	38.5	36.8
5 hours	1.4	28.1	689.3	45.1	46.4	41.0	38.3
6 hours	1.4	28.4	633.5	47.0	49.1	42.5	38.9
Windows closed (9th June 2014)							
0	1.8	26.0	642.2	17.0	17.0	17.0	17.0
10 min	1.5	25.8	646.8	17.2	17.1	16.7	17.0
15 min	1.3	25.9	648.1	17.3	18.0	17.0	17.1
20 min	1.8	26.0	649.0	17.5	18.7	17.5	17.2
30 min	1.2	26.0	650.1	18.5	20.4	19.3	17.2
1 hour	1.1	26.5	649.3	23.2	25.0	24.0	20.8
2 hours	1.2	27.0	629.9	31.9	31.6	30.4	25.6
3 hours	1.4	27.2	586.9	35.6	37.8	34.1	28.3
4 hours	1.5	27.3	528.5	39.0	41.3	36.1	29.7
5 hours	1.6	26.9	455.8	40.5	41.5	36.7	30.2
6 hours	1.5	25.9	382.3	39.6	32.0	35.8	29.8

Figure 3.5b shows that the roof and the seat temperature are within 10 °C of each other most of the time. In instances where there is a notable difference in the two temperatures, the seat temperature is often higher than the roof temperature. This trend is apparent in Figure 3.5b from 08h40 until 14h25. During this period the seat temperature reached a maximum of 60.9 °C when the cabin roof temperature was 50.7 °C.

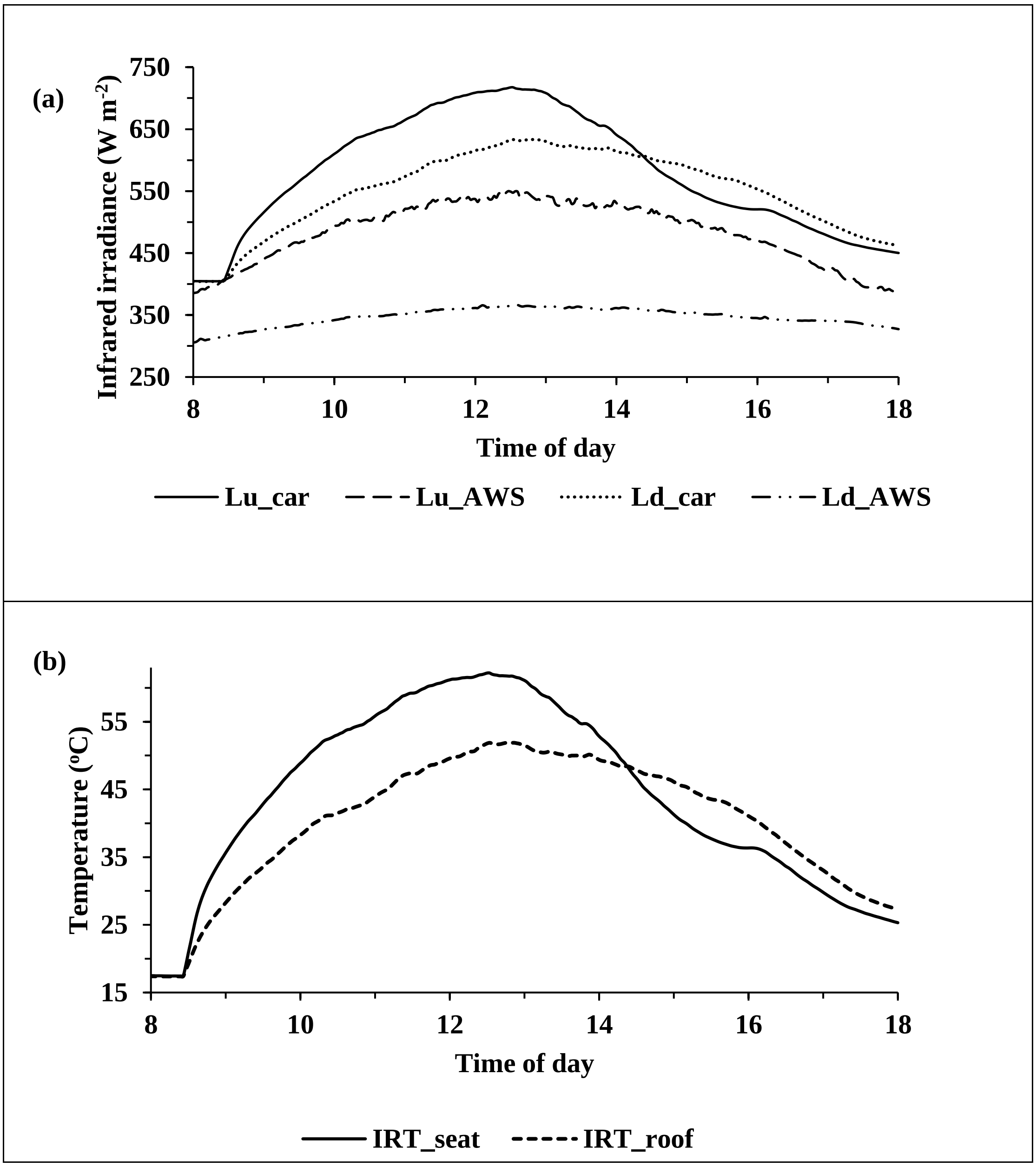

Figure 3.5: (a) The infrared irradiances inside the car and outside the car and (b) the seat and cabin roof temperatures measured using an infrared radiometer on the 3rd August 2014 when the car was parked facing north.

3.3.2.2 Solar irradiances inside a parked car

Figure 3.6 illustrates the shortwave irradiances measured at the AWS and that transmitted into the car on the 3rd August 2014. The maximum of the incoming solar irradiance transmitted (273.2 W m^{-2}) occurs at the same time as the maximum irradiance measured at the AWS (666.8 W m^{-2}).

Surprisingly, in spite of the high inside temperatures (Figure 3.5b), only 35% (Figure 3.6) of the incoming solar irradiance is transmitted into the car. The small percentage transmitted can be attributed to the low transmission coefficient of the front windscreen. Throughout the study, the reflected solar irradiance was very close to or zero. The low reflected solar irradiance can be attributed to a large proportion of shaded areas inside the car and the black floor areas.

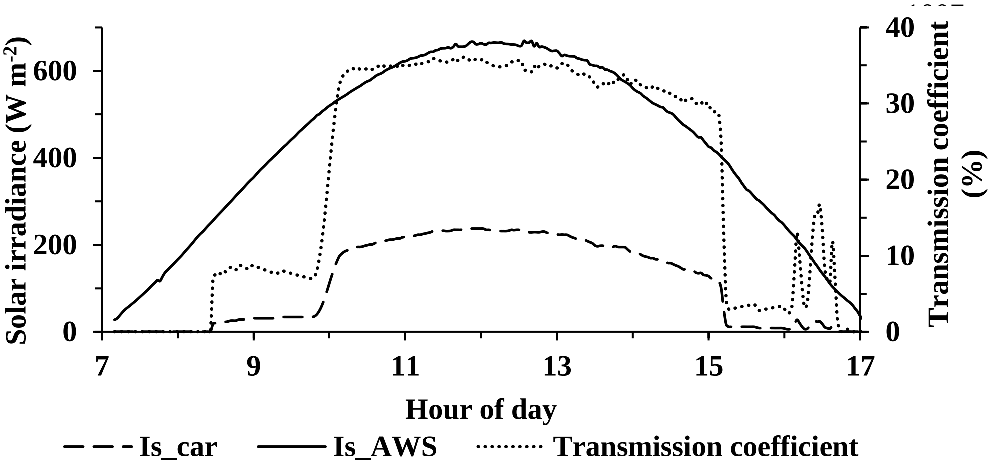

Figure 3.6: Diurnal solar irradiance inside the car and outside the car as well as the percentage of irradiance transmitted into car 2 on a cloudless day (3rd August 2014) when the car was parked facing north.

3.3.2.3 Net irradiances

The inside and outside net irradiance for the 3rd August 2014, for car 2 parked facing north are shown in Figure 3.7a. The net irradiance inside the car was obtained through averaging the computed net irradiance from the component measurement and that measured by the net radiometer. The net irradiance outside the car from 08h00 to 16h00 ranged from -38.6 to 342.0 W m^{-2} while it ranged between -2.0 and 216.2 W m^{-2} inside the car. From 10h20 until 13h30 the net irradiance inside the car was at its peak point but steady compared to that outside.

Figure 3.7b and c shows the net solar irradiances and the net infrared inside and outside the car respectively. The net infrared irradiance inside the car was greater than that outside, while a different trend can be seen in the net solar irradiance. The net infrared irradiance inside the car varied between

95.4 to 43.0 W m^{-2}, while it ranged from -185.0 to -55.0 w m^{-2} outside the car. The net solar irradiance inside the car ranged from 0 to 237.0 W m^{-2}, while it ranged between 50 to 500 W m^{-2} outside.

The results show that the partitioning of the radiation components inside a car parked in the sun, on a cloudless day, is different to the partitioning of the radiation components outside the car during the same time. While there is a large difference between the solar irradiance inside and outside the car (Figure 3.7b), the corresponding difference in net irradiance is not as large (Figure 3.7b). This is due to the increased net infrared irradiance inside the car compared to that outside (Figure 3.7c)

Transmitted solar irradiance is the dominant term of the radiation balance as it is wholly absorbed by the object that it strikes inside the car. In the absence of evaporative cooling and forced convection inside the car compared to transpiring and convectively cooled vegetation outside, the absorbed solar irradiance significantly heats the interior surfaces. This in turn heats the adjacent air. Essentially then the energy balance of the inside environment results in net irradiance equating to the seat-stored heat flux density compared to outside conditions for which the additional terms of sensible and latent energy occur. The latter, however, inside a vehicle is 0 W m^{-2}. In an enclosed car, the air adjacent the seat is heated and rises through free convection and causes dangerously high temperatures inside cars kept in the sun, even in winter when the air temperature outside is as low as 18 °C.

3.3.3 The apparent indices inside the car

Table 3.4 shows the duration of each category of the heat index inside and outside the car during 2014. The analysis was done using the 2-min data. Table 3.4 shows that the most adverse heat index conditions happened inside the car as opposed to outside the car. For 122.6 hours, the heat index inside the car was greater than 54.4 °C. According to the National Oceanic and Atmospheric Administration (2009), prolonged exposure to the environment with the heat index greater than 54.4 °C may lead to deadly heat related illnesses such as heat stroke. Heat stroke occurs when the core body temperature is at 40.6 °C or greater and it has been the prime diagnosis on children that die from being trapped in closed cars on a hot day (Grubenhoff *et al.* 2007) and those rescued after being left for an extended period.

For the duration of heat index reported in Table 3.4 for the outside, the heat index did not exceed the danger category. The large proportion of the time outside was when the heat index was less than 26.7 °C. For this category, the environment poses no danger at all to human comfort, to an extent that any strenuous activities can be carried out with no precautions with respect to the weather. This shows that the conditions inside the car are much more harmful as the significant duration of harsh index category are found inside the car compared to the outside, open environment.

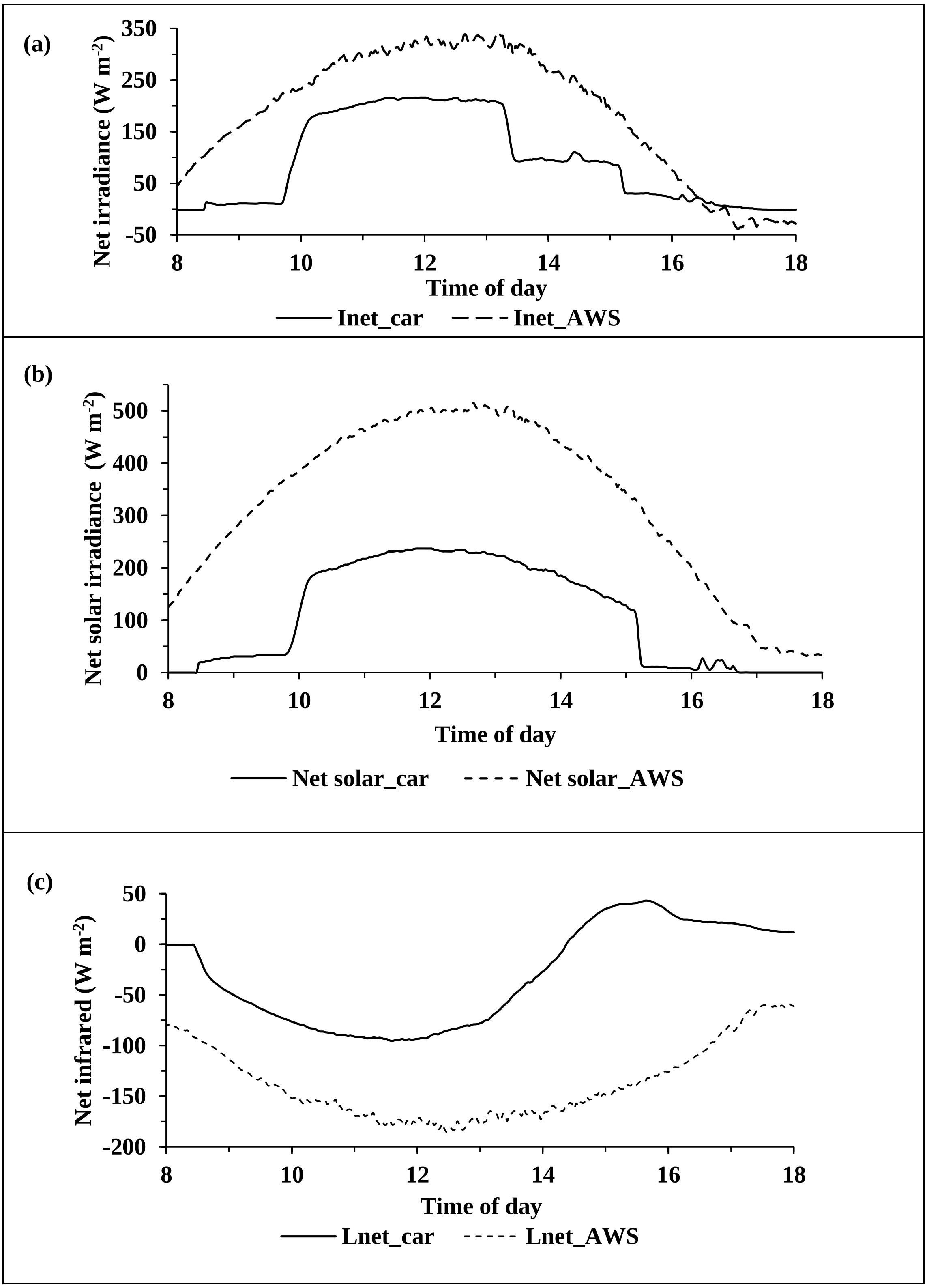

Figure 3.7: (a) Diurnal net irradiances; (b) net solar irradiances; (c) net infrared irradiances inside and outside the car on a cloudless day (3rd August 2014) when car 2 was parked facing north.

Table 3.4: The heat index duration and the heat index category inside car 2 and outside the car for the entire period

Heat index category	Duration (h)	
	Inside the car	Outside the car
No warning ≤ 26.7 °C	3056.2	5542.0
Caution 26.7 to 32.2 °C	1742.5	408.4
Extreme caution 32.2 to 40.6 °C	485.6	56.0
Danger 40.6 to 54.4 °C	596.3	0
Extreme danger ≥ 54.4 °C	122.6	0
Missing	3.2	0

Figure 3.8 shows the diurnal air temperature inside and outside the car as well as the HI and T_{mrt} inside the car. The maximum T_{mrt} was 97.8 °C after 3.5 h in the sun and it occurred at 14h30. At this time both the heat index and the air temperature were 65.0 °C and the air temperature outside the car was 33.0 °C. The results show that the increase in the heat index, air temperature inside and the air temperature outside was gradual. However, the increase of T_{mrt} was not gradual and it slightly resembled the typical curve of the incoming solar irradiance. This is because T_{mrt} is a measure of the solar irradiance, wind speed and air temperature.

The heat index was equal to the air temperature because the relative humidity was less than 40%. During this time another composite temperature is desirable to illustrate the levels of comfort of the environment. The results show that even when the heat index was equal to the air temperature, T_{mrt} was still far greater than both the heat index and the air temperature.

3.3.4 Policy measures of leaving children unattended in stationary hot cars

In many countries, laws regarding children left unattended in stationary cars do not exist. South Africa is no exception. Even the South African K53 driver's handbook does not state the responsibility of the driver in ensuring safety of the passengers in a stationary car. In the USA, in nine states, it is illegal to leave children unattended in stationary vehicles and the law has been proposed in eleven other states. In two other states, it is illegal only in the event of death or injury to impacted individuals (Null 2005). In some of these states, the laws do not specifically forbid leaving children in parked cars. However offenders are prosecuted based on an array of acts such as child endangerment, child negligence and manslaughter in the first degree.

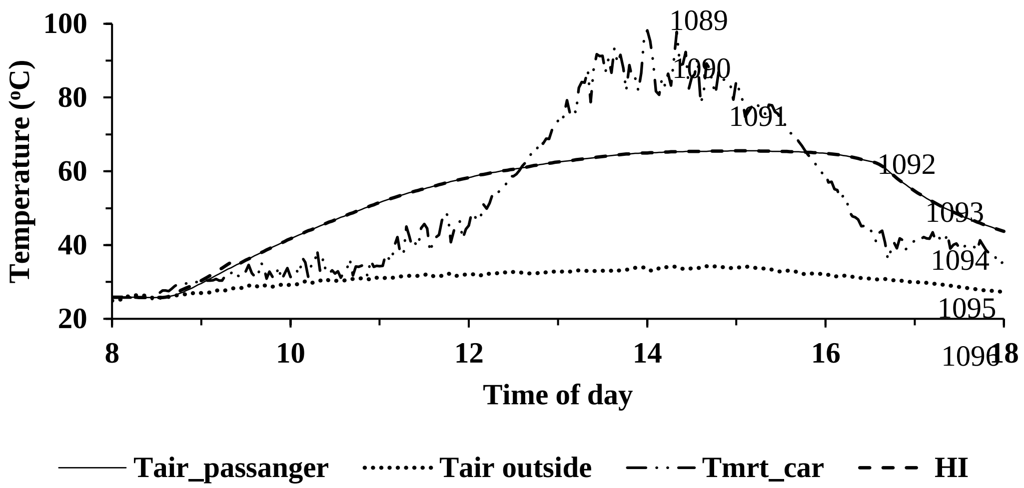

Figure 3.8: Diurnal air temperature outside car 2 (facing north) as well as the heat index inside, mean radiant temperature and air temperature inside the car on a warm cloudless day (23rd March 2014).

Similarly in South Africa, as the result of the lack of laws regarding children or pets left in hot cars, irresponsible offenders are charged with cases of child neglect or cruelty to animals. On the 17th July 2015 when parents had left their children inside the car at Liberty Midlands Mall in Pietermaritzburg, the air temperature recorded at the AWS around the same time of the incident was 20.0 ºC. Using the data collected from the previous year, similar conditions outside the car resulted in an interior air temperature of 49.0 ºC. For this case, no charges were laid against the parents (Peters 2015a) as the result of the absence of specific laws for children that are left unattended in cars parked directly under the sun, while in a similar case a father was charged with endangering the life of his child in Durban (Makamba 2013).

3.4 CONCLUSIONS

The microclimate of a car can become hot even on cool winter days and it can take less than an hour for the air temperatures inside the car to be double that outside. Therefore, it does not matter if one leaves a pet or a child in a car 'for a short while' as it can still pose a danger.

The magnitude of the component terms of the energy and radiation balances inside and outside a vehicle placed in the sun on a hot day is very different. In terms of the inside-car energy balance, there is no convection apart from free convection and no evaporation resulting in most of the net irradiance equating to stored heat in the interior surfaces. Through free convection, this heat is slowly transferred to the atmosphere of the vehicle. The magnitude of the net solar, net infrared and net irradiances are greater outside the vehicle compared to inside. In spite of this, the interior of a car can be a lethal environment to humans and animals, even in the very short term.

There is a lack of public awareness of the dangers of leaving children in parked cars. The efforts to avoid this human tragedy should start by educating motorists as early as when they take their driver's license test. Secondly, car manufacturers could be encouraged to design a tool that will remind the parents of their children or pets inside the car as soon as they vacate the car. This can range from a simple beeping sound that will go off as soon as the motorist opens the door of the car to sophisticated tools such as a motion detector inside the car. Lastly, there needs to be provincial and national laws that are specific to the problem so as to teach the motorists as well as amendments to the children's negligence act.

CHAPTER 4: EVALUATION OF THE IMPACT OF HEAT EXTREMES ON HUMAN COMFORT, SOCIETY AND OTHER ADVERSE WEATHER EVENTS IN PIETERMARITZBURG USING THE HEAT INDEX AND THE MEAN RADIANT TEMPERATURE

ABSTRACT

The study investigated human comfort in Pietermaritzburg in terms of the heat index, and the mean radiant temperature (T_{mrt}). Various meteorological sensors as well as cost efficient methods of obtaining weather data for humans were collected from the Agrometeorology Instrumentation Mast (AIM) situated at the University of KwaZulu-Natal (UKZN) in Pietermaritzburg (PMB), South Africa. A web-based data and information system was used to display near real-time information of human comfort. In addition, historic data from Cedara, Ukulinga and Baynesfield in KwaZulu-Natal were used for determining the heat vulnerability location. The results show that the cost efficient method of measuring the wet bulb temperature and the air temperature were much lower than using datalogger measurements. Discrepancies due to human error were very small. The heat index is highly affected by the changes in relative humidity even though in its calculation it assumes fixed values of wind speed and solar irradiance. On the other hand, the T_{mrt} may not be the best indicator of human comfort as it yields measurements as high as 87 ^{o}C when the surrounding air temperature is 34 ^{o}C, and the globe temperature is 43 ^{o}C. Ukulinga and Pietermaritzburg had 534 and 693 hours of extreme caution heat index category respectively, making them the most vulnerable sites. Cedara had 95% of the time in the no caution category and was therefore regarded as the least vulnerable site in terms of the extreme heat events. The high vulnerability to extreme heat events in Ukulinga and Pietermaritzburg can be attributed to a lower altitude and the urban island effect, while the low prevalence of extreme heat events for Cedara can be associated with its higher elevation and therefore lower temperatures. The RTI fitness test proved that there is a large gap between society and meteorology and that adverse weather will continue to be the human tragedy challenge until this gap is bridged.

KEYWORDS: Heat waves, globe temperature, society, sports events

4.1 INTRODUCTION

The association between weather mortality and morbidity will demonstrate an increased burden on society in the future for the enhancement of resources such as public health, water and sanitation and power generation in the face of climate change. Extreme heat is one of the adverse weather factors that has a profound adverse impact on the socio-economic and environmental parameters on earth. It is marked by an increased number of deaths, increased number of casualties suffering from heat-related illnesses, destruction of property due to fire outbreaks and a decrease in agricultural production as a result of dry-spells that usually accompany heat waves.

It has become clear that global climates are changing and humankind has to bear the brunt of the harsh direct and indirect impacts of these changes. According to Ziervogel *et al*. (2014), over the past 50 years, South Africa has seen an increase in the average annual temperatures which is 1.5 times higher than the observed 0.65 ºC for the entire globe. Future climate projections not only reveal an increase in the near surface air temperature, but also that the frequency, intensity and extended duration of heat waves are expected. Increasing local environmental temperature means increased human heat exposure during hot seasons. Already, it has been observed that hot weather extremes contribute more to human mortality as opposed to episodes of cold spells (Kalkstein and Valimont, 1987). In hot parts of the world, this heat exposure will continue to cause detrimental health effects (Kjellstrom 2009) and will compromise the days in which leisure and work can be carried out (Kjellstrom *et al*. 2014).

According to Omonijo *et al*. (2013), extreme heat events such as hot spells and heat waves have negative impacts on individuals and on a country at large. The impacts of days characterized by high air temperature, high relative humidity, stagnant wind and high solar irradiance include an increased death toll, reduced productivity, and other exacerbated adverse meteorological conditions such as droughts and hence an increased likelihood of wildfires. Such weather events cannot be prevented from occurring. However if daily weather is measured and predicted with reasonable precision, their impacts on society can be reduced if not totally avoided. Thermal comfort studies have attracted the attention of researchers in the field of biometeorology and urban planning (Mayer and Hoppe 1987, Nikolopoulou *et al*. 2001 and Thorsson *et al.* 2007). Biometeorologists became interested in thermal comfort studies due to the apparent death toll caused by excessive heat events, while urban planners gain interest due to urban centres having become much hotter in the face of climate change and are still expected to worsen in future, due to the impact of the urban heat island effect.

4.1.1 Impact of heat stress on the human body

Humans have the ability to maintain their core body temperature within a narrow range around 37 ºC. Parsons (2010) states that in order to maintain a heat balance, there should be a constant exchange of energy between the human body and the surrounding environment. According to Kjellstrom *et al*. (2009) and Lin *et al.* (2010), the body heat balance is governed by six central factors. These are namely:

1. Air temperature
2. Relative humidity
3. Wind speed
4. Solar irradiance
5. Level of clothing
6. Physical activity

The environmental heat that humans experience is a result of the combination of the first four above-mentioned factors. In addition to that, physical activity creates metabolic heat inside the human body that needs to be dissipated to the surrounding environment to avoid the increase in the core body temperature. If the body temperature rises above 37 °C due to physical activity or exposure to heat, cooling is achieved through thermoregulatory mechanisms which includes sweating and convection or through behavioural factors such as removing excess clothing, using air conditioners, drinking water or sitting in shade or doing all of the above. In the event where these become insufficient to dissipate heat from the human body, adverse effects occur. Kjellstrom *et al*. (2009) state that when the body temperature increases above 39 °C, severe heat disorders may occur. Beyond 40.6 °C, more severe effects such as heat stroke or even death occurs. Susceptibility to heat stress is further determined by demographic effects such as age and gender and other factors like health, economic status and isolated groups are regarded as more vulnerable (Stathopoulos *et al.* 2004).

4.1.2 Heat waves as an example of extreme heat events

There is no precise definition of a heat wave. It can simply be defined as an extended period of abnormally high temperature and relative humidity which causes discomfort. Robinson (2001) define a heat wave as the extended episode of abnormally high atmospheric heat stress, which may have adverse health consequences and may temporarily modify the lifestyle of affected individuals. Koppe *et al*. (2004) refer to it as a period of unusually and uncomfortable hot weather with increased relative humidity that normally lasts for a minimum of two days.

The South African Weather Services (SAWS) uses criteria based on air temperature and the number of days to define a heat wave. SAWS states that a heat wave occurs when the maximum air temperature for three consecutive days exceeds the maximum air temperature of the hottest month by 5 °C or more within the area (Jager, 2015). Heat waves pose a serious threat to human health as they have been found to cause or accelerate the rate of cardiovascular disease in those who are already suffering from it. The susceptible group to heat wave related sicknesses includes the elderly, very young children, and people who are ill or overweight.

Studies that link health and hot weather extremes become crucial to provide current precautions and to prepare for future hot weather dangers. Various studies have sought to determine the link between increased death rates and meteorological aspects under heat wave conditions. Some of these studies have used the diurnal and the nocturnal maximum temperatures (Hajat *et al.* 2002), while others have used the diurnal maximum air temperature (Curriero *et al.* 2002) and apparent temperature (Matzarakis and Nastos 2011). Heat waves depend upon a number of microclimatic conditions other than just the air temperature. As a result, a sound measure to quantify them should be the one that encompasses different microclimatic conditions that are relevant in terms of the impact on human comfort.

4.1.3 Alternative measure of heat burden on human beings

There is a wide range of indices that have been proposed throughout the world to assess the thermal burden on humans. Heat stress indices were developed on the premise that the air temperature cannot be used as the only measure to determine how humans would feel for a given weather condition as there are a variety of environmental factors that determine human comfort. These indices range from simple indices that only require environmental measurements as the inputs to sophisticated indices that include the human heat balance equation in addition to the environmental measurements (Epstein and Moran 2006). Regardless of the simplicity or the sophistication of these indices, they all require the use of expensive meteorological sensors which are not available to the general public or to resource-poor communities that are often more adversely affected by adverse weather conditions due to lack of water, air conditioning and poorly constructed dwellings.

An inexpensive and reasonably accurate method that provides instantaneous measurements of microclimates that are crucial in determining human comfort would be of great societal and economic assistance. Such a method can save lives and reduce the costs incurred during heat waves, for instance, which places more pressure on resources such as power supply, adequate water supply and increased hospital admissions.

In the efforts to link weather and health, numerous researchers have used the maximum daily air temperature as the main meteorological parameter for assessment of heat burden in the human body (Hart 2015). Because air temperature is not the only factor that governs the human energy balance, other researchers have used the heat index as the indicator for heat burden (Robinson 2001, Kim *et al.* 2006). The heat index is a composite temperature that accounts for relative humidity and air temperature that one experiences in a given environment. The commonly used heat index equation is the National Oceanic and Atmospheric Administration’s (NOAA) Heat Index formula given by Kim *et al.* (2006). The NOAA heat index is constructed from the Steadman (1979) heat index. It is different from the other indices because it contains the heat index chart, which categorizes the heat index values with possible health illnesses.

Other indices that quantify the heat burden on humans include the mean radiant temperature (T_{mrt}). The T_{mrt} sums the shortwave and infrared irradiances that the human body is subjected to from which the temperature-dimension index is calculated (Kantor and Unger 2011). There are various ways for estimating the T_{mrt} and these are given by Thorsson *et al*. (2007) and Kantor and Unger (2011). These methods range from different calculations which include measurements of black globe temperature, air temperature and wind speed to software models and to even more expensive methods which require the measurements of three net-radiometers arranged in different directions so that each measures the four radiation components of the radiation balance separately.

The aim of this study was to quantify outdoor excessive heat events using the Steadman (1979) heat index and the mean radiant temperature, and to determine the vulnerability of three locations in terms of the heat index. The study also investigates adverse weather experienced during extreme heat events. Lastly, the study investigates the use of an inexpensive and convenient method of assessing discomfort levels that would be of great significance in planning for strenuous outdoor human activities.

4.2 MATERIALS AND METHODS

4.2.1 Site and instrumentation mast description

Recent data reported on were collected from the Agrometeorology Instrumentation Mast (AIM) system situated at the University of KwaZulu-Natal (UKZN) in Pietermaritzburg, South Africa (altitude 684 m; 29.628° S, 30.403° E). Historic data for the inter-comparison of the extreme heat events were collected from three locations in KwaZulu-Natal. These include Ukulinga UKZN research farm (altitude 810 m; 29.669° S, 30.412° E), Cedara (altitude 1076 m; 29.533° S, 30.283° E) and Baynesfield Estate (altitude 758 m; 29.767° S, 30.350° E).

The AIM field site consists of two masts that contain instruments of an automatic weather station (AWS), amongst the other masts (Savage *et al.* 2014). These masts are, namely, mast 1, the main mast and mast 2, the backup mast. The measurements for human comfort were obtained from mast 2. Mast 2 is 3-m tall and in operation from December 2011, with the additional measurements of the globe temperature (T_g) since 30th January 2014.

4.2.2 Sensor arrangement and data acquisition

The microclimatic conditions were measured using various micrometeorological sensors (Table 4.1). Incoming solar irradiance was measured using a CMP3 thermopile pyranometer, while the reflected solar radiation was measured using a CM3. Wind speed and wind direction were measured using the RM Young 03001 instrument. Air temperature and relative humidity were measured using a CS500 air temperature and relative humidity sensor placed inside a six-plate Gill radiation shield. All measurements were taken at 2 m above the surface at mast 2.

Additionally, manual measurements of the wet- and dry-bulb temperature were collected using liquid-in-glass thermometers as shown in Figure 4.1. The thermometers were whirled using a thin rope attached to the one end. Measurements of wet and dry bulb temperature, allowed for the relative humidity and the heat index to be calculated. The globe temperature (T_g) was obtained from low-cost globe thermometers. The globe thermometer, painted matt-black, was made from a 150-mm hollow copper sphere, with a thermistor mounted at the centre.

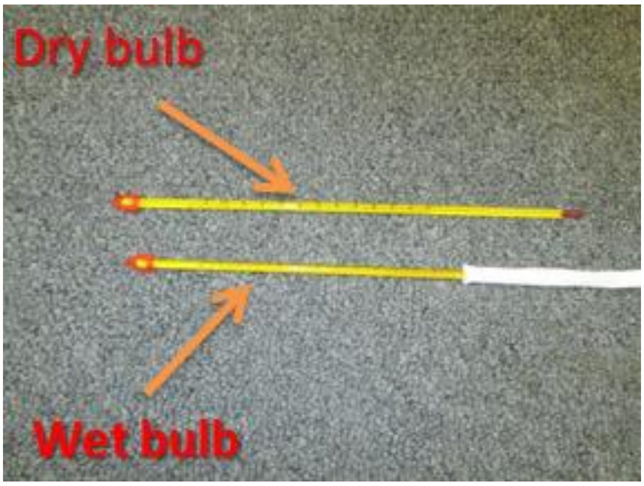

Figure 4.1: Liquid-in-glass thermometers used to collect wet and dry bulb temperature

Data obtained from these micrometeorological sensors allowed for the analysis of extreme heat events using calculations of different indices such as the heat index and the mean radiant temperature (T_{mrt}).

4.2.3 Calculation of heat stress indices

The mean radiant temperature was calculated using globe temperatures (T_g) with the globe placed 1.1 m above the surface, as suggested by Kantor and Unger (2011):

$$T_{mrt} = \left[\left(T_g + 273\right)^4 + \frac{1.10\times10^8 v_a^{0.6}}{\varepsilon D^{0.4}}\left(T_g - T_a\right)\right]^{\frac{1}{4}} - 273 \qquad [4.1]$$

where T_{mrt} is mean radiant temperature (°C), T_a is air temperature (°C), v_a is wind speed (m s^{-1}), D is globe diameter (m), and ε is the emissivity of the black globe. The calculated T_{mrt} was compared to the mean radiation temperature obtained using a four component net radiometer placed at 3 m above the surface in Mast 1.

Table 4.1: Description of sensor arrangement and data acquisition

Details of measurements	Apparatus used
Sensors	Air temperature and relative humidity were measured using the RH and air temperature sensor[1] in a seven-plate Gill radiation shield at 2 m, wind speed and direction sensor[2] at 2 m, four-component net radiometer (CNR1[3]), Solar irradiance (CMP3[3]) and diffuse irradiance using a CM3[3] shaded by an in-house radiation band, barometric pressure sensor (model CS106[4]), four copper globes painted in matte black with the thermistor at the centre and four glass thermometers.
Calculations	Calculations of heat index, the mean radiant temperature and the black globe temperature were done for this study.
Field data loggers	CR1000[4]and multiplexer AM16/32[4]- all measurements were taken every 2 min and averaged/totaled every 60 min
Field-to-base station communication	Datalogger to the antenna[5] which was in line-of-sight with the receiver.

Heat index was calculated using the following equation:

$$HI = (-42.379 + 2.04901523 \times (9 \times T_a/5 + 32) + 10.14333127 \times RH - 0.22475541 \times (9 \times T_a/5 + 32) \times RH - 6.83783 \times 10^{-3} \times (9 \times T_a/5 + 32)^2 - 5.481717 \times 10^{-2} RH^2 + 1.22874 \times 10^{-3} \times (9 \times T_a/5 + 32)^2 \times RH + 8.5282 \times 10^{-4} \times (9 \times T_a/5 + 32) \times RH^2 - 1.99 \times 10^{-6} \times (9 \times T_a/5 + 32)^2 \times RH^2) - 32 \times 5/9 \qquad [4.2]$$

Heat index was estimated using two methods. Firstly, it was estimated using the air temperature (T_a) and relative humidity (*RH*) data obtained from mast 2 of the AIM system. Secondly, it was estimated using the inexpensive method of measuring the dry- and the wet-bulb to calculate relative humidity and hence the heat index.

In order to calculate the heat index using the inexpensive method, air temperature measurements (dry-bulb temperature) were obtained using three 230-mm liquid-in-glass thermometers with the ends attached to a rope for whirling. Relative humidity was extracted from the wet-bulb and the dry-bulb temperature measurements. The wet-bulb temperature was attained from the glass thermometer with the wick attached to the sensing end of the thermometer.

[1] Vaisala Oyj, Helsinki, Finland
[2] RM Young Company, Traverse City, Michigan, USA
[3] Kipp & Zonen B.V., Delft, The Netherlands
[4] Campbell Scientific, Inc., Logan, Utah, USA
[5] Poynting antenna, Pointing Direct (Pty), Johannesburg, Gauteng, South Africa

The wick was wetted using distilled water and whirled for 30 seconds. The thermometers were whirled until two similar consecutive wet-bulb measurements were attained. Relative humidity (%) was calculated in Excel using the equation:

$$RH = (e/e_s) \times 100 \qquad [4.3]$$

where e_s (kPa) is the saturation water vapour pressure given by:

$$e_s = 0.6108 \times exp[17.2694.T_d/(237.3 + T_d)] \qquad [4.4]$$

and e (kPa) is the water vapour pressure given by:

$$\mathrm{e} = e_s(T_w) - \gamma(T_d - T_w).(1 + 0.00115\, T_w) \qquad [4.5]$$

where γ is the psychrometric constant (kPa $^{o}C^{-1}$). A table with the possible values of *RH* was extracted in Excel. A second table, with heat index values, was extracted from the measurements of the T_d and the calculated *RH*.

A Campbell Scientific CR1000 data logger, with a scan rate of ten seconds, was used to store the AIM system data at an interval of 2 minutes and 60 minutes. The near real-time data of daily heat index and T_{mrt} was displayed using a web-based data and information system: http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Human%20comfort

4.3 RESULTS AND DISCUSSION

4.3.1 Assessment of economical methods of data acquisition

An inexpensive and timely method for collecting data that can be used to calculate heat index in the resource poor areas and schools was done through the investigation of the wet bulb and the dry bulb measurements. The measurements were taken using the liquid-in-glass thermometer to mimic a sling psychrometer on both a cloudless day (8th May 2014) and a sunny day (2nd May 2014). The comparison of the wet- and dry-bulb temperatures obtained from the inexpensive sling psychrometer and mast 2 of the AIM system are shown in Table 4.2 for both days.

Table 4.2 shows that the measurements from the AIM system were lower than that of the inexpensive sling psychrometer on both days. The difference in the measurements can be attributed to the human error in data collection and the radiation error. The lower T_{dry} measurements obtained from the AIM may be due to the fact that the CS500 sensor was more adequately shielded than the liquid-in-glass thermometers.

Table 4.2: The average dry and wet bulb temperature (°C) measurements obtained using a liquid-in-glass thermometer and the corresponding datalogger measurements on a cool cloudy day (8th May 2014) and on a warm cloudless day (2nd May 2014)

Cool cloudy day				**Warm cloudless day**			
T_{wet} **Mast**	T_{wet} **Thermometer**	T_{dry} **Mast**	T_{dry} **Thermometer**	T_{wet} **Mast**	T_{wet} **Thermometer**	T_{dry} **Mast**	T_{dry} **Thermometer**
16.38	16.83	27.91	28.17	15.42	16.10	30.78	31.30
16.54	16.67	27.87	28.17	15.00	15.73	30.18	30.63
16.86	17.17	27.42	27.67	16.94	16.50	28.85	29.33
17.01	17.17	27.29	27.30	15.88	16.83	27.41	28.67
17.07	16.83	27.09	27.30	16.95	17.17	28.16	28.33
17.10	17.00	26.95	27.00	16.93	17.50	27.87	28.33
17.12	17.00	26.56	26.67	16.98	17.33	27.81	28.17
17.15	16.67	26.22	26.33	17.06	17.50	27.75	27.83
17.19	17.00	25.94	25.67	15.42	16.10	30.78	31.30
17.25	17.00	25.50	25.33	15.00	15.73	30.18	30.63

The liquid-in-glass thermometer dry-bulbs were greater than those from the AIM system and this was usually also the case for the wet-bulb measurements. This emphasizes the need to ensure that there is sufficient radiation shielding and ventilation when measuring the wet-bulb. While there were differences in datalogger measurements and those obtained manually, the differences were small. Therefore, the inexpensive sling psychrometer measurements are adequate for planning events in the resource poor communities or schools to provide for routine and timely measurements of relative humidity and air temperature. School sports events usually take place when weather conditions adverse to human health and comfort occurs. A useful heat index table for such situations is shown in Appendix A. The heat index table was generated in Excel using Equation 4.2 and allows for prompt heat index values. Precautions for human comfort, depending on the obtained values, can be taken as prescribed by the NOAA (2009) heat index table

4.3.2 Excessive heat events in human health and comfort

The assessment of extreme heat events was done using data collected for Pietermaritzburg from January 2014 until November 2015. The level of human comfort for a normal person exposed in the open environment, and the precautions that ought to be taken, were investigated using the heat index and the duration corresponding to these values (Table 4.3).

Table 4.3: Duration of each heat index category for Pietermaritzburg for the period February 2014 to November 2015 inclusive

Heat index category	Duration (hours)	Duration (days)
No warning ≤ 26.7 ºC	14311.40	596.3
Caution 26.7 to 32.2 ºC	1166.33	48.6
Extreme caution 32.2 to 40.6 ºC	284.27	11.8
Danger 41.6 to 54.4 ºC	0.07	0.0
Extreme danger ≥ 54.4ºC	0.00	0.0
Missing	408.7	17.0
Total	16170.80	673.8

Table 4.3 shows that for a large proportion of the time (88%), the heat index was less than 26.7 ºC. According to the NOAA (2009) there are no precautions that should be taken during this category and any strenuous activities can be undertaken without taking precautions against the weather. The duration of 48.6 days and 11.8 days was characterized by the caution and the extreme caution category, respectively. Prolonged exposure to weather conditions in the caution heat index category may lead to minor heat related symptoms such as fatigue (NOAA 2009) and heat oedema (Grubenhoff *et al.* 2007) for people who are carrying out physical activities and for risk groups such as the elderly (65 years and above), the young (0-5 years) and those living alone. Such symptoms can be treated through behavioural thermoregulatory measures such as seeking a cooler place, removing excess clothing and drinking more water.

Extended exposure to heat when the heat index is between 32.2 and 41.4 ºC requires extreme caution to be taken as it may lead to moderate to deadly heat related illnesses such as heat exhaustion, muscle cramps, and sunstroke. This category lasted for a period equivalent to 11.8 days during the study. Prolonged exposure to such conditions may increase the core body temperature above 37.0 ºC but below 40.4 ºC. An unhealthy person, who shows symptoms of moderate heat symptoms such as heat exhaustion, may experience illnesses which progress to heatstroke. Heatstroke is likely to occur when the heat index reaches 41 ºC or greater (danger and extreme danger category). However, the investigation shows that the environment in Pietermaritzburg was not more harmful to reach such conditions; hence the duration of the heat index in both the danger and the extreme danger was equal to 0 days.

Even though the study showed no significant duration in the extreme danger heat index category, the potential danger can be anticipated as a result of diagnosed or undiagnosed illnesses as well as prolonged exposure to environmental conditions. Therefore, the study investigated the time of day over which the heat index was in the harmful categories, which may lead to hazardous impacts (Figure 4.2).

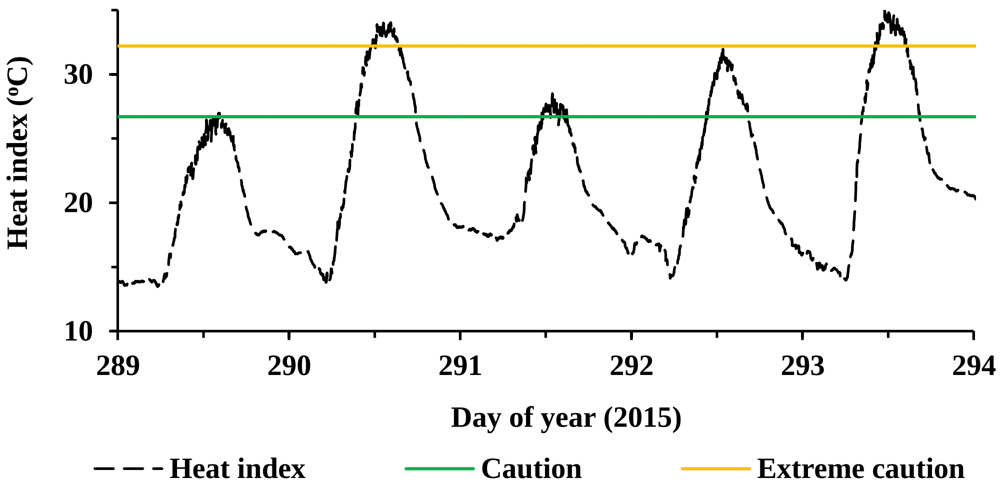

Figure 4.2: Heat index measured at the AIM site with respective heat index categories from the 17th until the 21st October 2015 inclusive

On the 21st October 2015 (day of year 293), the heat index reached a maximum of 34.7 ºC which is above the extreme caution category. For all the days reported in Figure 4.2, the maximum heat index occurred around 13h00. For all the days shown, there is a similar trend of gradual increase in the heat index that starts around 08h00 and a gradual decrease that occurs after 14h00. The night time conditions are characterized by a heat index that does not pose any danger to human comfort and human health.

On the 17th October 2015 (day of year 289), the heat index reached the caution category at 14h00 and lasted until 14h20. On the 18th, the heat index reached the caution category at 11h40 and lasted until 17h00, with the extreme category in between (from 09h22 to 11h35). On the 19th October 2015 the heat index reached the caution category at 11h38 and lasted until 14h58. On the 20th October 2015 the heat index reached the caution category at 10h30 and lasted until 16h22. On the 21st the heat index reached the caution category at 08h22 and lasted until 16h24, with the extreme category in between (from 10h22 to 14h38). These results show that the critical heat index occurs between 10h30 to 17h00, with most intense heat index between 12h00 and 15h00. These times of the day are normally associated with school sporting activities and therefore may have detrimental health impacts if the weather precaution is not taken into account.

4.3.3 Excessive heat events, vulnerable areas and critical months

A Boolean expression in Excel was used to identify the duration of the critical heat index categories using historic hourly data from all four locations. The heat index was used to determine the excessive heat events in vulnerable locations. The duration of the heat index categories and the time frame of data used per site are shown in Table 4.4. For this study the heat index category was used to identify the severity of the excessive heat events for the four locations. The location with the largest number of hours with the heat index category at extreme caution represents the location with severe excessive heat events while the "no warning" category depicts the insignificance of excessive heat events.

Table 4.4: Duration of different heat index categories for the four different locations in KwaZulu-Natal

Location	Duration (h) per heat index category							
	Extreme caution	% of time	Caution	% of time	No caution	% of time	Missing	% of time
Cedara (2002-2010)	295	0.59	2420	4.82	47491	95.59	633	1.25
Baynesfield (2008-2010)	230	1.51	853	5.61	14110	92.87	13	0.09
Ukulinga (2001-2010)	543	1.05	2673	5.14	48744	93.81	29541	36.25
Pietermaritzburg (2011-2015)	639	1.92	2300	6.90	30416	91.19	607	1.82

The results show that Pietermaritzburg had the greatest number of hours (639 hours and 1.92% of the time) where the heat index was in the extreme heat caution category, followed by Ukulinga with 534 hours. Cedara showed a lower percentage than Baynesfield with 0.59% of time, which was the lowest for all four locations.

Baynesfield and Cedara remain the least vulnerable sites for extreme heat events because of the lowest percentage of time the heat index was in the extreme caution and caution category. Again, Cedara demonstrated most number of hours where the heat index was in no caution category. This set it to be the location of least vulnerability among the four study areas. Its insusceptibility to extreme heat can be attributed to its high elevation which causes lower air temperature as a result of low pressure of the high altitude. It can be noted that the heat index is equal to the air temperature when the relative humidity is less than 40% and the air temperature is less than 26.7 ºC. Therefore, the higher number of hours of the no caution category may be due to the low air temperature (26.7 ºC) preventing the heat index to progress to other categories. The higher number of hours where the heat index was in extreme caution and caution for both Pietermaritzburg and Ukulinga can be attributed lower altitude and the urban heat island due to urbanization.

Figure 4.3 shows the average number of hours for different months when the heat index was in: (a) extreme caution category and (b) when it was in the caution category for the four locations. Figure 4.3 shows that May, June and July have no prevalence of the extreme caution heat index category for all four locations. Figure 4.3b June and July shows a low duration of heat index in the caution category. There was an average of 16.25 hours of caution for Pietermaritzburg in July and 4.8 hours for the other three locations. The results shows that the late autumn (May) and winter months are less affected by the excessive heat events that pose danger to human comfort and health, while the severity increases as the months progress from August to November. December to March experience the highest duration of the caution heat index category and therefore are considered the most vulnerable months.

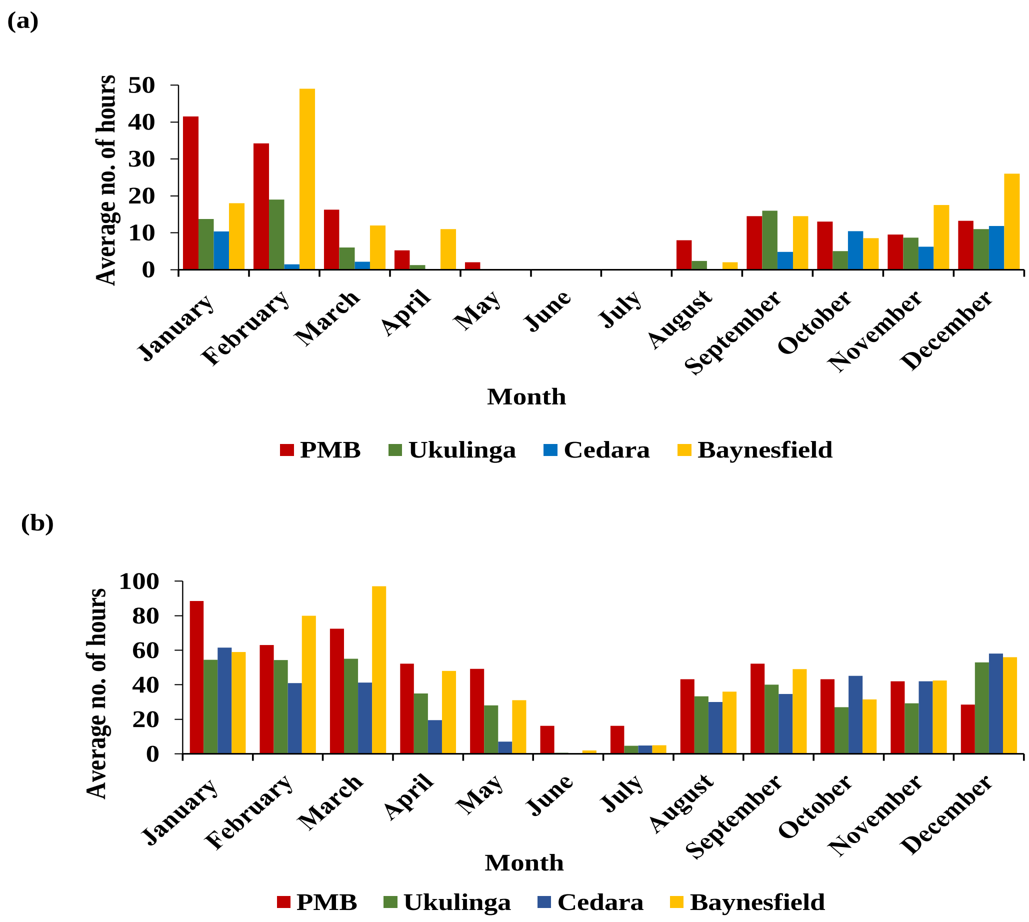

Figure 4.3: Average number of hours for: (a) extreme caution heat index category and (b) caution heat index category for each month for the four locations.

4.3.4 Alternative measures of evaluating human comfort

Since the body is governed by numerous meteorological parameters, a desirable index is one that takes most of these parameters into consideration. Even though the calculation of the heat index assumes some of the values of the significant parameters that govern the human energy balance such as radiation to and from the skin and wind speed, it is highly affected by air temperature and relative humidity. Figure 4.4 shows the changes in diurnal heat index when: (a) the relative humidity was greater than 40% on the 2nd February 2015, (b) the relative humidity was less than 40% on the 7th September 2015.

Figure 4.4a shows that the difference between the heat index and the air temperature at 11h30 was as low as 1.1 °C. This occurred when the relative humidity was 52%. A distinct difference between the heat index and the air temperature is notable as the relative humidity increases. From 14h40 the relative humidity started to increase rapidly from 60% until it reached its maximum of 70% at 15h30. The difference in the heat index and the air temperature was 2.6 °C at 14h40 and it was 3.0 °C at 15h30. Figure 4.4b shows that the heat index was equal to the air temperature throughout as the relative humidity was less than 40%.

Air temperature and relative humidity influences the convective energy fluxes of sensible heat and latent energy respectively, whilst wind speed influences both. Solar radiation also becomes a crucial determinant of one's thermal comfort. However, radiation energy fluxes reaching the person may be very complex due to many environmental possibilities. The mean radiant temperature was used as an alternative measure for human comfort that best summarizes these radiation energy fluxes and was compared to the heat index, air temperature and the globe temperature as shown in Figure 4.5.

Figure 4.5 shows that the air temperature and the heat index were the same. They both increased to a maximum of 34.0 °C. The mean radiant temperature reached a maximum of 87.8 °C at 13h30 when the air temperature was 34.0 °C. This made the T_{mrt} to be 53.8 °C, higher than the air temperature. Thorsson *at al.* (2007) found that the outdoor T_{mrt} obtained using a 38-mm grey sphere can be 30 °C higher than the air temperature. Similarly, Kantor and Unger (2011) state that on a sunny day, the T_{mrt} can be 30 °C higher than the air temperature outdoors, while it can be the same indoors. The measurements produced by the T_{mrt} calculated seem to be impractical, as they tend to be in a range that human beings cannot survive under. However, T_g alone, best summarizes these radiation energy fluxes as it does not vary too much with the air temperature and only decreases at sunset.

Even though it was a cloudless day, fluctuations in the T_{mrt} were observed between 09h00 and 13h00. Thorsson *at al.* (2007) showed similar findings, where there were irregularities in the T_{mrt} obtained using their 1 min data. The authors smoothed out the fluctuations using a 5 minute moving mean. These fluctuations may be attributed to the changes in the input values used in calculating T_{mrt}. The changes in air temperature, wind speed and solar radiation occurred at different times and affect the globe temperature but due to its response time, the globe does not respond instantaneously. Using data with a short time interval such as 2 min used in this study made these fluctuations more apparent.

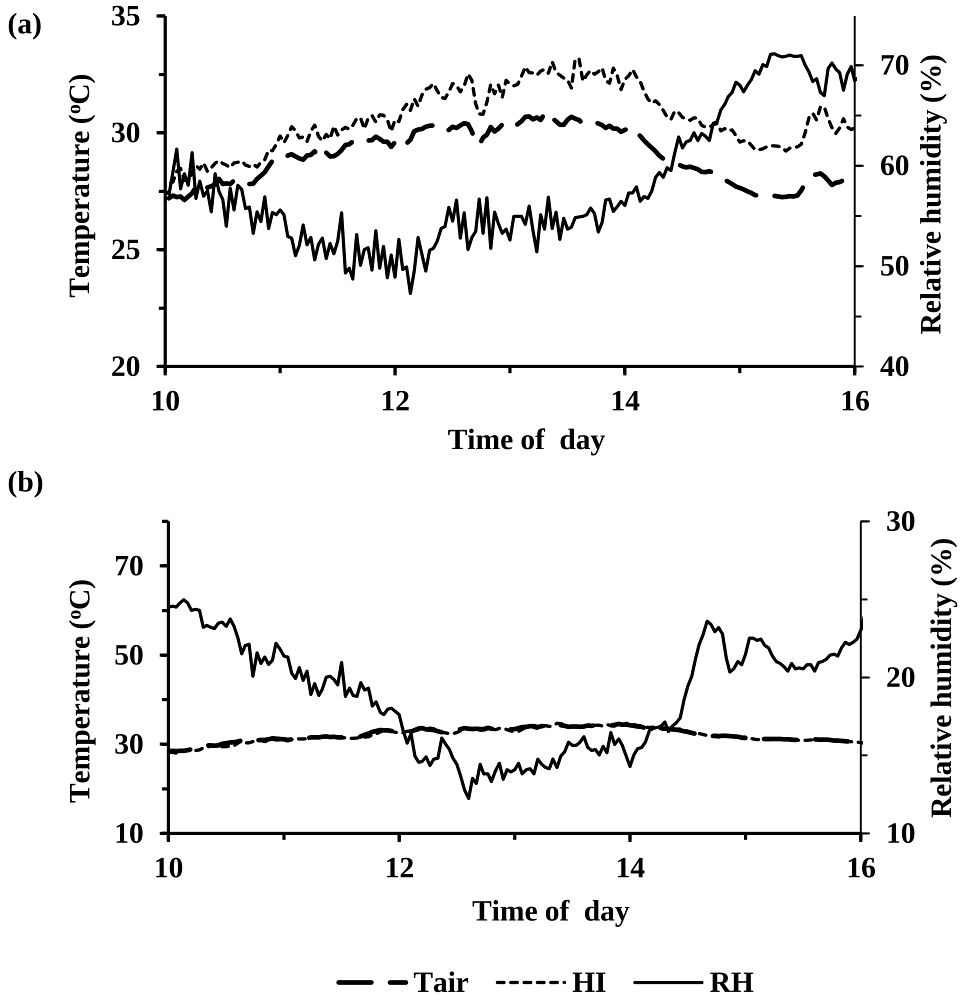

Figure 4.4: The 2-min changes in diurnal heat index: (a) when the relative humidity was greater than 40% on the 2nd February 2015, and (b) when the relative humidity was less than 40% on the 7th September 2015

4.3.5 Socioeconomic impacts of excessive heat events

On the 27th and the 28th December 2012, the maximum temperatures recorded at the UKZN AWS were 31.5 ºC and 29.7 ºC while the heat index was 34.0 ºC and 30.7 ºC respectively (Figure 4.6a and b). On both days, about 15 600 applicants for the Road Traffic Inspectorate (RTI) vacancies were at Harry Gwala Stadium, which has a carrying capacity of 13 000, to run a 4-km fitness test. The fitness test was conducted in order to decide which participants qualified for 90 available vacancies. Peters (2015b) states that only two ambulances and one water tap were available at the venue. During the test, eight people lost their lives, while hundreds were admitted to hospital suffering from various degrees of heat stress illnesses.

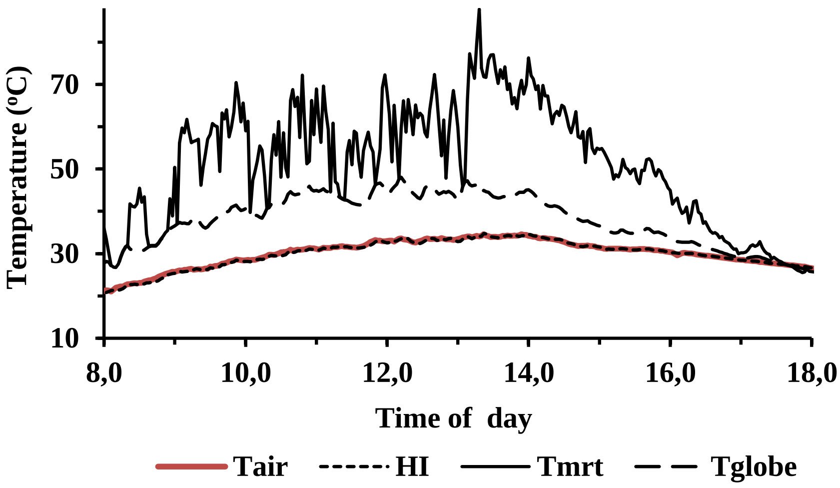

Figure 4.5: Diurnal air temperature, heat index, mean radiant temperature and globe temperature on the 15th September 2015

On the 27th December 2012, the weather conditions were between caution and extreme caution from 09h42 to 18h00. Radebe (2012) reported that the event on this day was stopped at 14h30 on the advice of doctors attending to hundreds of casualties that were transferred to the local hospital. The weather conditions, which were the crucial aspect of the health of the participants were ignored on the 27th. Hence the testing continued the following day which was also characterized by hazardous weather conditions. Radebe (2012) reported that people who were competing that day were not complaining about the strenuous activities but about sun burn.

The impact of the RTI fitness test on the participants however was a result of poor planning that could have been avoidable if the weather, which is the most crucial element of human health for outdoor activities, was taken into consideration in the preparation. An example of a foreseeable human tragedy is outlined by SABC (2016) whereby up to 11 people lost their lives in North West province as a result of the heat waves experienced during the 2015 El Niño phenomenon. Besides the actual loss of lives experienced during the 2014/15 El Niño, the heat waves and drought have had an immensely detrimental impact on both society and the economy by impacting mainly on food production and water security.

It is quite difficult to establish whether it is the weather that triggers the illnesses which lead to an individual's death, or if it is the individual's existing sicknesses that increases vulnerability to hot weather events resulting in mortality. Dixon *et al*. (2007) state that an individual's death cannot be causally linked to one event such as weather. However, an individual's mortality risk often increases with the number of risk factors, and also some weather variables may tend to intensify such a risk. Strangely, the recommendations of the report issued by the Commission of Enquiry that investigated the outcome of the event indicates nothing about weather variables. The lack of the inclusion of the weather parameters in such a societal matter can be defined by the gap in meteorological research and the society as outlined by Doswell (2003). Doswell (2003) states that the societal impacts of weather are normally viewed as a separate entity of meteorology, the same way that the literature on meteorology excludes the society but deals with the scientific aspects of the impacts of extreme weather events.

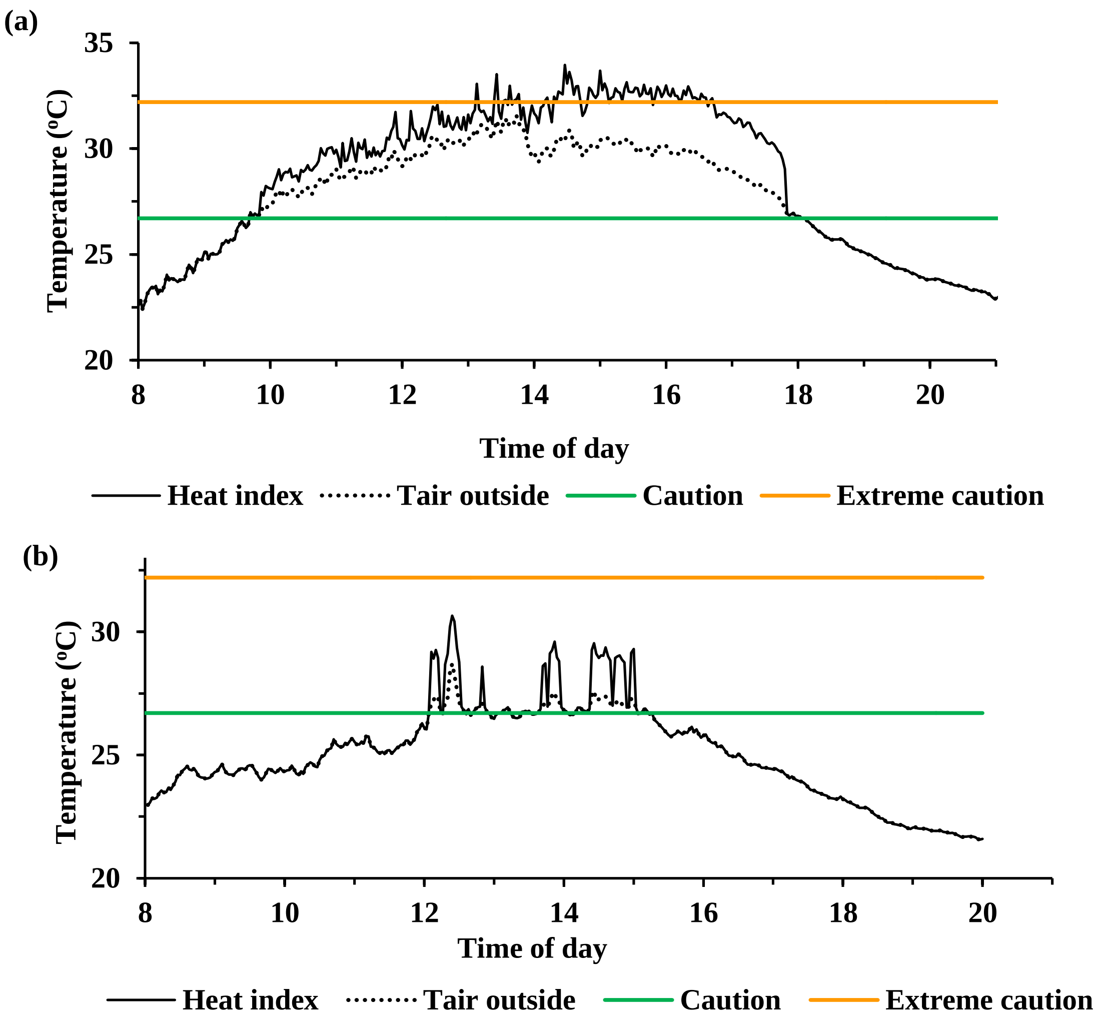

Figure 4.6: Two-minute heat index and air temperature on the day of the RTI fitness test: (a) on the 27th December 2012; (b) on the 28th December 2012.

Vulnerability to heat morbidity and mortality includes, among other things, age, social isolation, health status (Buscail *et al*. 2012), level of education and socioeconomic status (Harlan *et al.* 2006). In this regard, considering weather conditions on the 27th and the 28th December 2012, the RTI fitness test participants were exposed to dangers that they experienced due to their socio-economic status as these were unemployed people who were in urgent need for employment. Also the impact of urban heat island, particularly decreased air movement and increased relative humidity, increased the forecasted air temperature. Lastly, some of the participants came from different parts of the province and therefore were not acclimatized to the weather conditions of the area regardless of their physical fitness.

Regardless of the tragic nature of this event, there is also the tremendous economic loss which would have otherwise been prevented had the weather hazard been taken into consideration in both organizing the event and in the underlying policies which govern decision making during such events. The economic losses include those of treating the casualties on the days of the event as well as the department's compensation funds to the affected participants after the event. All 18 participants that were ill and hospitalized were compensated R10 000 each. One participant who had been hospitalized for a long period of time was paid R100 000 and the families of the deceased were to be visited individually to calculate the specific amount each family should be compensated. Placing a value on someone's life cannot address the social and economic ills that the families have undergone, as some families lost their bread winners.

4.3.6 Response plans on a larger scale

Responding to extreme heat events requires a comprehensive method which bridges the gap between both meteorology and society. Firstly, an accurate meteorological forecast of the development, severity and critical periods of these weather patterns can be regarded as the initial step in responding to excessive heat events. This may be useful in allowing the prompt preparedness in the case of excessive heat events and notification and response plans or to execute immediate actions that were not part of the initial response plans when the need arises. Notifications can be in a form of the real-time information that is accessible to the public using appropriate broadcasting channels, such as cell phones, media, telephone as well as websites, depending on the availability of resources of the impacted communities. Secondly, identification of the high-risk groups as well as the available facilities (e.g., air conditioners, shade and running water) to deal with excessive heat within the society can be useful to provide group-specific response actions.

4.4 CONCLUSIONS

The locations investigated show that Cedara is the least vulnerable in terms of extreme heat events as a result of its higher elevation. Ukulinga and Pietermaritzburg are the most vulnerable because of their lower altitude and they are located closer to the urban centre. In all four locations, there was no occurrence of the most harmful heat index categories, i.e. danger and extreme danger. Potential threat to human health in these locations exists because of the morbidity caused by the caution and extreme caution heat index categories which were found to be prevalent. The categories that were found in these areas are associated with heat illnesses such as heat exhaustion which lead to deadly heat illnesses when unmitigated or as a result of prolonged exposure to the prevailing heat. These illnesses will place a great burden on increased resources such as public health, water and energy in future in the face of climate change.

While fatalities of this kind still remain under-publicized, the case of the RTI fitness test proved that the poor will suffer the most and that there is a gap between meteorological research and society. Therefore, there is a need for a study that uses less sophisticated equipment like the cost-efficient method of calculating heat index used in this study which showed that it can compete, when used *in situ*, with expensive methods to link weather and society.

Lastly a variable adverse weather study can be done in conjunction with weather data to determine which weather variable is of more concern so as to close the gap between society and meteorology. The study will also assist in formulating advanced predictions and warning systems that may be useful in policy decision-making and in preparing for events such as the RTI fitness test and sporting events.

CHAPTER 5: EVALUATION OF OCCUPATIONAL HEAT EXPOSURE IN PIETERMARITZBURG USING THE WET BULB GLOBE TEMPERATURE

ABSTRACT

Apart from metabolic activity and the individual's level of clothing, high air temperature, high relative humidity, low wind speed and high solar irradiances are some of the environmental factors that contribute to human heat discomfort. People working outdoors are highly susceptible to these harsh conditions. For them, preventative measures include taking a break and reducing work intensity. These protective measures compromise productivity as well as income generation, while continuing to work under harsh conditions compromises workers' health or even lives. It is expected that the global temperatures will increase by 2 °C by 2050 if there are no efforts to halt greenhouse gas emissions. With the anticipated impacts of climate change, loss of productivity and economic instability will compromise the society's health, food security and income generation. The study made use of the automatic weather station (AWS) near real-time data to estimate the number of days for which labour is compromised now and in the future, due to the adverse effects of weather using the wet bulb globe temperature (WBGT) index which is the index used in many countries to protect the workers from excessive heat. One of the problems with using the WBGT is that it requires globe temperature measurements, which are measured using the globe thermometer that is often not used at a typical AWS. The study compared globe temperature measurements taken at different heights (1.1 and 2 m) and painted different colours (matt-black and grey). Also, different methods of estimating the WBGT were compared to one another and they were also compared with the heat index. The results show that there is little difference between the globe temperature values in terms of height and colour. The calculated globe temperature (T_g) was highly associated with the measured globe temperature with the R^2 value of 0.94 and a root square mean (RMSE) of 1.1 °C over two days, but with a RMSE value of 1.9 °C when using data for one month. Additionally, the WBGT calculated using the black globe temperature measurements and that calculated using the routinely measured AWS data showed a discrepancy of up to 5.3 °C, with the WBGT calculated using the routinely measured AWS data higher than that calculated using the black globe temperature measurements. The WBGT tended to underestimate the level of heat discomfort compared to the heat index. There were 7.55 days from February 2014 to November 2015 in which work of any intensity (200 to 600 W) was compromised due to taking breaks as recommended by the WBGT. The results show that adding 2 °C to the current air temperature can increase the number of days compromised due to taking breaks from 7.55 to 26.6 days.

KEYWORDS: Work, Heat, Globe thermometer, Climate change, Productivity, Health, Self-pacing

5.1 INTRODUCTION

Outdoor workers are highly vulnerable to numerous climate-related hazards such as solar radiation exposure, air pollution, increased air temperature, relative humidity and other adverse extreme weather events (Lundgren *et al*. 2013). Kjellstrom *et al*. (2009) state that increasing local surrounding air temperature as anticipated by global climate change will have a detrimental impact on the health of outdoor workers unable to protect themselves with cooling methods such as air conditioners.

Workers' susceptibility to heat not only arises as a result of direct exposure to such conditions, but also because of the heat that is generated by the body during work. Workers who are undertaking physical activity are extremely affected by heat because the physical activity creates additional heat that has to be dissipated (Kjellstrom *et al*. 2013). Increases in the body temperature beyond the normal range (around 37 ^{o}C) poses great danger to individuals' health as it increases the individuals' risk to illnesses such as heat stroke and heat exhaustion. On the other hand, measures to dissipate heat by a working person, involves reducing the body's internal heat flux generation through self-pacing or taking breaks during work. This then leads to decreased work capacity and labour and economic productivity. For that reason, not only is the health of the workers expected to be negatively impacted by the increase in the global climate, but also the economic productivity.

Lundgren *et al*. (2013) state that outdoor workers who are highly susceptible to weather-related hazards such as extreme heat events include agricultural workers, miners, and construction workers. Also, indoor workers such as found in factories that lack cooling effects such as air conditioners or ventilation are expected to be impacted by extreme heat events that are accelerated by the global climate change in resource-poor countries such as South Africa. Heat exposure in the working environment is the most crucial aspect of occupational health that does not receive the attention it deserves. Kjellstrom *et al*. (2014) state that increasing heat exposure in the work place will be the most common and expected occupational impact of climate change in South Africa. Direct negative impacts of episodes of hot weather events in agriculture for instance have been understood in view of plant yield loss (Schlenker and Lobell 2010) and death of livestock. In the mining sector, Kjellstrom *et al*. (2014) state that historic studies done in the 1960s show that heat related mortality and morbidity were high for workers 1000 m below the surface. However they decreased when occupational health procedures such as heat acclimatization at the ground level were introduced.

5.1.1 Estimating heat stress in the work place

Heat exposure hazards associated with the working population involve air temperature, wind speed, relative humidity and solar irradiance. A sound tool to quantify human heat exposure is the one that includes these parameters. One of the widely used measures to assess workplace heat stress is the wet-bulb globe temperature (WBGT).

According to Blazejczyk *et al*. (2012), the WBGT was developed in 1957 as part of the research on heat related injuries in the US Navy military training. The WBGT index is the measure of preference by the South African Occupational Health and Safety Act 85 of 1993 (1993). It takes into account air temperature, relative humidity as well as radiant temperature and wind speed through the temperature of the globe. WBGT is the weighted average of the black globe temperature (T_g), natural wet bulb temperature (T_w) and dry bulb temperature (). It is calculated for indoor a conditions in the absence of significant solar irradiance using:

WBGT = 0.7 wet bulb temperature + 0.3 globe temperature [5.1]

and

WBGT = 0.7 wet bulb temperature + 0.2 globe temperature + 0.1 dry bulb temperature [5.2]

for outdoor conditions.

One of the constraints of measuring the WBGT is that it requires a use of the black globe temperature T_g, which is often not measured routinely at an AWS. Kjellstrom *et al*. (2009) state that to appropriately investigate the past, present and future changes of human heat exposure during climate change, it would be beneficial if available weather station data could be used to estimate WBGT. There have been a number of efforts to either estimate the WBGT from the routinely measured AWS data (e.g., Australian Government Bureau of Meteorology (BOM) 2010)) or T_g (e.g., Hunter and Minyard 1999, Tonouchi *et al*. 2006, Liljegren *et al.* 2008, Dimiceli *et al*. 2011).

The WBGT provides recommendations and precautions based on measurements for sportsmen (Blazejczyk *et al*. 2012) and for workers at different work intensities (Kjellstrom *et al.* 2009 and Spitz *et al*. 2012). These recommendations range from possible illnesses to intake of a number of litres of fluid in a specific environment with a specific job to the working and resting period which is normally referred to as work/rest period. All recommendations using the WBGT are done so as to avoid an increase in the body temperature beyond 38 ^{o}C for an average worker (Kjellstrom *et al*. 2009). According to Kjellstrom *et al.* (2009) and Liljegren *et al.* (2008), the work/rest period provided by the WBGT becomes useful in calculating the labour productivity incurred during hot days. This study is aimed at quantifying occupational heat exposure in Pietermaritzburg, estimating the loss in labour productivity as well as assessing different methods of obtaining black globe temperature, i.e. evaluate T_g measured with T_g calculated. It is also aimed at comparing the WBGT calculated from the measured T_g and the BOM WBGT and the warning categories of WBGT and HI in Pietermaritzburg.

5.2 MATERIALS AND METHODS

5.2.1 Site and instrumentation mast description

Data reported on was collected from the Agrometeorology Instrumentation Mast (AIM) system situated at the University of KwaZulu-Natal (UKZN) in Pietermaritzburg, South Africa (altitude 648 m; 29.628° S, 30.403° E). The study used data mainly from mast 2 of the AIM system which is 3 m tall and has been in operation since December 2011, with additional measurements of the globe temperature (T_g) from 30th January 2014.

5.2.2 Globe temperature measurements

The globe temperature measurements were obtained from low-cost globe thermometers. The globe thermometer was made from a 150-mm diameter hollow copper sphere, with a thermistor mounted at the centre. For experimental purposes, the study made use of four globes painted in different colours and placed at different heights above the ground, as shown in Figure 5.1.

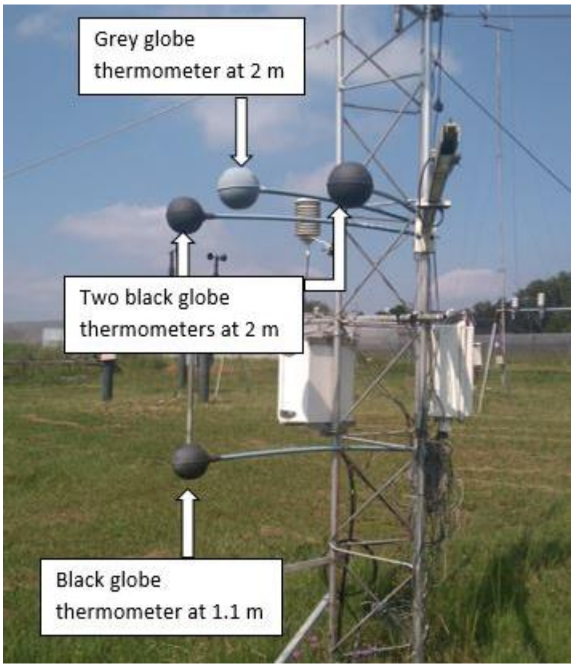

Figure 5.1: Four globe thermometers attached at the automatic weather station

The first globe thermometer was painted in matt-black and was placed at 1.1 m above the surface, meeting the placement requirements suggested by Mayer and Höppe (1987). The second globe thermometer was painted grey and placed at 2 m above the surface. The grey colour was used since Thorsson *et al* (2007) suggested that black is not the average colour for humans. The last two globes were placed at 2 m and were both painted matt-black. The globes were placed at 2 m because most of the meteorological data available at the AWS is at 2 m. Therefore, the study sought to investigate if there would be any changes in the measurements based on colour and the height of the globes. From the measurements of each globe, the WBGT index was calculated using Equation 5.2. The globes were tested in the laboratory at room temperature before they were attached to the AWS mast.

5.2.3 Estimating T_g and the WBGT from routinely measured AWS data

The study made use of the routinely measured AWS data in order to determine the globe temperature for the calculation of WBGT. The WBGT was also determined using the equation of the Australian Government Bureau of Meteorology (BOM) (2010) method of obtaining the WBGT from the routinely. AWS data. The BOM WBGT equation is given by:

$$\text{WBGT} = 0.567\ T_a + 0.393\ e + 3.94 \qquad [5.3]$$

where T_a is the air temperature (°C) and e the water vapour pressure (hPa).

The globe temperature (°C) was calculated using the equation given by Tonouchi *et al*. (2006) which is given by:

$$T_g = T_a\ +\ 0.0175\ I_s - 0.208\,u \qquad [5.4]$$

where T_a is the air temperature (°C), I_s is the solar irradiance (W m^{-2}) and u is the wind speed (m s^{-1}).

5.2.4 Other microclimatic measurements

Air temperature and relative humidity were measured using a CS500 air temperature and relative humidity sensor placed inside a six-plate Gill radiation shield. Incoming solar irradiance was measured using a CMP3 thermopile pyranometer. Wind speed was measured using the RM Young wind speed and wind direction sensors. All measurements were taken at 2 m above the ground surface. Data obtained from these micrometeorological sensors allowed for the comparison and calculation of the WBGT. A summary of all the sensor arrangements is shown in Table 5.1.

A CR1000 data logger at a scan rate of 30 seconds with a multiplexer was used to store all the data at intervals of 2 minutes and 60 minutes. The near real-time values of the WBGT as well as the recommended water intake for a working person were displayed using a web-based data and information system: http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Human%20comfort%201

Table 5.1: Description of sensor arrangement and data acquisition

Details of measurements	Apparatus used
Sensors	Air temperature and relative humidity were measured using the RH and air temperature sensor[1] in a seven-plate Gill radiation shield at 2 m, wind speed and direction sensor[2] at 2 m, solar irradiance (CMP3[3]), four copper globes painted in matt-black with the thermistor[6] at the centre
Calculations	WBGT was calculated using the outdoor equation.
Field data loggers	CR1000[4] and multiplexer AM16/32[4] - all measurements were taken every 2 min and averaged/totaled every 60 min
Field-to-base station communication	Datalogger to the antenna[5] which was in line-of-sight with the receiver.

5.3 RESULTS AND DISCUSSION

5.3.1 Assessment of globe temperature measurements

Globe temperature was measured from four low-cost globe thermometer sensors made from a copper sphere (1) painted matt-black and placed at 1.1 m, (2) painted grey and placed at 2 m while (3 and 4) were painted matt-black and placed at 2 m. Methods 1 and 2 have been found to be superior by previous researchers. Researchers who have found discrepancies in method 1 would suggest that method 2 be used instead, and vice versa. On the other hand, methods 3 and 4, to our knowledge have not previously been used.

Figure 5.2 shows the relationship between the different globe temperature measurements in October 2015. Figure 5.2 shows the relationship between (a) the measurements of the grey globe at 2 m versus the average of the two black globes at 2 m, (b) the measurements of the black globe at 1.1 m versus the grey globes at 2 m and (c) the measurements of the black globe at 1.1 m versus the average of the two black globes at 2 m. Using the 2-min data, the slope, the y-intercept and the R^2 values were calculated in Excel. There is a positive relationship between all the globe temperatures investigated. The R^2 value of 1.00 in Figure 5.2a and 0.99 in both Figures 5.2b and 5.2c.

[1] Vaisala Oyj, Helsinki, Finland
[2] RM Young Company, Traverse City, Michigan, USA
[3] Kipp and Zonen B. V., Delft, The Netherlands
[4] Campbell Scientific Inc., Logan, Utah, USA
[5]. Poynting antenna, Pointing Direct (Pty), Johannesburg, Gauteng, South Africa
[6] RS Components, Durban, South Africa

The results show that the grey globe temperature is highly correlated with the black globe temperature at 2 m (Figure 5.2a) and with the black globe temperature at 1.1 m (Figure 5.2b). Inserting the globe thermometer at 1.1 m for human comfort studies above the ground was advocated by Mayer and Hoppe (1987) because the height perfectly presents the average human height. Nikolopoulou and Lykoudis (2007) showed that the grey globe thermometer is more accurate for outdoor studies on human comfort as opposed to the black globe thermometer. They stated that the black globe thermometer requires the correction of people's solar thermal reflectivity, otherwise it assumes that everyone is wearing black.

The results show that the height and colour of the globe thermometer do not make any significant changes to the globe temperature measurements. It may be expected that in certain weather conditions the reading may be very different due to the colour of the globe thermometer. For example, the black globe thermometers may be expected to have higher values on a sunny, cloudless day when compared to the grey globe thermometer on a similar day. However, the results that were used for all the comparisons include both day time and night time readings for the full month with a wide range of weather conditions. Therefore, the globe temperature is not influenced significantly by the colour of the globe thermometer in all different weather conditions.

The 2-min globe temperatures ware tested against those calculated using Equation 5.3 and the results are shown in Figure 5.3. Figure 5.3 shows that the T_g measured and T_g calculated are non-linear but highly correlated as the R^2 value is 0.97. Using the *y*-equation shown on the graph, the residuals, square residuals and the root square mean error (RMSE) were calculated in Excel to see how much the calculated values deviate from the measured values. The RMSE for T_g measured versus T_g calculated for the two days shown in Figure 5.3 was 1.1 ^oC. For the larger data set (one month), a plot of T_g measured vs T_g calculated yielded a similar R^2 value and the RMSE value of 1.9 ^oC. The T_g calculated was often higher that T_g measured except at low and high temperatures. Nevertheless, the results found that the calculated values are fairly interrelated with the measured values and therefore can be used to compensate the measured values in the absence of the black globe thermometer.

5.3.2 WBGT calculated from routinely measured AWS

The 2-min data were used to investigate the relationship between the WBGT calculated using Equation 5.3 and the one calculated using Equation 5.2. The results are shown in Figure 5.4. Figure 5.4 shows the regression analysis of the BOM WBGT and the WBGT calculated using Equation 5.2 with an R^2 of 0.90 and an RMSE of 5.3 ^oC.

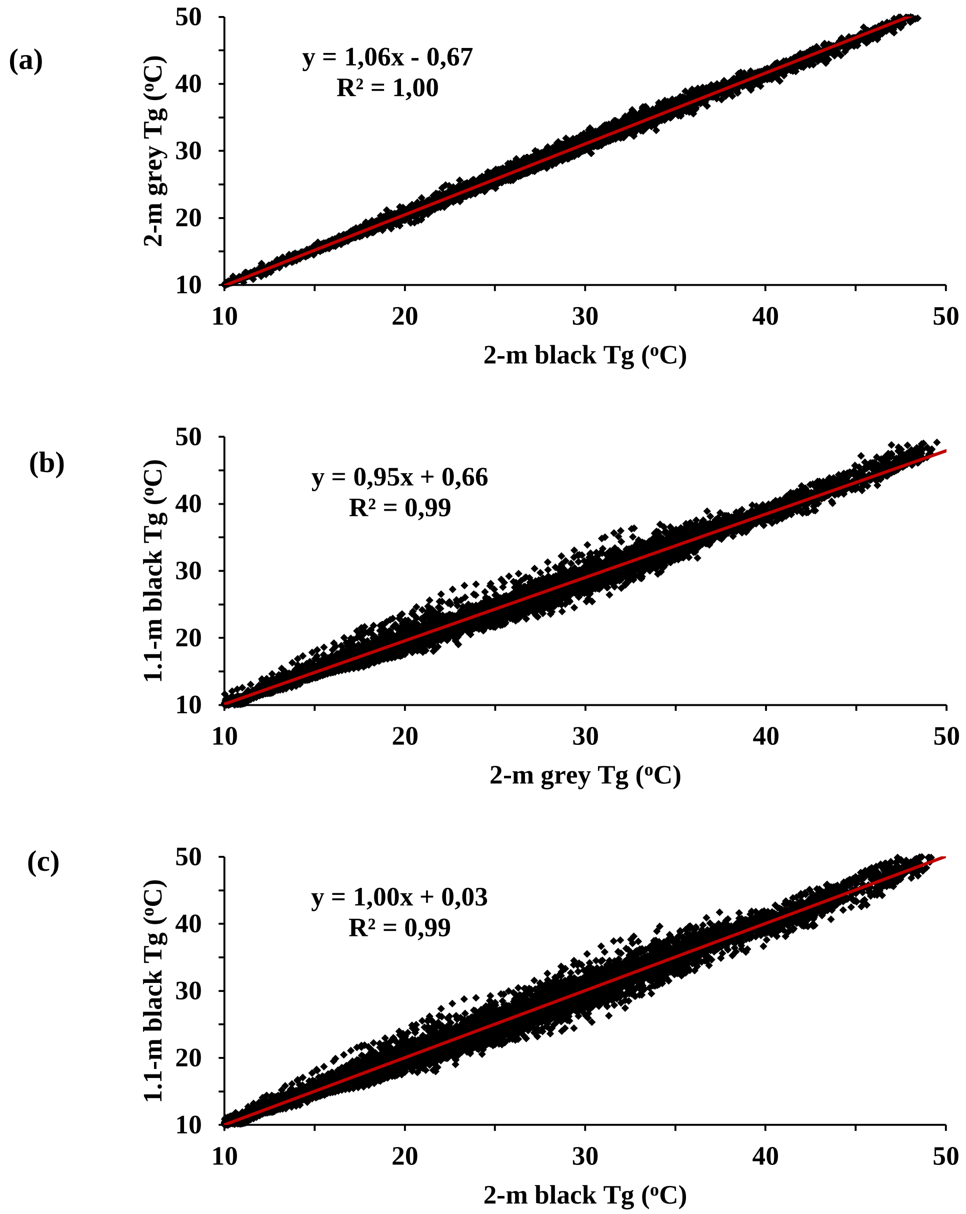

Figure 5.2: Two-min comparisons for October 2015 between: (a) the measurements of the grey globe at 2 m versus the average of the two black globes at 2 m; (b) the measurements of the black globe at 1.1 m versus the grey globes at 2 m and (c) the measurements of the black globe at 1.1 m versus the average of the two black globes at 2 m.

Further analysis of the difference between the two WBGTs was done for four days using the 2-min data from the 19th to the 22nd May 2015. The four-day relationship of the BOM WBGT and the WBGT calculated using the globe measurements is shown in Figure 5.5. Figure 5.5 shows that the WBGTs yielded the same pattern at different times of the day. However, the BOM WBGT yielded higher measurements when compared to the WBGT calculated using the globe temperature measurements

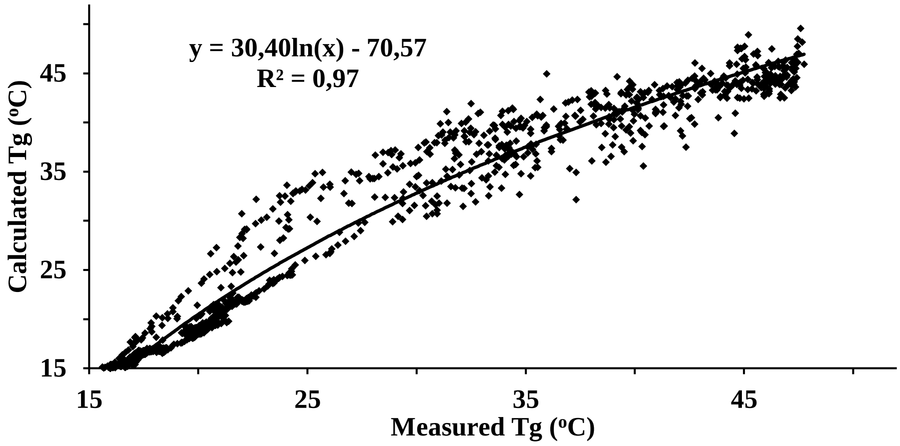

Figure 5.3: Regression plot of the measured globe temperature versus the globe temperature calculated using Equation 5.4 for the 15th and 16th March 2014.

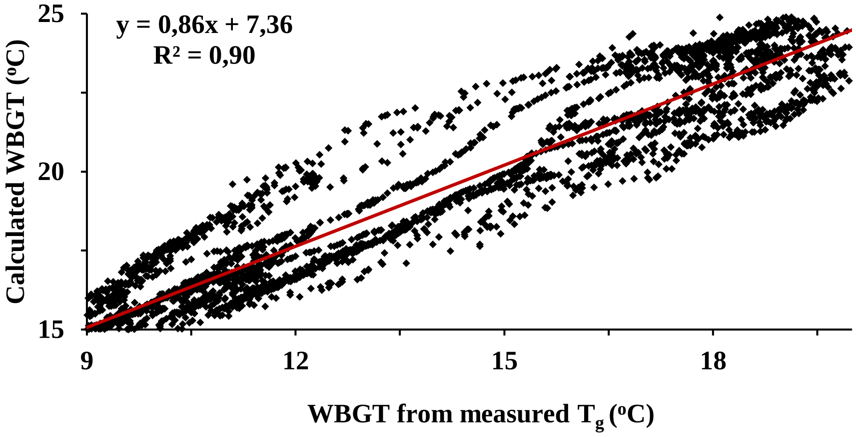

Figure 5.4: Regression plot of the WBGT calculated using the globe measurements and that calculated using the BOM equation for the period 19th to the 22nd May 2015

Although in its calculation the BOM WBGT does not consider all the parameters that influence human comfort such as relative humidity and wind speed, it yielded measurements that are larger and can be practically associated with other microclimatic values of interest. The WBGT calculated using Equation 5.2 tends to have results that are very low even when the measurements of air temperature, solar irradiance and relative humidity are very large.

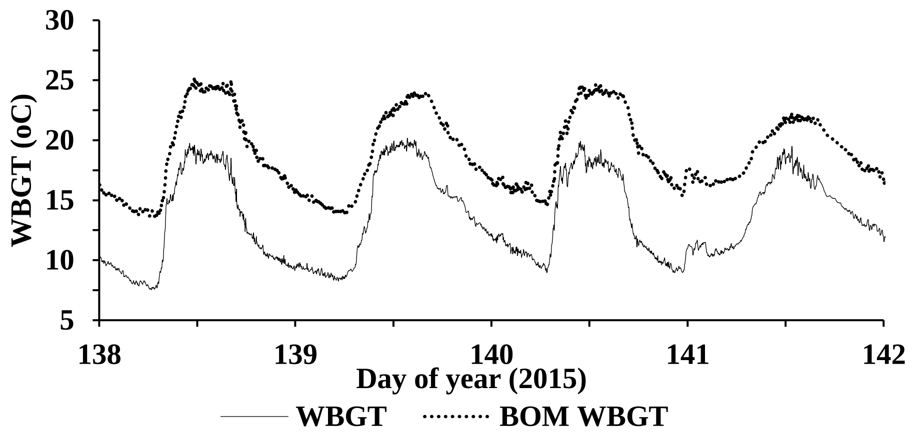

Figure 5.5: Diurnal variation of the WBGT calculated using the globe measurements and that calculated using the BOM equation from 19th May 2015 to the 22nd May 2015.

Comparing the WBGT calculated using Equation 5.2, the BOM WBGT as well as the heat index which is also used to quantify the heat burden on humans, the results reveal that the WBGT calculated using Equation 5.2 is far lower than the other indices. For example, Figure 5.6 shows that the difference between the heat index and the WBGT was 11 ºC at 11h30 and 14ºC at 16h04. The difference between the BOM WBGT and the heat index was 7 ºC and 8 ºC at 11h30 and 16h04, respectively. The maximum heat index on the day reached 32 ºC when the WBGT was 18 ºC and the BOM WBGT was 24 ºC. This category in the heat index is regarded as the extreme caution category and no strenuous activities should take place. The WBGT, which is the index recommended for working people misjudges the environmental conditions that are otherwise akin to discomfort in the heat index.

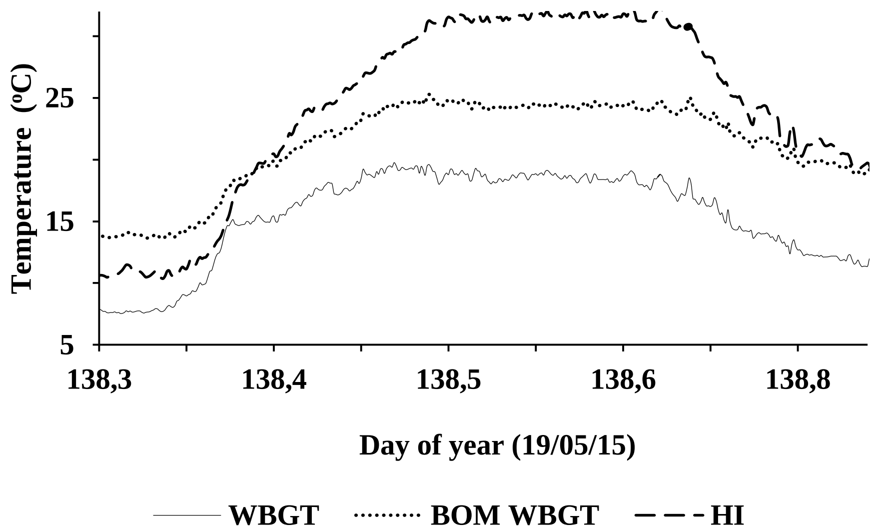

Figure 5.6: The heat index, WBGT calculated using the globe measurements and that calculated using the BOM equation on the 19th May 2015

5.3.3 Impacts of excessive heat events on labour productivity and economy

The duration of each category of the WBGT was calculated using the 60-min data (Table 5.2). Hourly data were used because the WBGT index provides the recommendations based on the weighted hourly average. Table 5.2 shows the duration of different WBGT measurements from February 2014 to November 2015 inclusive. There were 6274.94 days where the WBGT was less than 25.6 ºC and 6.73 and 0.66 days where it was between 25.6 and 27.7 ºC and 27.7 to 29.4 ºC respectively. There were 0.07 hours where the WBGT was between 29.4 ºC and 31.1ºC, 0.03 hours where it was between 31.1 ºC and 32.2 ºC and 3.83 hours where it was greater than 32.2 ºC.

This means that there were 7.55 days (from WBGT flag category 1 to WBGT flag 5) where labour cannot be executed by people who are working outdoors because the labourers are required to take breaks - which is one of the WBGT recommendations. Spitz *et al*. (2012) specify that workers who are doing hard work (600 W) may start taking breaks of 10 minutes in an hour at the WBGT of 25.6 ºC, while those that are performing light work (250 W) and moderate work (425 W) can carry on without taking breaks at this WBGT interval. Workers performing light work and moderate work can start taking 10 minute breaks per hour at a WBGT of greater than 32.2 ºC and 27.7 to 29.4 ºC respectively.

Table 5.2: Duration of different WBGT categories for February 2014 to November 2015 inclusive

WBGT flag category	**WBGT index (ºC)**	**Duration**	
		(h)	**(days)**
	< 25.6	15070.50	627.94
1. White	25.6 – 27.7	161.53	6.73
2. Green	27.7 – 29.4	15.90	0.66
3. Yellow	29.4 – 31.1	0.07	0.00
4. Red	31.1 – 32.2	0.03	0.00
5. Black	>32.2	3.83	0.16
Missing data		7.33	0.31
Total		**15259.20**	**635.80**

A useful table to estimate loss of work productivity is used by Kjellstrom *et al*. (2009). Kjellstrom *et al*. (2009) state that a rest of 25% of an hour can be taken by workers doing light work, medium, work heavy work and very heavy when the WBGT is 31.5, 29.0, 27.5 and 26.5 ºC respectively. Calculating the number of hours of lost productivity, according to Kjellstrom *et al*. (2009), Pietermaritzburg would have lost 4.2 days from February 2014 to November 2015 as a result of taking breaks to avoid adverse impacts of occupational heat.

A total of 4.2 days' worth of discomfort in two years may not be an indicator of an urgent crisis of occupational heat stress. However, with the anticipated impacts of climate change, occupational heat stress remains an area of interest and scrutiny and adaption. Stocker (2013) projects an increase of up to 2 ºC by 2050 if the greenhouse gas emissions continue at the current rate. The study sought to investigate the impacts of adding 2 ºC to the current air temperature on the working population. With 2 ºC added to the current air temperature, T_g was calculated using Equation 5.4 to obtain the WBGT (calculated using Equation 5.2) for analysis. Table 5.3 shows the number of hours of lost labour and the proportion of the WBGT resting period per hour with the 2 ºC addition to the current air temperature. The proportion of the WBGT resting period per hour used in Table 5.3 is based on the analysis table used by Kjellstrom *et al*. (2009).

Table 5.3 shows that an increase of 2 ºC, will mean an increased number of resting hours especially in the 25% resting period for medium, hard and very hard work. In a period of two years, the resting period for people who are carrying out medium work will increase from 0.13 to 65.73 hours, while hard work will increase from 20.87 to 163.57 hours and very hard work will shift from 69.37 to 206.23 hours. This will increase the number of days in which labour can be conducted from 7.5 to 26.6 days in two years.

Table 5.3: Duration of different WBGT categories for a 2 ºC increase in air temperature above that measured at the AIM AWS from February 2014 to November 2015 inclusive

	Duration (hours)							
Resting period (% break per h)	**Light**		**Medium**		**Hard**		**Very hard**	
	WBGT	WBGT +2 ºC	WBGT	WBGT +2 ºC	WBGT	WBGT +2 ºC	WBGT	WBGT +2 ºC
Continuous work	0.00	0.00	15258.03	15254.17	15237.37	15128.67	15178.03	14971.47
25	0.00	1.03	0.13	65.73	20.87	163.57	69.37	206.23
50	0.00	0.00	0.03	10.47	0.10	43.37	9.53	151.50
75	0.20	0.13	0.17	0.17	0.10	1.17	0.10	0.50
100	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

While the results show that there will not be a large increase in the number of hours of the 75 and 100% resting periods, a large increase is noted in the 50 and 25% resting periods for medium, hard and very hard work. This means that there will be a decrease in the productivity of people who are carrying out strenuous work activities, such as construction and agricultural work. For developing countries such as South Africa that depend heavily on sectors such as agricultural and construction, this will bring a great burden to bear on the economy and people's food security, especially in low latitude areas and urban areas, which are generally characterized by higher temperatures.

The South African Occupational Health and Safety Act 85 of 1993 (1993) states that if the WBGT exceeds 30 °C for a period over an hour, the employee has to make sure that the worker is acclimatized to such conditions and takes water breaks of at least 150 ml every 15 minutes. Each of these protective measures has its own drawbacks: firstly, acclimatization is a complicated process that requires time. The change in the global climate may be so irregular and occur so quickly that it does not allow for acclimatization and adaptation to be achieved at a similar pace to the environmental temperature change. Secondly, it is behavioural factors that determine whether an individual consumes the required liquid.

5.3.4 Clinical impacts of excessive heat on working population

Adverse clinical implications exist when excessive energy that is generated by the human body or transferred to the human body from the surrounding environment is not dissipated into the surrounding environment. The working person generates heat that needs to be dissipated into the surrounding environment to avoid the core body temperature increasing beyond 38 °C regardless of the surrounding air temperature. Figure 5.7 shows different WBGT values measured on different days in PMB. The minimum WBGT was 13.7 °C on a cool day on the 26th October 2014 and it reached a maximum of 16.1 °C that day. On a warm day the maximum WBGT reached 30 °C when the surrounding air temperature was 34.7 °C.

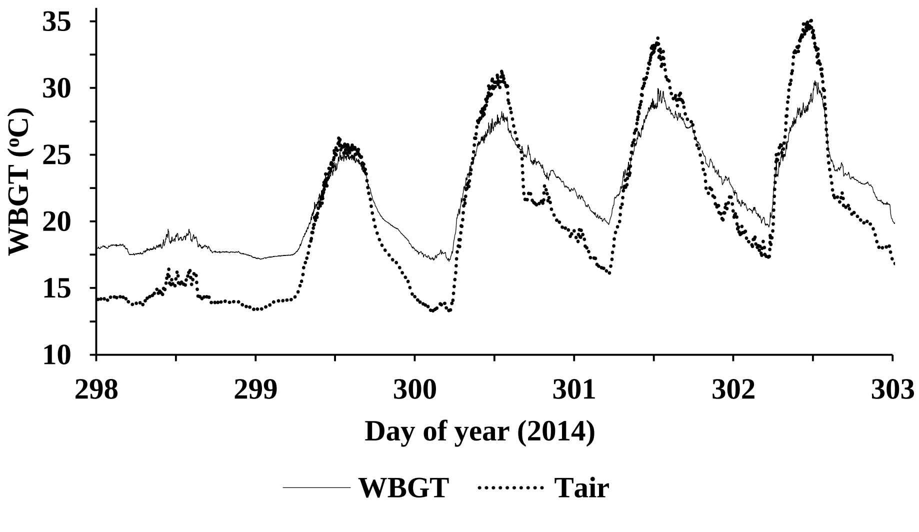

Figure 5.7: The WBGT and air temperature in Pietermaritzburg from the 26th to 30th October 2014 inclusive

Any work (200 to 600W) performed at a maximum WBGT similar to that on the 30^{th} October 2014 can lead to increased core body temperature beyond the desirable range. The consequence of a core body temperature beyond 38.0 $^{\circ}$C may lead to mild heat illnesses such as heat oedema and heat syncope while adverse effects such as heat exhaustion heat stroke or even death may result when the core body temperature rises to 40.0 $^{\circ}$C and beyond. Heat exhaustion is a moderate heat disorder that can occur when the core body temperature is elevated but less than 40 $^{\circ}$C, while heat stroke occurs when the core body temperature is 40.6 $^{\circ}$C or greater (Grubenhoff *et al*. 2007).

5.4 CONCLUSIONS

The WBGT index is a useful index for determining the required resting period of employees in a certain environmental condition at a certain work rate and amount of time lost as a result of taking breaks. However, it underestimates the level of discomfort when compared to other heat stress indices. Instead of using the WBGT calculated from the measurements of the globe temperature, a BOM WBGT can be used as it is practical even though it also provides lower values when compared to the heat index.

The increasing occupational heat exposure as a result of climate change is anticipated to result in substantial occupational health hazards and to bring significant adverse effects on the productivity of many workers. It is likely to place workers in areas of moderate risk occupational heat stress like Pietermaritzburg at high risk to occupational heat stress. However, if efficient preventative and adaptation methods of reducing the occupational heat stress are employed this will not be problematic to human health. On the other hand, preventative and adaptation measures may be expensive and possible only for indoor workers, but difficult, if not impossible to adopt for outdoor workers. The current preventative measures of occupational heat exposure for outdoor workers will in due course hinder economic and social development of individuals, employers and countries at large.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

6.1 GENERAL CONCLUSIONS

Human heat stress is a result of interactions of complex microclimatic factors, surrounding environment, individuals' socio-economic behaviour and health. Several human heat stress assessment methods have been developed and extensively used all over the world. However, these assessment methods only include meteorological parameters with the measurements or assumptions of the individuals' parameters that influence heat stress, but neglect some of the crucial aspects such as individuals' acclimatization, adaptation, regional, social and demographic factors. Selected heat stress assessment indices and micrometeorological sensors were used to evaluate the microclimate for human comfort in the natural environment and in a car parked in the open. Additionally, a web-based system was used to display near real-time data which allowed timely decisions to be made about what should be measured and where.

Both the natural environment and the inside of the car microclimates have demonstrated they pose a danger to human health and sometimes lead to tragic events such as death. This is because the magnitude of the component terms of the energy and radiation balances inside and outside a vehicle placed in the sun on a hot day are very different. Therefore, inside car microclimates are the most lethal when compared to that outdoors and can become hot even on cool winter days in a short period of time in Pietermaritzburg. However, the general public still lacks awareness of the dangers of leaving children in parked cars and of carrying out strenuous activities on hot days. The lack of awareness can be attributed to that gap between meteorological research and society. This information was concluded not by a survey but by literature review and recent events indicating lack of awareness.

Meteorological research often places society out of its design making it difficult to prepare and make deductive reasoning when faced with excessive heat events. Lack of inclusion of these parameters is evident in Chapters 3 and 4, whereby a gap between weather aspect and society lead to tragic events such as the RTI fitness test and death of children in stationary cars. Further, geographic location also becomes important in determining the heat stress. The investigation shows that areas that are in lower altitude are more prone to heat stress compared to those that are in high altitudes and in urban centres. In trying to bridge the gap between 'science' and society as well as to create public awareness, the study investigated the potential of less sophisticated equipment like the cost-efficient method of calculating heat index which can be used in resource-poor communities for events planning and for preparation of day to day activities in a certain weather condition. The cost-efficient method of calculating heat index used in this study showed that it can compete, when used *in situ*, with expensive methods.

6.2 RECOMMENDATIONS FOR FUTURE RESEARCH

All over the world, extreme weather events cause great destruction to the society. The rise in global temperature is expected to have a significant impact on human health, agriculture and mortality through severe weather extreme patterns. Other parts of the world have already experienced these negative impacts of climate change. People, property, and ecosystems remain susceptible to extreme weather, and in many situations vulnerability is increasing.

In South Africa, the number of deaths escalate as a result of adverse weather such as lightning, extreme temperatures, droughts and floods. Furthermore, adverse weather has resulted in a number of instances whereby people have been reported dead after carrying out extraneous activities in hot weather or children suffocating to death after being left in cars that are parked directly in the sun. Other than focusing on one type of extreme weather event, future research should be devoted to an array of adverse weather conditions that negatively impact the society. Additionally, regardless of the fatalities, the public still lacks recognition of the risks of adverse weather. Such research should be accessible to the society and meteorological apparatus should be used to look at the extent and magnitude of adverse weather in order to create public awareness, identify risk groups, and provide reasonable forecast and timely warning systems as well as to inform policies for adaptation in the face of climate change.

REFERENCES

Amengual, A., Homar, V., Romero, R., Brooks, H. E., Ramis, C., Gordaliza, M. and Alonso, S. 2014. Projections of heat waves with high impact on human health in Europe. *Global and Planetary Change*, 119, 71-84.

ASHRAE. 2001. ASHRAE Handbook of Fundamentals. *American Society of Heating, Refrigerating and Air-Conditioning Engineers*, Atlanta.

Arens, E.A. and Zhang, H., 2006. The skin's role in human thermoregulation and comfort (Chapter 16). In: Pan N. and Gibson P. (eds), *Thermal and Moisture Transport in Fibrous Materials*. Woodhead Publishing Ltd, Cambridge, pp. 560-602.

Auliciems, A. and Szokolay, S. V. 1997. Thermal comfort. PLEA. http://www.sheltercentre.org/sites/default/files/plea_2007_thermal_comfort.pdf. (Accessed 12 March 2014).

Australian Bureau of Meteorology. 2010. About the WBGT and apparent temperature indices. http://www.bom.gov.au/info/thermal_stress/#approximation (Accessed 04 March 2015).

Banitz, E. 2001. Evaluation of short-term weather forecasts in South Africa. *Water SA*, 27(4), 489-498.

Barnett, A. G., Tong, S. and Clements, A. C. A. 2010. What measure of temperature is the best predictor of mortality? *Environmental Research*, 110(6), 604-611.

Basu, R. and Samet, J. M. 2002. Relation between elevated ambient temperature and mortality: a review of the epidemiologic evidence. *Epidemiologic Reviews*, 24(2), 190-202.

Basu, R. 2009. High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. *Environmental Health*, 8(1), 40.

Benton, C., Bauman, F., and Fountain, M. 1990. A field measurement system for the study of thermal comfort. *ASHRAE Transactions*. 96 (1). Available at http://escholarship.org/uc/item/9cb6t2wz. (Accessed 11 March 2015).

Blazejczyk, K., Epstein, Y., Jendritzky, G., Staiger, H., and Tinz, B. 2012. Comparison of UTCI to selected thermal indices. *International Journal of Biometeorology*, 56(3), 515-535.

Booth III, J. N., Davis, G. G., Waterbor, J. and McGwin Jr, G. 2010. Hyperthermia deaths among children in parked vehicles: an analysis of 231 fatalities in the United States, 1999–2007. *Forensic Science, Medicine, and Pathology*, 6(2), 99-105.

Bouchama, A., and Knochel, J. P. 2002. Heat stroke. *New England Journal of Medicine*, 346 (25), 1978-1988.

Buscail, C., Upegui, E., and Viel, J. F. 2012. Mapping heatwave health risk at the community level for public health action. *International Journal of Health Geographics*, 11(1), 38.

Casa, D. J. and Csillan, D. 2009. Preseason heat-acclimatization guidelines for secondary school athletics. *Journal of Athletic Training*, 44(3), 332.

Curriero, F. C., Heiner, K. S., Samet, J. M., Zeger, S. L., Strug, L. and Patz, J. A. 2002. Temperature and mortality in 11 cities of the eastern United States. *American Journal of Epidemiology*, 155(1), 80-87.

Dadour, I. R., Almanjahie, I., Fowkes, N. D., Keady, G., and Vijayan, K. 2011. Temperature variations in a parked vehicle. *Forensic Science International*, 207(1), 205-211.

Delworth, T. L., Mahlman, J. D., and Knutson, T. R. 1999. Changes in heat index associated with CO_2-induced global warming. *Climatic Change*, 43(2), 369-386.

Deressa, T., Hassan, R., and Poonyth, D. 2005. Measuring the economic impact of climate change on South Africa's sugarcane growing regions. *Agrekon*. 44 (4), 524–42

Dimiceli V. E., Piltz S. F., and Amburn S. A. 2011. Estimation of black globe temperature for calculation of the wet bulb globe temperature index. In: Proceedings of the World Congress on Engineering and Computer Science, 19-21 October, San Francisco, USA.

Dixon, P. G., McDonald A. N., Scheitlin, K. N., Stapleton, J. E., Allen, J. S., Carter, W. M., Holley, M. R., Inman, D. D. and. Roberts. J. B. 2007. Effects of temperature variation on suicide in five US counties, 1991–2001. *International Journal of Biometeorology*, 51(5), 395-403.

Doswell, C. A. 2003. Societal impacts of severe thunderstorms and tornadoes: lessons learned and implications for Europe. *Atmospheric Research*, 67, 135-152.

Environmental Protection Agency. 2006. Excessive heat events guidebook. EPA-430-B-06-005. United States Environmental Protection Agency. Available at http://www.epa.gov/heatisland/about/pdf/EHEguide_final.pdf. (Accessed 12 April 2014).

Epstein, Y. and Moran, D. S. 2004. Extremes of temperature and hydration. *Travel Medicine*, 383-392.

Epstein, Y. and Moran, D. S. 2006. Thermal comfort and the heat stress indices. *Industrial Health*, 44(3), 388-398.

Ferrara, P., Vena, F., Caporale, O., Del Volgo, V., Liberatore, P., Ianniello, F. and Riccardi, R. 2013. Children left unattended in parked vehicles: a focus on recent Italian cases and a review of literature. *Italian Journal of Pediatrics*, 39(1), 1-4.

Fouillet, A., Rey, G., Laurent, F., Pavillon, G., Bellec, S., Guihenneuc-Jouyaux, C., Clavel, J., Jougla, E. and Hémon, D., 2006. Excess mortality related to the August 2003 heat wave in France. *International Archives of Occupational and Environmental Health*, 80(1), 16-24.

Gosling, S.N., McGregor, G.R. and Páldy, A., 2007. Climate change and heat-related mortality in six cities Part 1: model construction and validation. *International journal of biometeorology*, 51(6), 525-540.

Gosling, S.N., Bryce, E.K., Dixon, P.G., Gabriel, K.M.A., Gosling, E.Y., Hanes, J.M., Hondula, D.M., Liang, L., Bustos Mac Lean, P.A., Muthers, S., Nascimento, S.T., Petralli, M., Vanos, J.K.,and Wanka, E.R. 2014. A glossary for biometeorology. *International Journal of Biometeorology*, 58(2), 277-308.

Grubenhoff, J. A., du Ford, K. and Roosevelt, G. E. 2007. Heat-related illness. *Clinical Pediatric Emergency Medicine*, 8(1), 59-64.

Grundstein, A., Meentemeyer, V., and Dowd, J. 2009. Maximum vehicle car temperatures under different meteorological conditions. *International Journal Biometeorology*, 53, 255–261.

Grundstein, A., Meentemeyer, V., and Dowd, J. 2010. Quantifying the heat-related hazard for children in motor vehicles. *Bulletin of the American Meteorological Society*, 91(9), 1186-1191.

Grundstein, A., Null, J., and Meentemeyer, V. 2011. Weather, geography, and vehicle-related hyperthermia in children. *Geographical Review*, 101(3), 353-370.

Guard, A. and Gallagher, S. S. 2005. Heat related deaths to young children in parked cars: an analysis of 171 fatalities in the United States, 1995–2002. *Injury Prevention*, 11(1), 33-37.

Haines, A., Kovats, R. S., Campbell-Lendrum, D. and Corvalán, C. 2006. Climate change and human health: Impacts, vulnerability and public health. *Public Health*, 120(7): 585-596.

Hajat, S., Kovats, R. S., Atkinson, R. W. and Haines, A. 2002. Impact of hot temperatures on death in London: a time series approach. *Journal of Epidemiology and Community Health*, 56(5), 367-372.

Hales, S., Edwards, S. J. and Kovats, R. S. 2003. Impacts on health of climate extremes. Climate change and health: risks and responses. Geneva, World Health Organization. Available at http://www.who.int/globalchange/publications/climatechangechap5.pdf?ua=1 (Accessed 16 May 2015)

Harlan, S. L., Brazel, A. J., Prashad, L., Stefanov, W. L. and Larsen, L. 2006. Neighborhood microclimates and vulnerability to heat stress. *Social Science and Medicine*, 63(11), 2847-2863.

Hart, J. 2015. Association between air temperature and deaths due to cancer and heart disease in Alabama. *Applied Scientific Reports*, 2(1), 1-6.

Henson, R.H. 2008. *The rough guide to Climate Change*. *The symptoms. The science. The Solutions*. Rough Guides Ltd, London.

Hoppe, P. 1992. A new procedure to determine the mean radiant temperature outdoors. *Wetter und Leben*. 44: 147-151

Hoppe, P. 1999. The physiological equivalent temperature–a universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology*, 43(2): 71-75.

Houghton, J.T., Albritton, D.L., Meira Filho, L.G., Cubasch, U., Dai, X., Ding, Y., Griggs, D.J., Hewitson, B., Isaksen, I., Karl, T. and McFarland, M., 2001. *Technical summary of working group 1*. Cambridge University Press.

Howe, A. S. and Boden, B. P. 2007. Heat-related illness in athletes. *The American Journal of Sports Medicine*, 35(8): 1384-1395.

Huang, J., Laurent, J. G. C., Spengler, J. and Reinhart, C. 2012. A GIS-based assessment method for mean radiant temperature in dense urban areas. Available at http://web.mit.edu/tito_/www/Publications/SimBuild2012_MeanRadiantTemperature_Huang.pdf. (Accessed 22 June 2014).

Hunter, C. H., and Minyard, C. O. 1999. *Estimating Wet Bulb Globe Temperature Using Standard Meteorological Measurements*, Report WSRC-MS-99-00757, Westinghouse Savannah River Company, Aiken, South Carolina.

Hyatt, O. M., Lemke, B. and Kjellstrom, T. (2010). Regional maps of occupational heat exposure: past, present, and potential future. *Global Health Action*, 3.

IOL, 2014. Children suffocate in closed car. Available at http://www.iol.co.za/dailynews/news/children-suffocate-in-closed-car-1.1682226. (Accessed on 20th June 2014)

Jager, E. (2015). *And the heatwave continued*. Available at http://www.weathersa.co.za/images/documents/286/CLS-CI-GEN-INFO-101__Continuation%20of%20heat%20wave.pdf (Accessed 03 December 2015)

Johnson, D. P., Wilson, J. S. and Luber, G. C. 2009. Socioeconomic indicators of heat-related health risk supplemented with remotely sensed data. *International Journal of Health Geographics*, 8(57).

Kalkstein, L. S., and Valimont, K. M. 1987. Climate effects on human health. *Potential Effects of Future Climate Changes on Forest and Vegetation, Agriculture, Water Resources, and Human Health, EPA Science and Advisory Committee Monograph*, No. 25389, U.S. Environmental Protection Agency, 122–152.

Kantor, N. and Unger, J. 2011. The most problematic variable in the course of human-biometeorological comfort assessment—the mean radiant temperature. *Central European Journal of Geosciences*, 3(1), 90-100.

Kim, H., Ha, J. S. and Park, J. 2006. High temperature, heat index, and mortality in 6 major cities in South Korea. *Archives of Environmental and Occupational Health*, 61(6), 265-270.

King K., Negus K., and Vance J. 1981. Heat stress in motor vehicles: a problem in infancy. *Pediatrics*, 68, 579–582.

Kjellstrom, T. 2009. Climate change, direct heat exposure, health and well-being in low and middle-income countries. *Global Health Action*, 2.

Kjellstrom, T., Holmer, I. and Lemke, B. 2009. Workplace heat stress, health and productivity - an increasing challenge for low and middle-income countries during climate change. *Global Health Action*, 2.

Kjellstrom, T., Holmer, I. and Lemke, B. 2009. Workplace heat stress, health and productivity - an increasing challenge for low and middle-income countries during climate change. *Global Health Action*, 2.

Kjellstrom, T., Lemke, B. and Otto, M. 2013. Mapping occupational heat exposure and effects in South-East Asia: ongoing time trends 1980–2011 and future estimates to 2050. *Industrial Health*, 51(1), 56-67.

Kjellstrom, T., Lemke, B., Hyatt, O. and Otto, M. 2014. Climate change and occupational health: A South African perspective. *South African Medical Journal*, 104(8), 586-587.

Koppe, C., Kovats, S., Jendritzky, G., Menne, B. and Breuer, D. J. 2004. *Heat waves: risks and responses*. Copenhagen, Denmark: Regional Office for Europe, World Health Organization.

Kovats, R. S. and Hajat, S. 2008. Heat stress and public health: a critical review. *Annual Review of Public Health*, 29, 41-55.

Kruger, A. C. and Sekele, S. S. 2013. Trends in extreme temperature indices in South Africa: 1962–2009. *International Journal of Climatology*. 33(3), 661-676.

Kruger, A. C. and Shongwe, S. 2004. Temperature trends in South Africa: 1960–2003. *International Journal of Climatology*, 24(15), 1929-1945.

Liljegren, J. C., Carhart, R. A., Lawday, P., Tschopp, S., and Sharp, R. 2008. Modeling the wet bulb globe temperature using standard meteorological measurements. *Journal of Occupational and Environmental Hygiene*, 5(10), 645-655.

Lin, T. P., Matzarakis, A. and Hwang, R. L. 2010. Shading effect on long-term outdoor thermal comfort. *Building and Environment*, 45(1), 213-221.

Lindberg, F., Holmer, B. and Thorsson, S. 2008. SOLWEIG 1.0–Modelling spatial variations of 3D radiant fluxes and mean radiant temperature in complex urban settings. *International Journal of Biometeorology*. 52(7), 697-713.

Luber, G. and McGeehin, M. (2008). Climate change and extreme heat events. *American Journal of Preventive Medicine.* 35(5), 429-435.

Lundgren, K., Kuklane, K., Gao, C., and Holmer, I. 2013. Effects of heat stress on working populations when facing climate change. *Industrial Health*. 51(1), 3-15.

Luo, B.D., Zou, F., Wan, W.R., Hua, X.C., Yang, J. and Zhu S.C. 1999. Study on an effective method to accelerate body heat acclimatization. *Chinese Journal of Industrial Medicine*. 12 (6), 330–332

Maia, A. S. C .and Loureiro, C. B. 2005. Sensible and latent heat loss from the body surface of Holstein cows in a tropical environment. *International Journal of Biometeorology.* 50(1), 17-22.

Makamba, L. 2013. Father held for leaving baby in hot car. Available at http://www.iol.co.za/news/crime-courts/father-held-for-leaving-baby-in-hot-car-1.1501131. (Accessed 22 October 2015)

Maloney, S. K.and Forbes, C. F. 2011. What effect will a few degrees of climate change have on human heat balance? Implications for human activity. *International Journal of Biometeorology*, 55(2), 147-160.

Marty, W., Sigrist, T., and Wyler, D. 2001. Temperature variations in automobiles in various weather conditions. *American Journal of Forensic Medicine Pathology*, 22(3), 215–219.

Mathee, A., Oba, J.and Rose, A. 2010. Climate change impacts on working people (the HOTHAPS initiative): findings of the South African pilot study. *Global Health Action*, 3.

Matsueda, M. 2011. Predictability of Euro-Russian blocking in summer of 2010. *Geophysical Research Letters*, 38(6).

Matzarakis, A. and Nastos, P. T. 2011. Human-biometeorological assessment of heat waves in Athens. *Theoretical and Applied Climatology*, 105(1-2), 99-106.

Maughan, R. and Shirreffs, S. 2004. Exercise in the heat: challenges and opportunities. *Journal of Sports Sciences*, 22(10), 917-927.

Mayer, H. and Höppe, P. 1987. Thermal comfort of man in different urban environments. *Theoretical and Applied Climatology*, 38(1), 43-49.

McLaren, C., Null, J., Quinn, J. 2005. Heat stress from enclosed vehicles: moderate ambient temperatures cause significant temperature rise in enclosed vehicles. *Pediatrics*, 116, 109–112.

Meehl, G. A. and Tebaldi, C. 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. *Science*, 305(5686), 994-997.

Michelozzi, P., De Donato, F., Bisanti, L., Russo, A., Cadum, E., DeMaria, M. and Perucci, C. A. 2005. The impact of the summer 2003 heat waves on mortality in four Italian cities. *European Communicable Disease Bulletin*, 10(7), 161-165.

Moran, D. S., Shitzer, A., and Pandolf, K. B. 1998. A physiological strain index to evaluate heat stress. *American Journal of Physiology*, 275(1), R129 -R134

Nikolopoulou M., Baker N. and Steemers K. 2001. Thermal comfort in outdoor urban spaces: understanding the human parameter. *Solar Energy*, 70(3), 227–35.

Nikolopoulou, M. and Lykoudis, S. 2006 Thermal comfort in outdoor urban spaces: analysis across different European countries. *Building and Environment*, 41(11), 1455–1470.

Nikolopoulou, M., Baker N., and Steemers, K. 1999. Improvements to the Globe Thermometer for Outdoor Use. *Architectural Science Review*, 42(1), 27-34.

Nikolopoulou, M., Lykoudis, S. 2007. Use of outdoor spaces and microclimate in a Mediterranean urban area. *Building and Environment*, 42(10), 3691–707.

NOAA. 2009. Heat index chart. Available at http://www.srh.noaa.gov/ffc/?n=hichart. (Accessed 23 March 2015).

Null, J. 2005. A Stationary. *Weatherwise*, 58(4), 52-55, DOI: 10.3200/ WEWI.58.4.52-55.

Null, J. 2016 Heat stroke deaths of children in vehicles.available at http://noheatstroke.org/. (Accessed 15 March 2016)

Omonijo, A. G., Adeofun, C. O., Oguntoke, O. and Matzarakis, A. 2013. Relevance of thermal environment to human health: a case study of Ondo State, Nigeria. *Theoretical and Applied Climatology*, 113(1-2), 205-212.

Ongoma, V. and Muthama, J. N. 2014. A Review and Assessment of Applicability of the Heat Stress Indices in Kenyan Weather Forecast. *Open Journal of Atmospheric and Climate Change*, 1(1), 17-22.

OSHA. 1999. OSHA Technical Manual, Section III: Chapter 4, Heat stress. Available at http://www.osha.gov/dts/osta/otm/otm_iii/otm_iii_4.html. (Accessed on 20 June 2014)

Parson, K. 2010. Thermal comfort in buildings (pp. 127–147). In M. R. Hall (Ed.), *Materials for energy efficiency and thermal comfort in building*. Washington, DC: Woodhead Publishing

Parsons, K. 2014. *Human Thermal Environments: The Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort, and Performance*. CRC Press. Boca Raton, Florida.

Peters, S. 2015a. Kids locked in car: parents avoid charges. Available at http://www.iol.co.za/news/south-africa/kwazulu-natal/kids-locked-in-car-parents-avoid-charges-1.1890539. (Accessed 22 October 2015)

Peters, S. 2015b. RTI victims want justice done. Available at http://www.iol.co.za/news/south-africa/kwazulu-natal/rti-victims-want-justice-done-1830548. (Accessed 03 December 2015)

Radakovic, S. S., Maric, J., Surbatovic, M., Radjen, S., Stefanova, E., Stankovic, N., and Filipovic, N. 2007. Effects of acclimation on cognitive performance in soldiers during exertional heat stress. *Military medicine*, 172(2), 133-136.

Radebe, M. 2012. December 28. Heat fells job seekers. The Witness.

Rana, R., Kusy, B., Jurdak, R., Wall, J. and Hu, W. 2013. Feasibility analysis of using humidex as an indoor thermal comfort predictor. *Energy and Buildings*, 64, 17-25.

Robinson, P. J. 2001. On the definition of a heat wave. *Journal of Applied Meteorology*, 40(4), 762-775.

Rose-Innes, O. 2012. Why car heat is a child-killer. Available at http://www.health24.com/Lifestyle/Environmental-health/Climate-and-temperature/Why-car-heat-is-a-child-killer-20120721. (Accessed 20 June 2014).

Rothfusz, L. P., and Headquarters, N. S. R. 1990. The heat index equation (or, more than you ever wanted to know about heat index). *Fort Worth, Texas: National Oceanic and Atmospheric Administration, National Weather Service, Office of Meteorology*, 90-23. USA.

Russo, S., Marchese, A. F., Sillmann, J., and Immé, G., 2016. When will unusual heat waves become normal in a warming Africa. *Environmental Research Letters*, 11(5), p.054016.

SABC. 2016. *Heat stroke death toll rises to 11*. Available at http://www.sabc.co.za/news/a/66a6c6804b41c69c870def445cadceaa/Heat-stroke-death-toll-rises-to-11-20161001. (Accessed 13 January 2016)

SAPA. 2013. About 200 treated at RTI fitness test. Available at http://www.iol.co.za/news/south-africa/kwazulu-natal/about-200-treated-at-rti-fitness-test-1559932. (Accessed 22 January 2015)

Savage, M. J. 2015. August 13. Why cars get so hot. The Witness.

Savage, M. J., Abraha, M. G., Moyo, N. C. and Babikir, N. 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*, 31(1), 13-23.

Schlader, Z. J., Stannard, S. R. and Mündel, T. 2010. Human thermoregulatory behavior during rest and exercise—a prospective review. *Physiology and Behavior*, 99(3), 269-275.

Schlenker, W. and Lobell, D.B., 2010. Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*, 5(1), p.014010.

Sheridan, S. C. and Kalkstein, L. S. 2004. Progress in heat watch-warning system technology. *Bulletin of the American Meteorological Society*, 85(12), 1931–1942.

Solomon, S. (Ed.). 2007. *Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC (Vol. 4).* Cambridge University Press, United Kingdom.

South African Occupational Health and Safety Act No 85 of 1993 and its Regulations. 1993. *South African occupational health and safety act no 85 of 1993 and its regulations*, Johannesburg, Lex Patria Publishers.

South African Weather Services. 2016. *What Is the Heat index?* Available at http://www.weathersa.co.za/learning/educational-questions/53-what-is-the-heat-index. (Accessed 22 April 2016)

Spitz, M. G., Castellani, J. W., Freund, B. J., and Sawka, M. N. 2012. Management of Heat and Cold Stress-Guidance to NATO Medical Personnel (No. T3-13). *Army Research Institute of Environmental Medicine Natick Massachusetts Thermal and Mountain Medicine Division*. Available at http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA571324 (Accessed 21 June 2015).

Stathopoulos, T., Wu, H., and Zacharias J. 2004. Outdoor human comfort in an urban climate. *Building and Environment*, 39(3), 297–305

Steadman, R. G. 1979. The assessment of sultriness. Part II: effects of wind, extra radiation and barometric pressure on apparent temperature. *Journal of Applied Meteorology*, 18(7), 874-885.

Stocker, T. F. 2013. Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Thorsson, S., Lindberg, F., Eliasson, I. and Holmer, B. 2007. Different methods for estimating the mean radiant temperature in an outdoor urban setting. *International Journal of Climatology*, 27(14), 1983-1993.

Tian, Z., Zhu, N., Zheng, G. and Wei, H. 2011. Experimental study on physiological and psychological effects of heat acclimatization in extreme hot environments. *Building and Environment*, 46(10), 2033-2041.

Tonouchi, M., Murayama, K., and Ono, M. 2006. WBGT forecast for prevention of heat stroke in Japan. In Sixth Symposium on the Urban Environment. AMS Forum: Managing our Physical and Natural Resources: Successes and Challenges JP1 (Vol. 1). Available at https://ams.confex.com/ams/Annual2006/techprogram/paper_101722.htm (accessed 21 June 2015).

Vernon, H.M., 1932. The measurement of radiant heat in relation to human comfort. *Journal of Industrial Hygiene*, 14, 95-111. Cited by Lindberg, F., Holmer, B. and Thorsson, S. 2008. SOLWEIG 1.0–Modelling spatial variations of 3D radiant fluxes and mean radiant temperature in complex urban settings. *International Journal of Biometeorology*. 52(7), 697-713

Wyndham, C. H., Strydom, N. B., Morrison, J. F., Williams, C. G., Bredell, G. A. G., Maritz, J. S. and Munro, A. 1965. Criteria for physiological limits for work in heat. *Journal of Applied Physiology*, 20(1), 37-45.

Yaglou, C. P. and Minard, D. 1957. Control of heat casualties at military training centers. *AMA Archives of Industrial Health*, *16*(4), 302.

Yeargin, S. W., Casa, D. J., Armstrong, L. E., Watson, G., Judelson, D. A., Psathas, E., and Sparrow, S. L. 2006. Heat acclimatization and hydration status of American football players during initial summer workouts. *The Journal of Strength and Conditioning Research*, 20(3), 463-470.

Zanobetti, A. and Schwartz J. 2005. The effect of particulate air pollution on emergency admissions for myocardial infarction: a multicity case-crossover analysis. *Environmental health perspectives*, 113 (8), 978-982.

Ziervogel, G., New, M., Archer van Garderen, E., Midgley, G., Taylor, A., Hamann, R., Stuart-Hill, S., Myers, J. and Warburton, M. 2014. Climate change impacts and adaptation in South Africa. *WIREs Climate Change*, 5, 605-620.

Appendix A: Different heat index categories

Tdry	RH (%)																													
(°C)	40.0	42.0	44.0	46.0	48.0	50.0	52.0	54.0	56.0	58.0	60.0	62.0	64.0	66.0	68.0	70.0	72.0	74.0	76.0	78.0	80.0	82.0	84.0	86.0	88.0	90.0	92.0	94.0	96.0	98.0	100.0
26.0	26.2	26.3	26.3	26.4	26.5	26.6	26.6	26.7	26.8	26.9	26.9	27.0	27.1	27.1	27.2	27.3	27.4	27.4	27.5	27.6	27.7	27.7	27.8	27.9	28.0	28.0	28.1	28.2	28.3	28.3	28.4
26.5	26.5	26.6	26.7	26.8	26.9	27.0	27.1	27.2	27.3	27.4	27.5	27.6	27.7	27.8	27.9	28.0	28.2	28.3	28.4	28.5	28.7	28.8	28.9	29.1	29.2	29.3	29.5	29.6	29.8	29.9	30.1
27.0	26.9	27.0	27.1	27.2	27.3	27.4	27.5	27.7	27.8	27.9	28.1	28.2	28.4	28.5	28.7	28.9	29.0	29.2	29.4	29.6	29.7	29.9	30.1	30.3	30.5	30.7	30.9	31.2	31.4	31.6	31.8
27.5	27.2	27.4	27.5	27.6	27.8	27.9	28.1	28.2	28.4	28.6	28.7	28.9	29.1	29.3	29.5	29.7	29.9	30.2	30.4	30.6	30.9	31.1	31.4	31.7	31.9	32.2	32.5	32.8	33.1	33.4	33.7
28.0	27.7	27.8	28.0	28.1	28.3	28.4	28.6	28.8	29.0	29.2	29.4	29.7	29.9	30.2	30.4	30.7	30.9	31.2	31.5	31.8	32.1	32.4	32.7	33.1	33.4	33.7	34.1	34.5	34.8	35.2	35.6
28.5	28.1	28.3	28.5	28.6	28.8	29.0	29.2	29.5	29.7	30.0	30.2	30.5	30.8	31.1	31.4	31.7	32.0	32.3	32.7	33.0	33.4	33.8	34.1	34.5	35.0	35.4	35.8	36.2	36.7	37.2	37.6
29.0	28.6	28.8	29.0	29.2	29.4	29.7	29.9	30.2	30.4	30.7	31.0	31.3	31.7	32.0	32.4	32.7	33.1	33.5	33.9	34.3	34.7	35.2	35.6	36.1	36.6	37.1	37.6	38.1	38.6	39.2	39.7
29.5	29.1	29.3	29.6	29.8	30.1	30.3	30.6	30.9	31.2	31.6	31.9	32.3	32.6	33.0	33.4	33.9	34.3	34.7	35.2	35.7	36.2	36.7	37.2	37.7	38.3	38.9	39.4	40.0	40.6	41.3	41.9
30.0	29.7	29.9	30.2	30.5	30.7	31.0	31.4	31.7	32.1	32.4	32.8	33.2	33.7	34.1	34.6	35.0	35.5	36.0	36.6	37.1	37.7	38.2	38.8	39.4	40.1	40.7	41.4	42.1	42.8	43.5	44.2
30.5	30.3	30.6	30.8	31.1	31.5	31.8	32.2	32.6	33.0	33.4	33.8	34.3	34.7	35.2	35.8	36.3	36.8	37.4	38.0	38.6	39.2	39.9	40.5	41.2	41.9	42.7	43.4	44.2	44.9	45.7	46.6
31.0	30.9	31.2	31.5	31.9	32.2	32.6	33.0	33.4	33.9	34.4	34.8	35.4	35.9	36.4	37.0	37.6	38.2	38.8	39.5	40.2	40.9	41.6	42.3	43.1	43.9	44.7	45.5	46.3	47.2	48.1	49.0
31.5	31.6	31.9	32.3	32.6	33.0	33.5	33.9	34.4	34.9	35.4	35.9	36.5	37.1	37.7	38.3	39.0	39.6	40.3	41.1	41.8	42.6	43.4	44.2	45.0	45.9	46.8	47.7	48.6	49.6	50.5	51.5
32.0	32.3	32.6	33.0	33.5	33.9	34.4	34.9	35.4	35.9	36.5	37.1	37.7	38.3	39.0	39.7	40.4	41.2	41.9	42.7	43.5	44.4	45.2	46.1	47.0	48.0	49.0	49.9	51.0	52.0	53.1	54.2
32.5	33.0	33.4	33.8	34.3	34.8	35.3	35.8	36.4	37.0	37.6	38.3	38.9	39.6	40.4	41.1	41.9	42.7	43.6	44.4	45.3	46.2	47.2	48.1	49.1	50.2	51.2	52.3	53.4	54.5	55.7	56.9
33.0	33.8	34.2	34.7	35.2	35.7	36.3	36.9	37.5	38.1	38.8	39.5	40.3	41.0	41.8	42.6	43.5	44.3	45.3	46.2	47.2	48.1	49.2	50.2	51.3	52.4	53.5	54.7	55.9	57.1	58.4	59.7
33.5	34.6	35.1	35.6	36.1	36.7	37.3	38.0	38.6	39.3	40.1	40.8	41.6	42.4	43.3	44.2	45.1	46.0	47.0	48.0	49.1	50.1	51.2	52.4	53.5	54.7	56.0	57.2	58.5	59.8	61.2	62.5
34.0	35.4	36.0	36.5	37.1	37.7	38.4	39.1	39.8	40.6	41.4	42.2	43.0	43.9	44.8	45.8	46.8	47.8	48.9	49.9	51.1	52.2	53.4	54.6	55.9	57.1	58.4	59.8	61.2	62.6	64.0	65.5
34.5	36.3	36.9	37.5	38.1	38.8	39.5	40.3	41.0	41.9	42.7	43.6	44.5	45.5	46.4	47.5	48.5	49.6	50.7	51.9	53.1	54.3	55.6	56.9	58.2	59.6	61.0	62.5	63.9	65.4	67.0	68.6
35.0	37.2	37.8	38.5	39.2	39.9	40.7	41.5	42.3	43.2	44.1	45.1	46.0	47.1	48.1	49.2	50.3	51.5	52.7	54.0	55.2	56.5	57.9	59.3	60.7	62.2	63.7	65.2	66.8	68.4	70.0	71.7
35.5	38.2	38.8	39.5	40.3	41.1	41.9	42.7	43.6	44.6	45.6	46.6	47.6	48.7	49.8	51.0	52.2	53.5	54.7	56.1	57.4	58.8	60.3	61.7	63.3	64.8	66.4	68.0	69.7	71.4	73.1	74.9
36.0	39.1	39.9	40.6	41.4	42.3	43.1	44.1	45.0	46.0	47.1	48.1	49.3	50.4	51.6	52.9	54.2	55.5	56.8	58.2	59.7	61.2	62.7	64.3	65.9	67.5	69.2	70.9	72.7	74.5	76.4	78.2
36.5	40.2	40.9	41.7	42.6	43.5	44.4	45.4	46.4	47.5	48.6	49.8	51.0	52.2	53.5	54.8	56.1	57.6	59.0	60.5	62.0	63.6	65.2	66.9	68.6	70.3	72.1	73.9	75.8	77.7	79.7	81.6
37.0	41.2	42.0	42.9	43.8	44.8	45.8	46.8	47.9	49.0	50.2	51.4	52.7	54.0	55.4	56.8	58.2	59.7	61.2	62.8	64.4	66.1	67.8	69.5	71.3	73.2	75.1	77.0	79.0	81.0	83.0	85.1
37.5	42.3	43.2	44.1	45.1	46.1	47.2	48.3	49.4	50.6	51.9	53.2	54.5	55.9	57.3	58.8	60.3	61.9	63.5	65.2	66.9	68.6	70.4	72.3	74.2	76.1	78.1	80.1	82.2	84.3	86.5	88.7
38.0	43.4	44.4	45.3	46.4	47.5	48.6	49.8	51.0	52.3	53.6	55.0	56.4	57.8	59.4	60.9	62.5	64.2	65.9	67.6	69.4	71.3	73.2	75.1	77.1	79.1	81.2	83.4	85.5	87.8	90.0	92.4
38.5	44.6	45.6	46.6	47.7	48.9	50.1	51.3	52.6	54.0	55.4	56.8	58.3	59.8	61.4	63.1	64.8	66.5	68.3	70.1	72.0	74.0	76.0	78.0	80.1	82.2	84.4	86.7	89.0	91.3	93.7	96.1
39.0	45.8	46.8	47.9	49.1	50.3	51.6	52.9	54.3	55.7	57.2	58.7	60.3	61.9	63.6	65.3	67.1	68.9	70.8	72.7	74.7	76.8	78.8	81.0	83.2	85.4	87.7	90.1	92.4	94.9	97.4	99.9
39.5	47.0	48.1	49.3	50.5	51.8	53.2	54.5	56.0	57.5	59.0	60.6	62.3	64.0	65.8	67.6	69.5	71.4	73.4	75.4	77.5	79.6	81.8	84.0	86.3	88.7	91.1	93.5	96.0	98.6	101.2	103.9
40.0	48.3	49.5	50.7	52.0	53.4	54.8	56.2	57.8	59.3	61.0	62.6	64.4	66.2	68.0	69.9	71.9	73.9	76.0	78.1	80.3	82.5	84.8	87.1	89.5	92.0	94.5	97.1	99.7	102.4	105.1	107.9
40.5	49.6	50.8	52.1	53.5	54.9	56.4	58.0	59.6	61.2	62.9	64.7	66.5	68.4	70.3	72.3	74.4	76.5	78.7	80.9	83.2	85.5	87.9	90.3	92.8	95.4	98.0	100.7	103.4	106.2	109.1	112.0
41.0	50.9	52.2	53.6	55.1	56.6	58.1	59.7	61.4	63.2	65.0	66.8	68.7	70.7	72.7	74.8	77.0	79.2	81.4	83.7	86.1	88.6	91.1	93.6	96.2	98.9	101.6	104.4	107.3	110.2	113.1	116.1
41.5	52.3	53.7	55.1	56.6	58.2	59.9	61.6	63.3	65.1	67.0	69.0	71.0	73.0	75.2	77.3	79.6	81.9	84.2	86.7	89.1	91.7	94.3	96.9	99.7	102.5	105.3	108.2	111.2	114.2	117.3	120.4
42.0	53.7	55.1	56.7	58.3	59.9	61.7	63.4	65.3	67.2	69.2	71.2	73.3	75.4	77.6	79.9	82.3	84.7	87.1	89.6	92.2	94.9	97.6	100.4	103.2	106.1	109.0	112.1	115.1	118.3	121.5	124.8
42.5	55.1	56.7	58.3	59.9	61.7	63.5	65.4	67.3	69.3	71.3	73.5	75.6	77.9	80.2	82.6	85.0	87.5	90.1	92.7	95.4	98.2	101.0	103.9	106.8	109.8	112.9	116.0	119.2	122.5	125.8	129.2
43.0	56.6	58.2	59.9	61.7	63.5	65.4	67.3	69.3	71.4	73.6	75.8	78.1	80.4	82.8	85.3	87.8	90.4	93.1	95.8	98.6	101.5	104.4	107.4	110.5	113.6	116.8	120.0	123.4	126.8	130.2	133.7
43.5	58.1	59.8	61.6	63.4	65.3	67.3	69.3	71.4	73.6	75.8	78.2	80.5	83.0	85.5	88.1	90.7	93.4	96.2	99.0	101.9	104.9	107.9	111.1	114.2	117.5	120.8	124.2	127.6	131.1	134.7	138.3
44.0	59.6	61.4	63.3	65.2	67.2	69.3	71.4	73.6	75.9	78.2	80.6	83.1	85.6	88.2	90.9	93.6	96.4	99.3	102.3	105.3	108.4	111.5	114.8	118.1	121.4	124.9	128.4	131.9	135.6	139.3	143.0
44.5	61.2	63.1	65.0	67.0	69.1	71.3	73.5	75.8	78.1	80.6	83.1	85.6	88.3	91.0	93.8	96.6	99.6	102.5	105.6	108.7	111.9	115.2	118.6	122.0	125.4	129.0	132.6	136.3	140.1	143.9	147.8
45.0	62.8	64.8	66.8	68.9	71.1	73.3	75.6	78.0	80.5	83.0	85.6	88.3	91.0	93.8	96.7	99.7	102.7	105.8	109.0	112.2	115.6	119.0	122.4	125.9	129.6	133.2	137.0	140.8	144.7	148.7	152.7

Caution Extreme caution Danger Extreme danger