MONITORING FIRE DANGER IN NEAR REAL-TIME USING FIELD- BASED AGROMETEOROLOGICAL MEASUREMENT SYSTEMS

by

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Agrometeorology, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The research was financially supported by the University of KwaZulu-Natal, University 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.

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Signed: Professor M.J. Savage

Date: 27 November 2014

DECLARATION 1: PLAGIARISM

I, Sheldon Strydom, 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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(vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

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

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Signed: Sheldon Strydom

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DECLARATION 2: PUBLICATIONS

My role in each paper and presentation is indicated. The * indicates corresponding author.

Strydom S, Savage MJ* 2013. A near real-time fire danger index measurement system. Paper presentation to South African Society of Atmospheric Sciences Conference 2013, 26th to 27th Sept, 2013, Durban, South Africa.

I presented the paper based on my BSc(Hons) project.

ABSTRACT

Africa has been termed the ‘Fire Continent’ due to its high annual fire frequency. Wildfires are considered one of the most common disasters in South Africa resulting in a high number of human fatalities and financial loss on an annual basis. It is believed that increased population growth, as well as more concentrated settlement planning is likely to result in increased fire disasters and increased human fatalities as a direct result of wildfires. The high number of human fatalities and high financial loss associated with wildfires served as the main motivation for the research throughout all studies. While wildfires may provide beneficial environmental service, increased wildfire activity can result in a number of adverse effects on the environment, for example the removal of vegetation, fascilitating/aggravating floods and soil erosion but do bring with them positive effects such as nutrient recycling and removal of alien species.

In order to better understand the spatial and temporal variations and characteristics of wildfires in South Africa an 11-year dataset of MODIS-derived Active Fire Hotspots was analysed using an open source geographic information system. The study included the mapping of national fire frequency over the 11-year period. Results indicate that the north-eastern regions of South Africa experience the greatest fire frequency, in particular the mountainous regions of KwaZulu-Natal, Mpumalanga and the Western Cape. Increasing trends in provincial fire frequency was observed in eight out of the nine provinces with Mpumalanga being the only province where a decrease in annual fire frequency over the study period was observed. Temporally, fires have been observed in all months for all provinces although distinct fire seasons were observed, largely driven by rainfall seasons. The South-Western regions of South Africa (winter rainfall patterns) experienced higher fire frequencies during the summer months with the rest of the country (summer rainfall) experiencing higher fire frequencies during the winter months. Regions which experience bi-modal rainfall seasons did not display distinct fire seasons. The study included an investigation into the likely effects of climate change on South African fire frequency. Three of the 11 years were identified as being climatologically anomalous. Fire frequencies in 2005 and 2010 (two of the warmest years in recent history) were significantly greater than normal years. Observed fire frequencies in 2008 were also significantly greater. The increased fire frequency was attributed to a severe La Niña event which may have resulted in increased vegetation growth prior to the dry season.

A current issue with the mitigation of wildfires is the lack of proper real-time monitoring and measurement systems which can aid decision makers in the timing of controlled

fires. The development of a system for improved monitoring of meteorological conditions conducive to fire was investigated. The traditionally used nomogram and lookup table used by Lowveld fire danger index (LFDI) system was replaced by mathematical functions which were then programmed into an automatic weather station datalogger. Near real-time results of the calculated LFDI were displayed in a web-based teaching, learning and research system found at: http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Fire%20danger%20index.

Warm, dry mountain winds known as Berg winds have a direct link to fire weather, enhancing the danger of uncontrollable fires. Berg winds are associated with periods of increased air temperature, decreased relative humidity and increased wind speeds. This increases the potential for the development and spread of wildfires. The effects of Berg winds on the microclimate and fire danger were quantified. For this purpose, historic hourly meteorological data, local and international, were used together with a fuzzy logic system for determining Berg wind conditions in near real-time. This included the use of modelled diurnal sinusoidal functions for solar irradiance, air temperature, relative humidity, wind speed and direction, for various locations. Application of the system demonstrated that out of four sites in the KwaZulu-Natal Midlands, South Africa, Baynesfield was the most vulnerable to Berg wind occurrences, followed by Ukulinga (near Pietermaritzburg) and lastly Cedara. Boulder in Wyoming, USA, experienced a larger frequency of Berg wind events compared to Sidney in Montana, USA, despite being located at a higher altitude.

The McArthur Fire Danger Meters (FDM) have been used to monitor and measure fire danger in Australia since the 1950s when they were first developed following severe wildfires. The McArthur FDM has traditionally made use of nomograms to calculate grassland and forest fire danger. In the 1980s mathematical descriptions of the McArthur FDM were developed. These then allowed for the sub-daily and near real-time measurement of grassland and forest fire danger. While commercial forestry contributes only a small percentage of South Africa's GDP, forest fires have been identified as a common occurrence in commercial forestry plantations and natural forests, which can at times spread to neighbouring grasslands or non-forest vegetation. Forest fire disasters in South Africa are well documented by the mainstream media and it is believed that proper monitoring of forest fire danger, along with grassland fire danger, may mitigate potential wildfire disasters and limit human fatalities and financial loss. The McArthur FDM also provides opportunity to model fire behaviour – a component of wildfire mitigation lacking in the Lowveld fire danger index. The study utilized the equations developed to investigate the use of the McArthur FDM in South Africa by applying the

equations to historical hourly meteorological data recorded at four locations in the KwaZulu-Natal Midlands, South Africa. Modifications to the McArthur grassland fire danger index (GFDI) were needed and resulted in the development of a method to calculate vegetation curing as a function of micrometeorological variables. Datasets were analysed to investigate seasonal curing at the four locations with results indicating high monthly curing averages in all months, with the greatest range of curing averages experienced in the winter months. Frequency analysis of both the GFDI and the forest fire danger index (FFDI) indicate that lower fire danger ratings are more common than high danger ratings as one would expect. The GFDI and FFDI displayed acceptable sensitivity to changes in the microclimate as observed through conducting sensitivity analysis and by plotting diurnal variations of GFDI and FFDI during Berg wind events. The fire behaviour modelling component of the McArthur FDM does not yield realistic results on steep topography but does provide a baseline on fire characteristics on gentler slopes.

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Hebrews 11:3 By faith we understand that the universe was created by the word of God, so that what is seen was not made out of things that are visible

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CHAPTER 1: INTRODUCTION

1.1 Background

Fire has played an integral part in the maintenance of earth systems, aiding in the regulation of climate by providing ‘shocks’ which maintain and rejuvenate ecological systems (Keywood *et al*., 2013). The extent of fire activity on the African continent has been well documented with Africa being dubbed the “fire continent” (Archibald *et al.*, 2010). Excessive fire activity can, however, adversely impact on earth systems and it is believed that anthropogenic activities may be enhancing the likelihood of fire disasters thereby enhancing the adverse impacts of fires. South Africa, which is a water scarce country, experiences a number of fires annually, with the Fire Protection Association of South Africa (FPASA) (2010) reporting high numbers of human fatalities and financial loss across most sectors. Documented financial loss across sectors exceeds R1 million in most years, with annual fatalities well over the 100s (FPASA, 2010, 2011, 2012).

1.1.1 Overview of Meteorological Conditions Conducive to Fire Development and Spread

Meteorological conditions conducive to fires are strongly linked with fire disasters. A substantial amount of research has been conducted in parts of the world where fire disasters are common, yet in South Africa little research has been done on the subject. Research indicates that atmospheric conditions leading to fire disasters include mountain wave flow events where air parcels are orographically forced to ascend the windward slope of a mountain or mountain range (Ives, 1950; Gaffin, 2007). During the ascent of the air parcel, adiabatic cooling occurs until the cloud reaches the lifting condensation level of dew point temperature upon which condensation and precipitation begins (Gaffin, 2007). With further flow the air parcel is forced to descend over the ridge on the lee of the mountain or mountain range where adiabatic warming occurs which leads to the desiccation of the air parcel (McRae *et al*., 2010). The air parcel reaches the valley floor as a warm and dry wind. A number of synoptic factors have been identified which aid in the creation of these warm mountain winds known around the world as ‘foehn winds’, ‘chinook winds’ or ‘Berg winds’.

In the United States of America (USA) foehn winds are generally associated with surface low pressure systems and troughs at 85 kPa which result in cross-mountain surface air pressure gradients resulting in cross mountain flow (Gaffin, 2007). During foehn wind events, a stable boundary layer extending to 70 kPa is common on the leeward slopes. Foehn wind events in Antarctica have similar characteristics and are experienced when low pressure systems are situated over the Ross Sea resulting in midlevel capping inversions due to stable boundary layer conditions (Bromwich *et al*., 2010). Foehn wind events are also common when offshore cyclonic systems result in strong air pressure gradients over mountain valleys. In Australia foehn wind events are most common in the eastern regions of the continent where low pressure troughs in the south-east result in strong air pressure gradients in which flow is from the north-west over mountain ranges (McRae *et al*., 2010). Foehn winds in South Africa, known as Berg winds, are most common when high pressure systems are situated over the interior of the country and coastal lows are situated off the coast resulting in air flow descending the escarpment warming adiabatically (Preston-Whyte and Tyson, 2000). This scenario is common with the procession of cold frontal systems across the country (Preston-Whyte and Tyson, 2000).

1.1.2 Overview of the Effects of Fires on the Environment

Fires play a vital part in the maintenance of the natural environment but can result in a number of adverse effects on the environment. According to Duncan *et al*. (2009), fires contribute to a declining air quality with research indicating the possibility of fires emitting large amounts of trace gases such as carbon monoxide and ozone. Emissions of methane result in smoke haze and have the potential to negatively influence agricultural production. Greenhouse gases emitted during fires contribute to the global greenhouse effect. Keywood *et al*. (2013) state that black carbon emitted during fire events has the potential to enhance snowmelt and result in further positive warming feedbacks accelerating any warming that may occur. Pyroconvection is also a common weather modification process that occurs due to fires (Keywood *et al*., 2013).

Fire has been thought to influence seed bank management, although some experts in the field claim the effect is minimal. For example, Adams *et al*. (2012) found little influence on the variety and integrity of seed bank by fire, however, it was acknowledged that further investigation would be needed. According to Myers (2006), fires do play a significant role in nutrient recycling, where the burning of biomass is reintroduced into the soil profile as ash and is once again available for plant uptake. The fynbos floral kingdom in South Africa is a region of highly endemic plant species in which fire as a management tool has played an important role not only in the rejuvenation of saplings but also in the eradication of certain alien invasive species in the area (Van Wilgen, 2009). Fire in the fynbos region can also enhance alien invasive species spread as many other invasive species are fire independent while many fynbos species are not (Van Wilgen, 2009). Fires also play a role in the hydrological cycle when severe fires result in vegetation reduction leading to increased runoff and soil erosion which in turn may lead to increased sedimentation in water bodies (Merz, 2004).

1.2 Motivation for the Study

Fire disasters result in a large financial loss and fatalities every year and these serve as the main motivation for the research. If a better understanding of conditions conducive to fire danger can be determined then better warning systems can be developed which may lower the amount of damage and death fires cause every year. With a better monitoring system in place, local fire managers will have an up-to-date resource to utilize in determining fire regimes and burning times which is likely to limit the number of wild fires and uncontrollable fires that occur due to adverse meteorological conditions during prescribed burnings. A predictive function would enable the early warning of conditions conducive to fire weather thereby aiding decision making as to when prescribed fires should be conducted.

1.3 Aims and Objectives

This section will discuss the main aims of the research project and will identify objectives that need to be completed to accomplish the main aims. As such, the objectives are steps towards completing the aims.

1.3.1 Aims

The research project is divided into three main aims:

1. investigation of the spatial and temporal variations of fire activity in South Africa and identify fire activity drivers,

2. quantification of the effects of Berg winds on fire danger conditions and development of a near real-time fire danger measurement system using the Lowveld Fire Danger Index, and

3. development of a near real-time fire danger measurement system using the McArthur Fire Danger Meters and investigate their suitability as alternatives to the Lowveld Fire Danger Index.

1.3.2 Objectives

The three aims each have with them a number of objectives that need to be accomplished in order to complete the aim.

1. Investigation of the spatial and temporal variations of fire activity in South Africa and identify drivers of fire activity. The objectives of this aim included accessing a database which provides information on the location and timing of wildfire events over a sufficiently long time period. This included investigating the role of non-meteorological variables such as topography and vegetation on fire distribution. The likely effects of climate change was also investigated which will require accessing climatic data.

2. Quantification of the effects of Berg winds on the microclimate and fire danger conditions and development of a near real-time fire danger measurement system using the Lowveld Fire Danger Index - objectives included the setting up of an AWS with the necessary sensors for relaying data in near real-time to a web-based platform which allowed for the near real time monitoring of meteorological conditions. A fuzzy logic system for defining Berg wind events, was required for application to hourly meteorological data recorded in the KwaZulu-Natal midlands and the United States of America to quantify the effects of Berg winds on the microclimate and fire danger.

3. Development a near real-time fire danger measurement system using the McArthur Fire Danger Meters for investigating their suitability as alternatives to the Lowveld Fire Danger Index. This objective included finding suitable equations that allow for the McArthur Fire Danger Meters to be programmed into an AWS datalogger and adding relevant sensors to the AWS if not already in place. Hourly historical meteorological data will be utilized to assess the McArthur Fire Danger Meters' ability to model fire behaviour and to develop seasonal curing charts.

1.4 Structure of the Dissertation

The dissertation is structured in the "Paper Based" method in which certain chapters can be viewed as individual papers. As such, each experimental chapter will include its own introduction, materials and methods, results and discussion and conclusion sections. The dissertation will consist of six chapters.

The current chapter, Chapter 1, provides an overview of literature which includes the meteorological conditions conducive to the development and spread of wildfires as well as the effects, both positive and negative, of fires on the environment. The motivation for the study is discussed and the overarching aims and objectives are provided. Chapter 2 provides a documentary review of the literature relevant to the study and expands on the overviews provided in Chapter 1. The literature includes the economics of fire disasters in South Africa, the micrometeorological considerations of Berg wind activity as well as the synoptic meteorological considerations of Berg winds around the world. The effects of fires on the environment are discussed in detail. Methods of forecasting and monitoring fire danger are also discussed. Chapter 3 serves as the first experimental chapter in which an 11-year dataset of fire activity is analysed through the use of a geographic information system (GIS). The chapter includes an investigation into the spatial and temporal variations in fire activity over the 11 year period at a national and provincial level. Fire activity under different climate change scenarios is also investigated and discussed. Chapter 4, the second experimental chapter, discusses the development of a near real-time fire danger index measurement system using the Lowveld fire danger index. A fuzzy logic system for identifying periods of Berg winds is discussed and applied to historical data from four different locations around the KwaZulu-Natal Midlands. The effects of Berg winds on the microclimate and fire danger are quantified and discussed using both local and international data. Chapter 5, the final experimental chapter, investigates the McArthur Fire Danger Meters as expressed by Noble *et al*. (1980). A near real-time fire danger measurement system using the McArthur Fire Danger Meters is discussed and presented. Fire behaviour charts are presented using historical meteorological data from the four locations as described in Chapter 4. A seasonal curing chart is also presented for each of the four locations. Chapter 6 provides a summary of all previous chapters and discusses recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

Fire plays an important role in the regulation and maintenance of numerous environmental systems (Keywood *et al*., 2013). While natural wild fires can be beneficial to the environment it has also been acknowledged that increased wild fires, due to anthropogenic activity, can result in adverse effects to the environment causing widespread destruction to both the natural environment and the built environment. Fire disasters due to human negligence will often result in a high number of fatalities.

The Fire Protection Association of South Africa (FPASA) stated that between 2002 and 2010 a total loss of R18.4 million was incurred due to fire disasters along with a combined total of roughly 2500 fatalities (FPASA, 2010). Open flames used in the burning of refuse and both grasslands and bushlands are reported to be the leading causes of anthropogenic fire disasters (FPASA, 2010).

Numerous studies have been undertaken to identify the relationship between weather and fire, resulting in the branch of meteorology known as 'fire meteorology'. Works such as the study by Ives (1950) on mountain wave dynamics and links to fire disasters in the United States have paved the way for more recent studies such as Gaffin (2007) in which 30 years of mountain wave flow events in the Appalachian Mountains were studied. Globally mountain wave dynamics and their relationship to fires have been studied on almost every continent or area that is prone to fire disasters such as Australia (McRae *et al*., 2010), South Africa (Preston-Whyte and Tyson, 2000) and surprisingly even Antarctica (Bromwich *et al*., 2010). While studies have generally focussed on the role of mesoscale meteorological processes in relation to fire, few have studied the micrometeorological relationship with fire. In South Africa Preston-Whyte and Tyson (2010) provide an insight into the micrometeorological outcomes of mountain wave flow. More recently, the role of micrometeorological variables in fire danger has been studied (Strydom and Savage, 2013). The micrometeorological considerations in fire meteorology and the synoptic scale considerations are presented.

2.1 Synoptic Scale Meteorological Considerations

As stated in the introduction, the role of synoptic scale weather patterns has a direct influence on periods of fire danger. The role of mountain wave dynamics has long been studied and has been proven to have a direct link to periods of fire danger. Mountain wave winds are given different terms depending on the location of study. For example in South Africa mountain wave winds associated with the Drakensberg Mountains are termed ‘Berg winds’. According to Ives (1950) a Chinook wind is defined as a trans-mountain wind warmed by desiccation over the windward region of the mountain range and warmed further by adiabatic warming during descent on the leeward side of the range. Literature on different mountain winds is presented.

2.1.1 United States of America

In the United States of America (USA), warm mountain winds are given a number of terms varying from the ‘foehn winds’ in the Appalachian Mountains in the east to ‘Chinook winds’ in the Rocky Mountain area to ‘Santa Anna winds’ near the southern California Mountains (Ives, 1950; Gaffin, 2007). In this investigation the term ‘foehn wind’ will be used synonymously to include both Chinook and Santa Anna winds despite the differences in locations across the United States.

Gaffin’s (2007) study which investigated 30 years of mountain wave flow events over the Appalachian Mountains indicated that western slope foehn winds are common when a surface low pressure system is situated over the mid-Mississippi River valley and a trough is present at 85 kPa over the same area.. A cross-mountain surface pressure gradient, brought about by the coupled effect of the surface low and the 85 kPa trough, produces southerly winds across parts of the southern range with parcels of warm air being advected across the mountains by the 85 kPa winds. A stable boundary layer extending up to the 70 kPa level was also noted to be common during mountain wave flow events. The 85 kPa layer is near the mountain ridges at 1500 m and it is likely that these advecting warm air parcels are the source of foehn winds over the western slopes (Gaffin, 2007).

Eastern slope foehn winds are dominant when a surface high pressure system is situated over the US Plains which ridges over the southern parts of the range resulting in north-to-northwest surface winds proceeding behind a cold-front (Gaffin, 2007). Strong surface pressure gradients are again created with a stable and drier boundary layer evident between 85 kPa and 70 kPa (Gaffin, 2007). Strong surface pressure gradients result in the warm air at 85 kPa level advecting down slope resulting in adiabatic warming.

Chinook winds occur when strong surface pressure gradients advect air masses across the Rocky Mountains (Ives, 1950). Air masses cool at the dry adiabatic lapse rate and relative humidity increases as the air parcels are orographically forced upwards until the air masses reach the dew point level (or lifted condensation level, LCL) (Ives, 1950). Crest clouds form at the LCL and precipitation is common on the windward side of the range. Air masses that are further advected eastwards over the ridge on to the leeward side of the range will descend and warm by compression at the dry adiabatic lapse rate. As a result the potential temperature (temperature of an unsaturated parcel of air at a standard pressure of 100 kPa (American Meteorological Society, 2012)) increases, arriving at the lower levels (or to a measuring station) warmer and drier due to the loss of moisture at the LCL or crest cloud (Ives, 1950). On the leeward plains the Chinook wind may be warmer than the air mass of the windward region but may not always be warmer than air it will displace. Thus the airflow may not always be recognized as being warm (Ives, 1950).

2.1.2 Australia

In Australia bushfires pose a significant environmental problem with high fire danger indices being associated with foehn-like winds (McRae *et al*., 2010). The Australian Alps situated in the south-east mainland of Australia experience a number of foehn wind events in a year. The mechanics for foehn winds experienced in the Australian mainland are typical of foehn wind mechanics elsewhere on the globe, where moist low-level air parcels are orographically influenced to rise up the windward side of the Austalian Alps and to descend on the lee of the range as a warm, dry wind (McRae *et al*., 2010).

Synoptic analyses of Australian foehn winds indicate that the winds are commonly associated with low pressure troughs passing over the eastern regions of south-east Australia, resulting in strong surface pressure gradients and strong north-westerly winds (McRae *et al*., 2010). Cold frontal passages through the region have also been noted to result in strong pressure gradients and again typical north-westerly winds across the range, ahead of the cold front. Topographic ‘blocking’ of moist low-level winds on the windward side of the range can often result in the descending of warm upper-level winds on the lee side of the range resulting in a foehn wind (McRae *et al*., 2010).

2.1.3 Antarctica

Bromwich *et al*. (2010) describe the foehn like winds that occur in the McMurdo dry valleys (MDVs) of Antarctica, situated in the ‘Transatlantic Mountain range’ which is bordered by the Ross Sea to the east and by the eastern region of the Antarctic ice sheet to the west (Bromwich *et al.*, 2010). The MDVs consist of three valleys spreading from the northeast to the southwest with the highest peak situated roughly 200 m above sea level. The wind regimes within the valleys are predominantly up and down slope winds but easterly valley winds occur due to thermal activity in the summer period.

The MDV foehn winds are topographically induced and occur regularly on the leeward regions of the valleys resulting in the warming of the valley (Bromwich *et al*., 2010). It has been considered the foehn winds in the MDVs may be associated with katabatic winds advected from the polar plateau that have been warmed adiabatically although Bromwich *et al*. (2010) consider this unlikely. The MDV foehn winds main development occurs when an air parcel is forced to descend leeward slopes of a mountain range by large amplitude mountain waves. This is evident by the recording of warm westerly flow as well as the presence of lenticular clouds (Figure 2.1) which indicate mountain wave flow (Bromwich *et al*., 2010) Synoptic analysis of foehn wind events in the MDVs indicate that these events are more common when a low pressure system is active over the Ross Sea coupled with a stable boundary layer over the MDVs resulting in a midlevel capping inversion (Bromwich *et al.*, 2010). The offshore cyclonic systems result in strong surface pressure gradients over the MDVs resulting in foehn wind activity (Bromwich *et al*., 2010).

Figure 2.1: Lenticular clouds are associated with mountain flow events and can be used to identify periods of mountain winds. Shown here are lenticular clouds over Howick, South Africa in 2013

2.1.4 South Africa

Warm mountain winds are given the term 'Berg winds' in South Africa. The synoptic dynamics of Berg winds are the same as those of the foehn and Chinook winds. Berg winds in South Africa are most common during the late winter and early spring months and can last anywhere between a few hours and a number of days (Preston-Whyte and Tyson, 2000).

The synoptic scale systems that lead to the occurrence of Berg winds in parts of South Africa are discussed by Preston-Whyte and Tyson (2000). Anti-cyclones (high pressure systems) situated over central South Africa may lead to the subsidence of air masses and result in dry weather and Berg winds along the eastern escarpment and the southern and south-eastern coastlines. Strongly linked with the occurrence of Berg winds is the development of coastal low pressure systems which develop due to a cyclonic vorticity component of easterly flowing air from the plateau (Preston-Whyte and Tyson, 2000). Coastal lows form off the west coast of South Africa and move eastwards as Kelvin waves trapped under a strong low-level capping inversion. As these coastal lows travel along the south and east coast they result in warm offshore flow ahead of the frontal passage and cool offshore flow behind the system (Preston-Whyte and Tyson, 2000). Along the east coast, coastal lows may extend as far inland as the KwaZulu-Natal midlands, resulting in warm offshore flow from the Drakensberg in which moist upper level winds may warm adiabatically resulting in Berg winds (Preston-Whyte and Tyson, 2000). Berg winds are most notably associated with the passage of a frontal system over the country, where pre-frontal divergence occurs resulting in adiabatic warming of offshore winds (Preston-Whyte and Tyson, 2000).

2.2 Micrometeorological Considerations of Fire Meteorology

Wildfire activity is highly dependent on environmental and meteorological variables. Variables such as weather, fuel and topography have been identified to influence fire behaviour (Lindley *et al*., 2011). While much research has been done on the synoptic and mesoscale meteorological influences on fire activity, little has been done on local meteorological conditions and their influence on fire activity. Lindley *et al*. (2011) state that wildfire behaviour dependent on local meteorological conditions (micrometeorology) as components of micrometeorology, such as moisture and air temperature, are variable and can change within short periods. A review of the available literature of fire micrometeorology is presented, making use of case studies and recent research.

2.2.1 Air Temperature

According to Lindley *et al*. (2011), the most common variables that have been studied in relation to fire have been relative humidity and wind speed. While these do play significant roles, the role of air temperature cannot be excluded as mountain wave dynamics greatly influences air temperature.

In the U.S.A. foehn winds have been observed to greatly increase air temperatures in the Appalachian Mountain ranges. Air temperatures can increase by an average of 5 to 6 ^{o}C during a mountain wave wind event on the leeward slopes of the mountain range (Gaffin 2007). Lindley *et al*. (2011) studied wildfire starts in west Texas and concluded that 77% of the wildfires recorded during their study (2006 - 2010) started when air temperatures were greater that of the expected seasonal average. Bromwich *et al*. (2010) report that a strong foehn wind experienced between the 20th and 27th of May 2007 in the MDVs increased air temperatures by 48.5 ^{o}C. While it is unlikely that fires have occurred in the MDVs in recent times, the case study highlights the ability of mountain wave winds to influence the microclimate of a region thus influencing the potential for wildfires. In South Africa Berg winds have the ability to bring about sharp increases in air temperatures. According to Preston-Whyte and Tyson (2000), almost all above average increases in air temperature during autumn are as a result of Berg winds. Australian mountain wind events also have the ability to increase air temperatures. A well-documented case occurred in the town of East Sale between the 20th and 27th of May 2007 (the same week as the case study in the MDVs). Air temperature increased by roughly 5 ^{o}C (McRae *et al*., 2010)

2.2.2 Relative Humidity

Relative humidity is an important variable when it comes to mountain wave events and their link to fire events. During the process of being orographically lifted, air parcels cool and condense on the windward slopes while desiccation occurs on the leeward slopes. Mountain wave flow usually results in warmer and drier air reaching the plains or valley floor of the leeward slopes. The warm, dry air and wind aid in starting fires as vegetation can become dry too and lead to increased fuel loads (Preston-Whyte and Tyson, 2000; Gaffin, 2007; Lindley *et al*., 2011). In their four year study on west Texas fires, Lindley *et al*. (2011) found that 72% of wildfires started when relative humidity ranged between 4 and 12% with a total of 92% of wildfires starting when relative humidity was less than 20%.

2.2.3 Wind Speed and Direction

Foehn winds are strong wind events associated with warm and dry mountain flow. A number of case studies indicate that due to frontal passages or cold passages, wind speeds ahead of the frontal passage can increase and it is these increases that generally coincide with warm mountain winds due to surface pressure gradient flow ahead of the cold passage. On the 27th of May, 2007 an observed foehn wind event in the MDVs of Antarctica resulted in wind gusts of around 39 m s^{-1} being recorded (Bromwich *et al*. 2010). AWS stations situated in the MDVs recorded wind speeds of less than 5 m s^{-1} prior to the onset of the foehn wind conditions, after which wind speeds were sustained above 10 m s^{-1}.

2.3 Impacts of Fires

2.3.1 Social Impacts and the Economics of Fire Disasters

Fire disasters result in large financial losses for a number of stakeholders such as industry, agriculture and residents which in turn influences the country's Gross Domestic Product. The FPASA publishes annual reports on the statistics of the year's fire season. In discussing the economics of fire disasters, this section will draw on the statistics provided in the 2008 to 2010 annual reports.

The 2008 fire season saw roughly 35 500 fires being reported (FPASA, 2010), with the majority being caused by open flames used in household waste, grass or bush burnings. The 2008 fire season resulted in 377 fatalities and R2.3 billion lost in the industrial sector (which incurred the greatest loss). The 2008 statistics show that the agriculture sector was responsible for only 67 of the total fires, although the category of grass and bush burnings may include agricultural practices such as fire break burning (Figure 2.2) and vegetation clearing burns which will increase the total number of fires started by the agricultural sector (FPASA, 2010).

Figure 2.2: Burning of fire breaks at Midmar Dam, Howick, South Africa.

During the 2009 fire season roughly 40 000 fires were reported with the majority of these fires again due to open flames during household waste, grass or bush burnings (FPASA, 2011). Fire disasters during the 2009 season resulted in more than 350 fatalities and around R3.9 million in losses due to damage, however, unlike the 2008 fire season, in which the largest loss was incurred by the industrial sector, in 2009 the residential sector saw the greatest sum of financial loss due to fire disasters (FPASA, 2011). The 2010 fire season had 26 500 fires reported, resulting in 224 deaths and R1.3 billion in financial loss (FPASA, 2012). As in the 2009 fire season the main cause of fire disasters were open flames during household waste, grass and bush burnings. The residential sector again suffered the most in terms of financial loss with around R6 million of damage reported (FPASA, 2012).

The above statistics indicate that fire, in most cases wild fire disasters, results in great financial loss in South Africa not to mention the overwhelming number of fatalities that have occurred due to fire disasters. The FPASA (2010) states that it should be of great embarrassment that the country still suffers so much at the hands of fire when great strides have been taken to improve the understanding of fire dynamics and to improve the technology available to us to aid our defence of natural disasters.

A sometimes ignored component of the social impacts of fire disasters is that of human health. Clements (2009) states that wildfires can result in a number of health issues and injuries with the most obvious being direct injury from fires such as skin burns. Smoke from wildfires remains a particular health concern as the impacts can range from respiratory irritation to smoke asphyxiation. Smoke from wildfires may also contain potential allergens, carcinogens, mutagens and teratogens (Clements, 2009).

2.3.2 Air Quality

Duncan *et al.* (2009) discuss the impacts fires, both natural and anthropogenic in origin, have on air quality (Figure 2.3). Biomass burnings associated with wildfires have been observed to release concentrations of trace gases such as carbon monoxide and ozone during and after the burnings (Duncan *et al.*, 2009). Cai *et al.* (2012) states that much research indicates that ozone production during wildfires may be insignificant and the topic remains open to debate. According to Keywood *et al.* (2013), tropical and boreal forest fires contribute largely to the global carbon emission levels. The severity and frequency of these forest fires depends on a number of meteorological conditions. Keywood *et al*. (2013) discuss the 1997 El Niño event in the Amazon, where up to 26 000 km^2 of forest was burned, releasing up to of 0.4 Pg of

Figure 2.3: Concentration of aerosols during and after burnings can have an adverse impact on the local air quality. Shown is a haze layer (at Midmar Dam), a common sight during the winter fire season as aerosols become trapped under inversion layers

carbon which is considered to be double the annual amount released through deforestation in the Amazon (Keywood *et al*., 2013). A common adverse result of wild fires is smoke haze (Duncan *et al*., 2009) which poses major concerns for human health and agricultural crop productivity through the emission of carbon and methane. Local air quality is also influenced by large scale burnings or during uncontrolled burning events (Duncan *et al*., 2009). During the 1997 El Niño event land-clearing fires, which became uncontrollable, resulted in a maximum total particulate matter (TPM) of 4000 μg m^{-3} which exceeded any air quality standards and posed a serious health concern (Duncan *et al*., 2009). Neighbouring countries' air quality can also be impacted despite dilution due to cross-boundary transportation (Duncan *et al*., 2009).

2.3.3 Climate Change and Weather Modification

The intensive research on the impacts of agricultural and forest fires on climate change and weather modification indicates that fires can result in large aerosol concentration in the Arctic and Antarctic regions (Keywood *et al*., 2013). Black carbon, which originates in biomass emissions released during burnings, contributes a large portion of pollution in the Polar Regions. Black carbon has a positive feedback effect resulting in further warming of the atmosphere through absorption of solar radiation. Black carbon accumulated in snow and ice also enhances snowmelt as it reduces the snowpack's reflective coefficient (Keywood *et al*., 2013). Positive feedbacks of warming, enhancing global warming, have been observed during forest fires which emit large concentrations of greenhouse gases. It is believed that with a change in global climate that regional vegetation zones may transition or change. A long held belief states that the semi-arid deserts of South Africa will migrate and extend eastward into the grassland regions of the country. Recent research by Masubelele *et al.* (2014) indicates that grass cover has actually increased in semi-arid shrub lands over the last 50 years. While fire affects both shrub lands and grasslands, the increase in grasslands may lead to more intense and fast moving wildfires. Keywood *et al*. (2013) discuss weather modification processes associated with fires. Pyroconvection, a process whereby deep convection occurs as a result of heat and water vapour from strong fires, is a common observation. Surface heating and forced instability generate strong updrafts which develop into clouds called 'Pyrocumulus' (Figure 2.4) (Keywood *et al*., 2013). During vegetation burning, large concentrations of cloud condensation nuclei (CCN) are emitted which influence the cloud drop size (Rosenfeld, 1999). Large concentrations of CCN may result in water vapour being distributed as smaller raindrops due to reduced coalescence efficiency, resulting in less precipitation over a larger area.

Figure 2.4: During periods of burning aerosols can contribute as cloud condensation nuclei and under the right moisture and thermodynamic conditions can result in the development of Pyrocumulus clouds atop of smoke plumes. Shown is a Pyrocumulus cloud in the Mooi River area, South Africa

2.3.4 Ecosystems

Naturally occurring fires are recognized as integral parts of ecosystem lifecycles such as in savannah ecosystems (Vanderpost *et al*., 2009). Increased anthropogenic activity in these ecosystems has led to land surface changes and difficult resource management. In many cases anthropogenic activity has resulted in an increase in fire frequencies in ecosystems which require less frequent fire regimes (Vanderpost *et al*., 2009). It is assumed that increased burning in ecosystems may have adverse effects but a study done by Vanderpost *et al*. (2009) on the impacts of fires in savannah ecosystems indicates the opposite. Vegetation analysis in the savannah ecosystem of the Okavango region indicated that fire frequency does not have a direct long term negative impact on vegetation structure or species composition. This is mainly due to the fact that many species removed during burnings are replaced the next season by means of seed bank legacy or succession (Vanderpost *et al*., 2009). Ecosystems which experience more frequent burning generally indicate a higher biodiversity, for example grasslands (Vanderpost *et al*., 2009). South African Savannah regions which are burnt every fire season show high levels of new plant growth compared to areas where little or no burning has occurred. Burning practices are thus employed to enhance forage quantity for both livestock and wildlife (Myers, 2006).

Adams *et al*. (2012) state that burning practices are employed in the southern Appalachian Mountains to restore forest seed bank structures and to reduce fuel loads that may threaten the forest should a wildfire or uncontrolled burn occur. Fires are also often used to promote the regeneration of tree species and increase diversity. The study done by Adams *et al*. (2012) indicated the opposite in such that prescribed burning practices had little effect on the density or composition of the seed bank. It was acknowledged that the study done by Adams *et al*. (2012) yielded results which are not in agreement with previous research. It is believed that prescribed burns which are low intensity burns may not affect the seed bank although high intensity burns may. During low intensity fires the presence of a litter layer and duff may protect the seed bank due to incomplete burning and insulation (Adams *et al*., 2012).

Fires also play an important role in nutrient cycling in grassland communities. Fire is seen as the primary mode of decomposition which returns nutrients into the soil resulting in increased productivity (Myers, 2006). Depending on the vegetation structure of the grassland, burning may benefit soil nutrients directly after the burn or over a period of a few years after the initial burn. Fires in shrub lands tend to move through the stem and leaf parts of shrub plants relatively quickly. Thus fires in shrub lands do not have a direct influence on the soil nutrients or surface vegetation composition (Myers, 2006). Nutrient release occurs due to the fires burning the stem and leaf parts of plants where the fire aids decomposition of woody material.

Classified as a world heritage site, the nutrient poor fynbos region of South Africa is highly influenced by fire activity (Van Wilgen, 2009). Many plant species within the fynbos region are fire-adaptive or fire-dependent, highlighting the importance of fire in the region (Van Wilgen, 2009). Fire activity can also have negative impacts on the fynbos region as many alien species are adaptive to fire and as a result can dominate regions due to fast growth rates and adaption to fires. In an attempt to ensure the protection of nutrient and water resources in the fynbos region, management practices have recently shifted from fire protection practices to prescribed burning practices (Van Wilgen, 2009). Prescribed burning is also seen as a method of reducing fuel loads and creating a mosaic vegetation structure. Prescribed burning has been used as a management practice since the late 1960s (Van Wilgen, 2009) (Figure 2.5). A number of conclusions have been developed that examine the role of fire in the fynbos region. It is felt that natural wildfires are sufficient in aiding vegetation rejuvenation, thus prescribed burning practices have little role in fynbos fire regimes. There is little evidence to support the assumption that prescribed burns remove excess fuel load while reductions in fuel loads have historically not suppressed wildfires during Berg wind events (Van Wilgen, 2009). Increased anthropogenic activity in the form of human settlements has resulted in increased fire frequencies and it is argued that increased Berg wind events (associated with climatic changes) have resulted in further increases in fire frequencies (Van Wilgen, 2009). Fires in grassland ecosystems have varied results. Infrequent burnings in semiarid grasslands, used as a management tool, may not promote invasive species as one would expect in the Fynbos floristic kingdom. Frequent burnings may have notable adverse effects and reduce the production of C_3 plants (Augustine *et al*., 2014).

According to Townsend and Douglas (2000) and Merz (2004), fires can lead to increased surface runoff rates which can often lead to flooding and enhanced erosion. Intense or long-lived fires can remove surface vegetation cover which decreases infiltration rates and increase surface runoff after precipitation events.

Figure 2.5: Fires can have both beneficial impacts on grassland communities when properly controlled and adverse impacts when not controlled. Shown is a wildfire in the Ngogo region, Newcastle, South Africa

Fires occurring on mountain slopes can reduce infiltration rates by up to 50% meaning that less precipitation would be needed to flood the mountain catchment area (Merz, 2004). Areas of bare soil with increased susceptibility to erosion have also been linked to fires. Fires during the dry season can result in decreased tree density, litter cover and increase the area of bare soil (Townsend and Douglas, 2000). Water quality has been linked to erosion rates with studies showing a direct influence of erosion rates on water quality due to larger stream loads brought about by bare soils and increased pollutants running into watercourses with pollutants and ash being observed in watercourses post burn (Townsend and Douglas, 2000). Soil erosion and runoff may indeed increase due to vegetation loss post fire but a number of non-fire related variables play a role in runoff and soil erosion. The slope level, slope vegetative cover and the period between burning and precipitation all influence the amount of runoff and soil erosion (Townsend and Douglas, 2000).

2.4 Forecasting and Modelling Fire Danger

The links between both synoptic and mesoscale weather patterns and outbreaks of wildfires have been apparent to meteorologists for a number of years. As early as the 1950's meteorologists have been studying this relationship between large scale weather patterns and fire outbreaks (Huang *et al*., 2009). Due to this known relationship it has long been the goal of 'fire meteorologists' to develop accurate forecasting and modelling tools to aid in the early warning and mitigation of fire outbreaks. Forecasting techniques are as varied as the weather - as such this section will present an overview of the most common forecasting techniques and tools and will provide an insight into the varied indices used to forecast and monitor fire danger.

2.4.1 Numerical Weather Prediction

Numerical weather prediction (NWP) is defined by Schulze (2007) as "the production of a forecast through the time-integration of a comprehensive set of mathematical equations that describe...dynamical and physical processes in the atmosphere using numerical procedures" (Schulze, 2007: 318). Stensrud (2007) defines NWP as computer software programmes that utilize mathematical equations describing the flow of fluids. Stensrud (2007) also states that NWP is playing an important role in meteorology and is essential for short to medium range forecasts and predictions. Numerical weather prediction projects started as early as the 1940s and in the 1950s the Joint Numerical Weather Prediction Unit (JN-WPU) officially started in the U.S.A. with the first official numerical weather forecast issued out of the JN-WPU (Harper *et al*., 2007; Schulze, 2007). Numerical weather prediction has its roots in the modelling and forecasting of barotropic vorticity with forecast maps developed 40, 70 and 90 kPa heights. While the early forecast maps exceeded expectations, they did not provide any meaningful weather information (Harper *et al*., 2007).

According to Landman *et al*. (2012), most operational weather centres today rely on numerical weather predictions to generate reliable and accurate weather forecasts. The advances from early NWP to today's NWP have been described as extraordinary and the important role that computer technology has played in advancing NWP has to be noted (Schulze, 2007). NWP relies on the basic principle that any information that describes the current state of the atmosphere can be used to predict or forecast the state of the atmosphere at some point in the near future (Doswell and Schultz, 2006), and today also relies on observational data which is converted through a number of stages or phases into a weather forecast through the use of a model (or a set of equations) (Schulze, 2007). The stages, described by Schulze (2007), through which observational data is processed to obtain a forecast will be presented.

2.4.1.1 Input Stage

The input stage of producing a weather forecast relies heavily on observational data. As stated by Doswell and Schultz (2006) observational data describing the current state of the atmosphere can be used to predict the future state of the atmosphere. The accuracy of the forecast output is subject to the accuracy of observational data (Schulze, 2007). The accuracy of the forecast can also be increased by increasing the quantity of observational data inputs.

For most forecasting purposes, observational data can include a number of differently sourced data. Surface observation stations or Automatic Weather Station (AWS) systems play a dominant role in weather forecasting (Schulze, 2007). While AWS systems provide insight to microclimatic weather variables and conditions they do not provide any information regarding the state of the upper atmosphere. In order to collect data on the upper levels of the atmosphere radiosondes are employed along with aircraft meteorological data relay (AMDAR).

2.4.1.2 Modelling/Data Assimilation Stage

Modelling of observational data into weather forecasts makes use of a number of basic equations which govern the atmosphere. Atmospheric modelling consists of two diagnostic equations namely the equation of state and the hydrostatic equation (Schulze, 2007). The equation of state describes the relationship between atmospheric pressure, density and temperature while the hydrostatic equation defines the relationship between air densities with increased height in the atmosphere (Schulze, 2007).

A number of prognostic equations is used in conjunction with the diagnostic equations to model atmospheric phenomena. The main prognostic equations include the equation of motion which defines the movement of particles in the atmosphere; the thermodynamic equation which defines the relationship between adiabatic temperature exchanges with increased height in the atmosphere and the equation for the conservation of water which takes into account the role of exchanges in water due to evaporation and precipitation (Schulze, 2007).

It is important to note the role of technological advances on the modelling stage of weather forecasting. Prior to the 1960s NWP was mainly focused on implementing a simple barotropic model over smaller scales (Schulze, 2007). During the 1960s and 1970s modelling processes were limited to the equations described above and at best were accurate at the hemispheric scale. During the 1980s models began to accurately represent global climate mainly due to the development of global observation networks and the improvement in computer technology. From the 1990s onwards the forecasting process became increasingly accurate and longer range forecasts became possible largely due to the technological advances in computer engineering and software (Schulze, 2007).

2.4.1.3 Output Stage

The final stage in forecasting of weather results from the graphical display of modelled data (Schulze, 2007). The outputs of the modelling stage can either arise directly from the model or they arise from the statistical manipulation of modelled data (Schulze, 2007). When providing information and weather predictions for disaster related weather events the user needs often outweigh the skill of the forecast i.e. a critical decision maker (CDM) may find an hourly forecast of fire danger to be more useful than a daily fire danger forecast which may be slightly more accurate.

Two types of forecasts are usually utilized by meteorologists and CDM - deterministic and ensemble forecasts. Deterministic forecasts provide a prediction of the state of the atmosphere at a time in the future where the model identifies that and only that scenario as being possible. Alternatively, ensemble forecasts consider the possibility of errors in the conditions of the model that may affect the state of the atmosphere during an event (Schulze, 2007). In ensemble forecasting outputs are analysed statistically to yield a set of probabilities and a probabilistic distribution of a dominant weather event (Schulze, 2007).

2.4.1.4 Numerical Weather Prediction in South Africa

South Africa's usage of NWP began in the early 1950s during a joint project between the Council for Scientific and Industrial Research (CSIR) and the South African Weather Service (SAWS), then the South African Weather Bureau (SAWB). The earliest model run by the joint project was a single level barotropic model (Engelbrecht *et al*., 2007; Schulze, 2007). As computing power increased through advances in computer engineering, the role of NWP in producing forecasts became more relevant and in the 1980s the SAWB started using the UK global model numerical guidance in the forecast products (Engelbrecht *et al*., 2007). According to Schulze (2007) the operational use of the numerical guidance increased the accuracy of 3- to 4-day forecasts. The 1990s saw the implementation of the Eta model which featured 17 vertical levels and a horizontal resolution of 80 km. In 2006 the SAWS began operations using an adapted version of the Unified Model (UM), with the adapted version featuring a 32 km horizontal resolution and 38 vertical levels or heights (Engelbrecht *et al*., 2007; Schulze, 2007).

According to Landman *et al*. (2012) the SAWS utilizes the Unified Model (UM) developed by the UK Met Office to produce forecasts. The UM is a non-hydrostatic model that can be used to produce short range forecasts or long range climatic trends. The UM is run using 40 km resolutions and is updated four times a day (Landman *et al*. 2012). The UM has been operational since 2006 and is utilized in three different configurations, each having different horizontal resolutions, parameterization schemes and configuration settings (Landman *et al*., 2012). The first configuration of the UM used by the SAWS is the 12-km configuration with no data assimilation (DA) which covers southern Africa and the surrounding oceans (Landman *et al*., 2012). The UM no DA is run daily utilizing 38 vertical levels and is able to produce forecasts 48 hours in advance. The UM Global Model (18:00 UTC run) is used to provide initial conditions for the forecast run at 00:00 UTC. The 12-km configuration with DA is the second configuration used by the SAWS. While it runs on the same domain as the 12-km no DA, it utilizes a 3-dimensional variational (3DVAR) which statistically combines observational data with first guess fields from previous forecast runs (Landman *et al.*, 2012). The data assimilation is run every six hours producing 6 hour forecasts and can be used to forecast events 48 hours in advance.

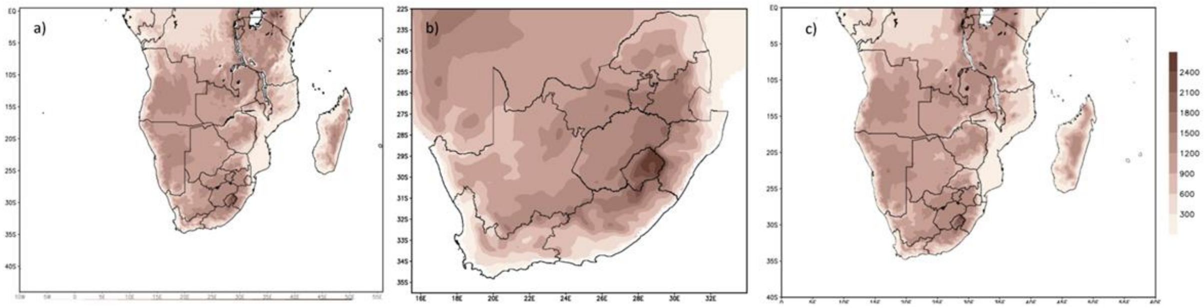


Figure 2.6: Domain sizes for the different configurations of the UM utilized by the SAWS with a) representing the 12-km configuration, b) representing the 15-km no-DA configuration and c) representing the CCAM model resolution (Landman *et al.*, 2012).

The third configuration of the UM is a 15 km model with no DA. The 15-km UM covers just South Africa and as such is considered to be computationally less expensive but also uses the 18:00 UTC UM Global Model for initialisation of the 00:00 UTC forecast (Landman *et al*., 2012). In addition to the various UM configurations used by SAWS the conformal-Cubic Atmospheric Model (CCAM) is also utilized. The CCAM is able to produce high resolution weather forecasts when utilized in a stretched-grid mode. The CCAM was developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and is able to solve the primitive hydrostatic equations (Landman *et al*., 2012). The CCAM is initialised using the Global Forecasting System (GFS) 00:00 UTC model run and is able to produce two different 7 day forecast scenarios (Figure 2.6).

2.4.2 Modelling of Fire Danger

A number of models have been developed by different countries in order to accurately monitor and model fire danger. These 'Fire Danger Indices' generally take into consideration micrometeorological variables such as air temperature, relative humidity, rainfall and wind vectors (Fujioka *et al*., 2009). Certain indices also consider the role of fuel loads and plant or soil moisture. This section will provide an overview of the most commonly used indices worldwide.

2.4.2.1 The United States National Fire Danger Rating System

The United States National Fire Danger Rating System (USNFDRS) utilized by the National Weather Service (NWS) is based on the Rothermel fire behaviour model and is applicable in a number of climatic and vegetation zones (Willis *et al*., 2001). According to Fujioka *et al*. (2009) the USNFDRS utilizes a number of indices to express fire danger. An Ignition Component (IC) has values ranging from 0 to 100 which indicate the probability of a prescribed burning leading to the growth and spread of an uncontrolled fire. The Spread Component (SC) is based on Rothermel's Rate of Spread model and is described in feet per second. The SC is highly dependent on wind speed and fuel loads while topography in terms of slope steepness also influences the SC. Along with the IC and SC the USNFDRS utilizes an Energy Release Component (ERC) which represents the energy flux experienced along the leading flank of the fire (Fujioka *et al*., 2009). As with the SC the ERC is influenced by the local fuel load as well as fuel moisture. Combining the SC and the ERC yields a Burning Index (BI) based on the relationship between the flame length and the rate of spread or residency time of the fire (Fujioka *et al*., 2009).

2.4.2.2 The Canadian Forest Fire Danger Rating System

The Canadian Forest Fire Danger Rating System (CFFDRS) was developed in Canada and has since been adopted in numerous countries to monitor and forecast fire danger (Fujioka *et al*., 2009). The CFFDRS consists of the Canadian Forest Fire Weather Index (FWI) and the Canadian Forest Fire Behaviour Prediction (FBP) System. The main use of the FWI is to estimate the severity of conditions conducive to outbreaks of fires which includes estimations of fuel load and fuel moisture. The FBP system utilizes outputs from the FWI to produce estimations of fire behaviour of larger areas with different fuel types. In order to estimate fire behaviour, the FBP system also uses site specific data such as topography and season (Fujioka *et al*., 2009). The FWI includes two "components that have not been formally developed or implemented nationally" (Fujioka *et al*., 2009: 477). The Accessory Fuel Moisture System (AFM) which contains additional information of fuel moisture which allows the addition of a temporal resolution to operational models or to provide fuel moisture estimates to specific layers of the fuel load. The Fire Occurrence Prediction System (FOP) indicates the actual fire risk component of the fire danger rating system but has not been operationally utilized throughout Canada (Fujioka *et al*., 2009).

The FWI system defines the relationship between meteorological conditions and fire danger for standardised forest types. Meteorological conditions are measured at 12:00 local standard time and include measurements of air temperature, relative humidity, wind speed and a 24-hour accumulated precipitation measurement. All measurements are taken at a height of 1.4 m except wind speed which is measured at 10 m (Fujioka *et al*., 2009). Along with the standard meteorological measurements the FWI system relies on estimates of fuel moisture at three different layers of the forest floor.

2.4.2.3 The McArthur Fire Danger Meters

According to Fujioka *et al*. (2009), Australia makes extensive use of the McArthur Fire Danger Meters. The McArthur Fire Meters consist of the McArthur Forest Fire Danger Index (FFDI) and the McArthur Grassland Fire Danger Index (GFDI) (Willis *et al*., 2001). The FFDI utilizes a 100-point scale system in which fire danger is ranked between 0 and 100 where fire danger is estimated using input variables such as air temperature, relative humidity and wind speed (Willis *et al*., 2001; Fujioka *et al*., 2009). Additionally the FFDI requires the calculation of a drought index to estimate fire danger. The drought index is based on the Keetch-Byram Drought Index (KBDI). The KBDI provides a measure of soil moisture content using a field capacity of 200 mm with values ranging from 1 to 10 (Fujioka *et al*., 2009). The FFDI is also able to calculate the rate of fire spread of a fire burning in an open eucalyptus forest with a relatively flat topography and minimal fuel load (Willis *et al*., 2001). The FFDI is further subcategorised into different classes based on the difficulty of fire suppression ranging from low to extreme suppression.

The Grassland Fire Danger Index has a similar design to that of the FFDI with the exception that the availability of fuel is calculated using a degree of curing component which considers the ratio between the moisture content of dead grass and the moisture content of live grass. The differences in moisture content between dead and live grass is considered to be a vital component affecting the ignition risk of grasslands (Willis *et al*., 2001). Later adaptations of the McArthur GFDI also included a measure of fuel load weight (Fujioka *et al*., 2009). The GFDI also allows the calculation of a rate of spread (ROS) which combines the fuel water content with wind speed (Willis *et al*., 2001).

2.4.2.4 The Lowveld Fire Danger Index

The Lowveld Fire Danger Index (LFDI) was developed in South Africa and is based on the Fire Hazard Index developed by Laing in the 1960’s. The LFDI requires inputs similar to those of the FFDI - air temperature, relative humidity, wind speed and rainfall data (Willis *et al*., 2001). Using the basic micrometeorological variables the LFDI is calculated through the combination of various derived components. A nomogram is utilized to derive the Burning Index (BI) which is derived using air temperature and relative humidity measurements. The BI is then adjusted upwards (BIPWS) for wind speeds exceeding a threshold speed (Willis *et al*., 2001; Strydom and Savage, 2013). While the LFDI does not directly incorporate any measurements of fuel load or degree of curing as with other FDIs, it does infer fuel availability using short term historical rainfall data into a Rainfall Correction Factor (RCF) which does not exceed a value of 1. The LFDI is simply calculated by multiplying the BIPWS by the RCF (Willis *et al*., 2001; Strydom and Savage, 2013).

Due to the explicit relationship between Berg winds and fire danger in South Africa, the South African Weather Service (SAWS) will often identify areas at risk of wildfires by identifying areas where Berg winds are forecast to occur. Used in conjunction with NWP the SAWS utilizes a Severe Weather Warning System (SWWS) which became operational in 2010. The SWWS provides users with public warnings at a provincial level and in times of severe fire danger will liaise with local disaster management centres to mitigate any fire disasters (De Jager, pers. comm. 2013).

2.5 Conclusion

The intricate link between warm mountain winds and wild fires has been a theme of much research especially in countries prone to fire disasters. The effects of fire disasters are evident in the South African context where annually fires are responsible for a high number of fatalities and large financial losses. While fires have a marked effect on society, they too provide a number of benefits to the environment and have always been a naturally occurring phenomena in nature. Fires are able to aid in nutrient recycling and are often used as a management tool in preventing the spread of alien invasive flora. Despite the number of environmental benefits associated with naturally occurring fires,

they are also able to negatively impact the environment with uncontrolled fires destroying large areas of habitats and increasing the risk of erosion. By-products from fires, such as released carbon dioxide, can also influence local air quality and contribute to concentrations of greenhouse gases and other atmospheric pollutants. The management and understanding of fire disasters has become a major concern for numerous countries and is evident by the number of country specific fire danger indices that have been developed. Forecasting of fire weather has also become more advanced due to technological developments in the field of numerical weather prediction while technologies such as remote sensing have allowed for monitoring of fires over large spatial and temporal scales, with indices being developed from remotely sensed data to better monitor the seasonality of fire danger

CHAPTER 3: A CONTEMPORARY SPATIO-TEMPORAL ANALYSIS OF SOUTH AFRICAN FIRES

Abstract

Africa has been termed the 'Fire Continent' due to its high annual fire frequency. Wildfires are considered one of the most common disasters in South Africa resulting in a high number of human fatalities and financial loss on an annual basis. It is believed that increased population growth, as well as more concentrated settlement planning is likely to result in increased fire disasters and increased human fatalities as a direct result of wildfires. In order to better understand the spatial and temporal variations and characteristics of wildfires in South Africa an 11-year dataset of MODIS-derived Active Fire Hotspots was analysed using an open source geographic information system. The study included the mapping of national fire frequency over the 11-year period. Results indicated that the north-eastern regions of South Africa experienced the greatest fire frequency. In particular the mountainous regions of KwaZulu-Natal, Mpumalanga and the Western Cape. Increasing trends in provincial fire frequency was observed in eight out of the nine provinces with Mpumalanga being the only province where a decrease in annual fire frequency was observed. Temporally, fires were observed in all months for all provinces although distinct fire seasons were observed, largely driven by rainfall seasons. The South-Western regions of South Africa (winter rainfall patterns) experienced higher fire frequencies during the summer months and the rest of the country (summer rainfall) during the winter months. Certain regions, which experienced bi-modal rainfall seasons, did not display distinct fire seasons. The study included an investigation into the likely effects of climate change on South African fire frequency. Three of the 11 years were identified as being climatologically anomalous. Fire frequencies in 2005 and 2010 (two of the warmest years in recent history) were significantly greater than normal years. Observed fire frequencies in 2007 were also significantly greater. The increased fire frequency was attributed to a severe La Niña event which may have resulted in increased vegetation growth.

KEYWORDS: MODIS, fire frequency, active fire hotspots, spatio-temporal analysis, wildfires, mitigation and monitoring, climate change

3.1 Introduction

The African continent has for years been termed the "Fire Continent" due to the high number of fires that occur (Archibald *et al*., 2010). The development of advanced remote sensing technologies has allowed the study of fires at a greater spatial resolution and in the context of vegetation communities and topography, and more recently in the context of climate change (Archibald *et al*. 2010). Remote sensing has also allowed for the study of fires in larger regions compared to the highly localised research of the past.

3.1.1 Fires as Disasters in South Africa

Fires have always and will always be a natural and important phenomenon in environmental systems. However, due to increased fire disasters brought on through anthropogenic activities, fires are having a negative impact on the environment and more so on society and the economy. Arturson (2000) states that the likelihood of an 'accident' fulfilling the requirements to be classified as a disaster is increasing due to increased population densities and increased settlement in high risk areas. Fire disasters are of great concern in South Africa and using the statement by Arturson (2000) one can conclude that these disasters are only going to increase. Due to its political legacy, South Africa has a large percentage of the population located in rural areas where the underprivileged have settled in what is harshly known as 'squatter camps' or 'informal settlements'. The construction of houses in these areas is often done without significant planning and houses are often built in close quarters allowing for fires to spread rapidly through the structures. These rural areas are also generally situated in fire prone regions of the country.

According to the Fire Protection Association of South Africa (FPASA), a total of roughly 35000 fires were reported during the 2008 fire season with a majority originating from open flames during waste, grass or bush burnings leading to close to 380 fatalities and more than R2.3 billion in financial losses (FPASA, 2010). The 2009 fire season experienced more than 40000 fires reported resulting in 376 fatalities and R4 billion in financial loss with open flames during waste, grass or bush burnings being identified as the source of most of the fires (FPASA, 2011). The 2010 fire season experienced similar statistics with a high number of fatalities due to fires and a large financial loss (FPASA, 2012). These statistics clearly indicate the potential of fires to result in both life and financial loss. The South African National Veld and Forest Fire Act of 1998 (Act 101 of 1998) specifies for the prevention of wild fires through the implementation of a National Fire Danger Rating System (NFDRS) under the responsibility of the Department of Water Affairs and Forestry. The NFDRS is currently operational and is being utilized by the South African Weather Service and other interested parties to mitigate wild fire outbreaks. Under the Act fire prevention is considered the responsibility of the landowner and lack of regional co-ordination is visible (de Ronde and Goldammer, 2001). While regional co-ordination is lacking a number of regional fire prevention or protection agencies have been established, consisting of mostly private land owners and agro-forestry managers working as 'umbrella' fire protection associations (de Ronde and Goldammer, 2001). The National Veld and Forest Fire Act of 1998 promotes the formation of these regional fire protection associations and requires all landowners to be members of local fire protection associations but co-ordination between different fire protection associations is minimal (Working on Fire, 2012).

3.1.2 Adverse Effects of Fires

Fires have been associated with poor air quality and atmospheric pollution largely due to the release of carbon monoxide and ozone during biomass burnings (Duncan *et al*., 2009) as well as carbon dioxide. Smoke haze has also been linked to human respiratory diseases and poses a concern for agricultural crop productivity. The burning of biomass attributed to wild land fires has a direct impact on climate change. Burning of biomass releases high concentrations of black carbon which acts as a greenhouse gas by absorbing and re-emitting infrared radiation (Keywood *et al*., 2013). Black carbon has also been linked to positive feedback mechanisms when deposited on surfaces such as snow where it alters the surface radiation balance. Altering the surface radiation balance leads to the snow surface having a warmer temperature leading to snowmelt which further exposes darker surfaces leading to further warming (Keywood *et al*., 2013). It is acknowledged that fire may be a necessary evil when it is used as a land surface management tool. However, by identifying areas prone to wild fires one may at the same time identify areas that contribute largely to atmospheric pollution and focus mitigation resources to the identified areas. Of concern is when a highly populated area experiences high fire frequencies, as the by-products of the fires may adversely affect those populations.

Fires also have the ability to enhance or increase soil erosion. Particularly severe fires have been shown to remove surface vegetation. This loss of vegetation effectively decreases the surface's ability to infiltrate surface runoff after a precipitation event (Townsend and Douglas, 2000; Merz, 2004). Increased surface runoff then results in increased soil removal but may also result in flash floods or increased sedimentation of water systems. Fires on mountain slopes have been shown to decrease infiltration by as much as 50% increasing the catchment's risk of flash flooding (Merz, 2004). Meadows and Hoffman (2002) state that much of South Africa is vulnerable to severe land degradation due to improper agricultural practices such as overgrazing. The already vulnerable areas may experience exacerbated degradation due to increased fire activity. A province like the Eastern Cape, which is notorious for its severe soil erosion, may be able to mitigate and limit further degradation by identifying areas prone to fires and assessing the role of fires in removing land cover in those areas. Mountainous regions may also be vulnerable due to the steepness of slopes and the high fire frequencies associated with mountain wave Berg winds. By identifying these areas, managers may be able to combat further degradation by limiting fire activity and ensuring the prevention of uncontrollable fires.

3.1.3 Need for a Detailed Spatio-temporal Analysis of South African Fires

Despite the implementation of the NFDRS, the country still experiences a number of fire disasters annually. It is believed that a lack of understanding exists as to the spatial and temporal characteristic of fire seasons in the country. Maps have traditionally been used to display information that has both spatial and temporal characteristics. Detailed spatio-temporal studies on wild fires in South Africa are lacking with only a few localised studies published (van Wilgen *et al*., 1998; 2000; Archibald *et al*., 2010). Archibald *et al*. (2010) state that inter-annual variability studies focussing on wild fire extent are important in Africa which experiences extensive burning annually. Previous research on variability of fires in Africa have been limited to protected areas which cannot be extrapolated to the rest of the continent with satisfactory accuracy (Archibald *et al*., 2010). A detailed spatio-temporal study can be utilized to identify areas within the country that are prone to fire activity and can also identify times when fire activity is at its highest, with temporal scales ranging from months to years.

3.1.4 Motivation for the Study

Fires have played a significant role in the morphology of the African continent. Fires do indeed provide a number of environmental services but increased fire activity due to anthropogenic activities may result in adverse effects such as loss of human life and property, enhanced environmental degradation and increased greenhouse gas concentrations. In order to mitigate the loss of human life and other adverse effects of wild fires, a spatio-temporal analysis of South African fires was undertaken so as to provide landowners and critical decision makers with a better insight into the time and spatial variation of fires in South Africa.

3.2 Methodology

3.2.1 Data Acquisition

One of the challenges faced when initiating the study was the lack of a national database of fires listing the times and locations of active fires. As no dataset was available from government or independent research groups, it was decided to acquire raw data through the National Aeronautics and Space Administration's (NASA) Earth Observing System Data and Information System (EODIS). The EODIS allows a registered user to download data in a specified format for a specified area during a user selected time frame.

3.2.1.1 Data Characteristics

Using the EODIS website (https://earthdata.nasa.gov/data/near-real-time-data/firms/active-fire-data) made it possible to access archived active fire data through NASA's Fire Information for Resource Management System (FIRMS) acquired using NASA MODIS satellites. The FIRMS is based at the University of Maryland and distributes fire hotspot information to a number of countries (Tanpipat *et al*., 2009). FIRMS data are obtained from the Moderate Resolution Imagining Spectrometer instruments aboard NASA Rapid Response satellites (Tanpipat *et al*., 2009). FIRMS incorporates remote sensing and GIS technology to produce MODIS fire data. According to Justice *et al*. (2011), FIRMS provides MODIS fire data in three unique ways- firstly through an online mapping interface, secondly through customized email alerts and thirdly through text messaging.

In South Africa the MODIS satellites have two flyover times. The Terra MODIS flyover occurs in the morning roughly around 10:00 SAST and the Aqua MODIS in the afternoon around 14:00 SAST, thus providing remotely sensed images at a high temporal resolution. NASA offers two fire related products derived from MODIS data- the Active Fire Product and a Burned Area Product. For this study only Active Fire Data was used. The Active Fire product uses contextual algorithms which utilized data obtained from the mid-infrared (3.929 – 3.989 µm) and thermal infrared (10.780 – 11.280 µm) wavelengths as well as a 'fire radiative power parameter'. Products are generated daily at full resolution and plotted to 0.5^{o} grids (Justice *et al*., 2011).

As the timespan of the dataset needed exceeded eight days archived data was needed. Using the EODIS Archive Data Tool a polygon was inserted surrounding the areas of interest- in this case South Africa. In order to select the entire South African land surface a polygon larger than South Africa was drawn. Once an area of interest was selected a time frame of 11 years was selected using a calendar tool to span from 1st January 2003 to 31st December 2013.

3.2.1.2 Limitations

As stated previously one of the main challenges to the study was acquiring a database containing national fire point locations with a temporal analysis. Reaching out to government departments and private research institutes proved fruitless resulting in having to acquire the database through NASA's EODIS. While the data were available it made validating the data a challenge as it is relatively impossible to ground truth a fire detected by the MODIS satellites in 2003. Tanpipat *et al*. (2009) provide methods for validating the MODIS Active Fire Product and Burned Area Product. The methods set forth by Tanpipat *et al*. (2009) require extensive ground truthing and time spent in the field shortly following the detection of a fire by MODIS. Ground truthing involves investigating areas identified as recently experiencing a fire to identify residues of fires such as burn scars.

While ground truth validation was not possible in this study, Justice *et al*. (2011) provide insight into the validation techniques used by FIRMS to ensure observational accuracy. According to Justice *et al*. (2011) the Active Fire product is validated using sample locations representative of the general area's vegetation - i.e. hotspots detected in South Africa are validated using a tropical savannah/grassland biome to mask out hotspots created by waterbodies, mines and power stations.

3.2.2 Data Processing

3.2.2.1 Quantum GIS

As the aim of the study was to analyse the distribution of fires in South Africa over space and time it was decided that a geographic information system would be the best to allow for both visual display and mapping of data as well as analysing and processing data. Quantum GIS or QGIS was selected to process and analyse the data as it is open-source spatial analysis software developed by the Open Source Geospatial Foundation. QGIS is available to download at http://www.qgis.co.za/en/site/forusers/download.html.

3.2.2.2 Processing of Data

Data were downloaded using EODIS Archive Download Tool. For convenience a shapefile format was selected to display the total number of fires detected within the area of interest between 2003 and 2013. The shapefile included an attribute table with information regarding time of detection, date of detection, location of hotspot, brightness as well as a confidence level. The shapefile containing vector points of hotspots was projected in QGIS using the Hartebeeshoek94 co-ordinate reference system. All shapefiles added to QGIS thereafter were projected using the Hartebeeshoek94 co-ordinate reference system to ensure spatial accuracy. The total hotspot shapefile was clipped to the borders of South Africa, eliminating any detected hotspots that were not within South Africa. To ensure the study focussed on hotspots created by fires, only points with a confidence level of 100% were selected for analysis.

Analysing national fire distribution required the attribute table of 100% confidence level fires to be exported to Microsoft Excel, where simple statistics were applied to the table in order to investigate annual trends as well as monthly averages. QGIS was used to create a map illustrating the total distribution of 100% confidence level fires in the country between 2003 and 2013 which was overlaid with a shapefile of South African province boundaries. A shapefile of vegetation zones was added to the QGIS project to analyse fire distribution as a variable of vegetation. In order to calculate the total number of fires in each vegetation class QGIS' 'Spatial Query' tool was used. In order to better understand the role of vegetation on fires the 11-year fire point dataset was combined with a 1:50 000 vegetation shapefile which included 67 different vegetation classes. Fire points in each vegetation class were counted. This was done for all vegetation classes and then exported to Microsoft Excel for further investigation. Analysing provincial fire distribution used a similar method, where fire totals per province was calculated using the spatial query tool and then exported to Excel. As the attribute table included time of detection for each fire spot, temporal variations were possible to study.

It must be noted that while only 100% confidence level fire points were considered in the study, the study may not have included all actual fires that occurred between 2003 and 2013 due to operational errors of the MODIS which may detect an actual fire and only assign it a confidence level of less than 100% depending on its brightness and track. Cloud cover during the MODIS overpass may also reduce the number of active fires detected. The study can still be seen as valid as only guaranteed fire points were used which was dictated by the lack of a national fire database and a lack of collaboration on the part of independent research units.

3.3 Results

3.3.1 National Fire Statistic

Using an 11-year dataset of fire points a map was created to indicate the total distribution of fires in the country per province. Figure 3.1 gives a clear indication that the north eastern and the eastern regions of the country have experienced the most frequent fires over the last ten years. The south-west regions of the country also appear to have a high fire frequency compared to surrounding regions. From Figure 3.1 it is clear that topography and climate play a significant role in fire totals. For example, the main spread of fires in the south-west regions can be associated with the Cape Fold Mountains while the western border of KwaZulu-Natal experiences a high concentration of fires along the Drakensberg mountain range. The Free State's highest fire concentration is situated along the Lesotho border which is also part of the northern Drakensberg range.

3.3.1.1 Vegetation Statistics

As stated earlier, South Africa experiences two different rainfall seasons. These different rainfall seasons have led to a wide variety of vegetation types to become established in the country. The country's ranging topography has also lead to different vegetation patterns in mountainous areas where air temperature and rainfall gradients vary over small areas resulting in pockets of different vegetation. Table 3.1 provides a list of the 'top ten' vegetation classes. These ten vegetation types have the highest number of fires over the 11-year period. Table 3.1 also includes a percentage to indicate the ratio of fires in the vegetation class to the total number of fires.

Table 3.1: Total number of fires per vegetation class and percentage of total fires

Vegetation	No. of Fires	Percent
North-Eastern Mountain Grassland	4513	12.71
Mountain Fynbos	3291	9.26
Moist Upland Grassland	2711	7.63
Mixed Bushveld	2516	7.08
Sour Lowveld Bushveld	1633	4.60
Moist Sandy Highveld Grasslands	1598	4.50
Rocky Highveld Grassland	1596	4.49
Moist Cool Highveld Grasslands	1228	3.46
Natal Central Bushveld	1225	3.45
Wet Cold Highveld Grassland	1113	3.13

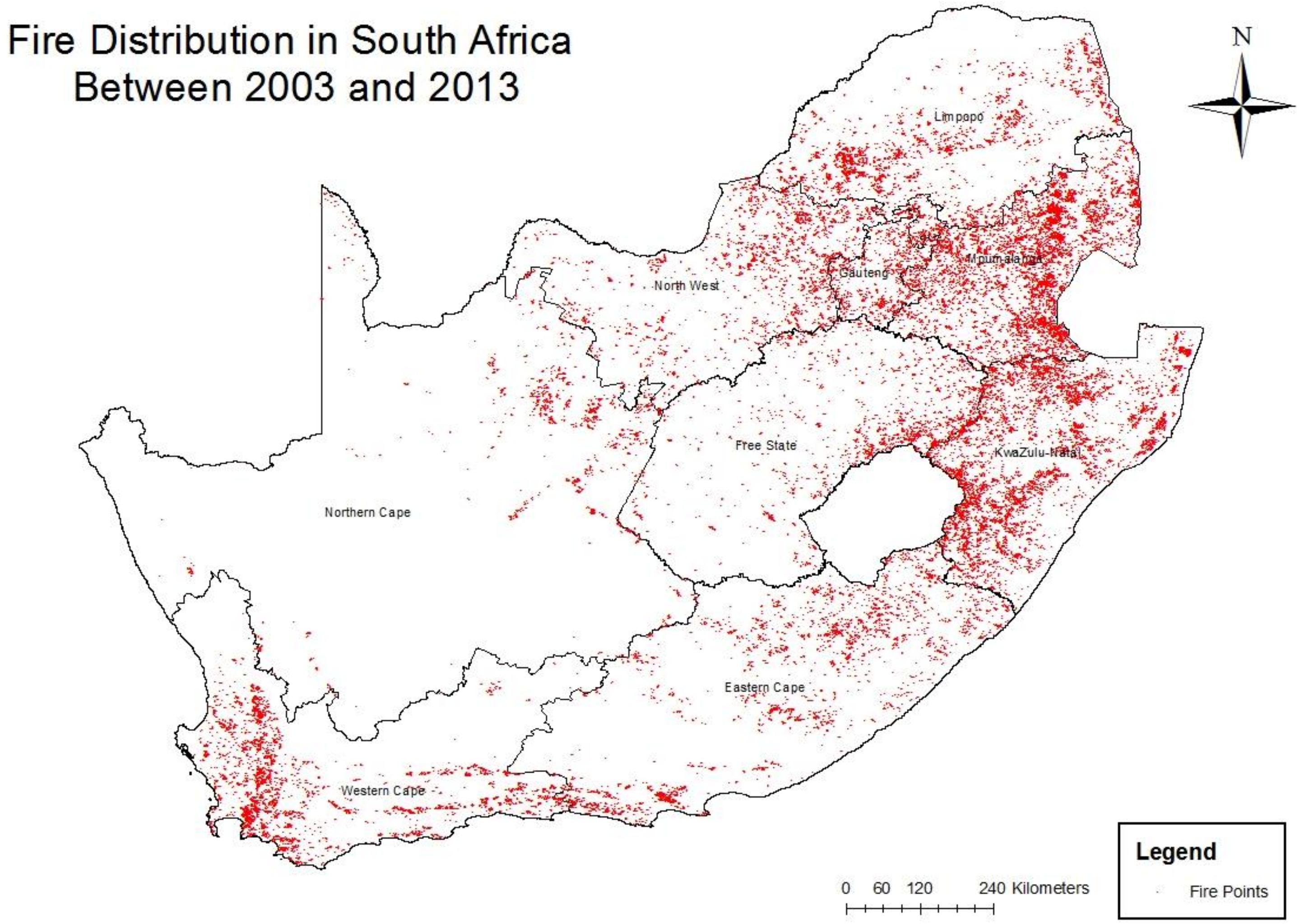


Figure 3.1 Fire distribution in South Africa between 2003 and 2013

Mountain grasslands in the north-eastern regions of the country experienced the most fires over the 11-year period followed by mountainous fynbos. The top ten vegetation types can easily be categorised into three main ‘biomes’ namely grasslands, bushveld and fynbos. Of note is that while grasslands feature in the top ten, these grasslands are mostly associated with upland or mountainous areas such as southern KwaZulu-Natal or north-western KwaZulu-Natal rather than the open plains type of grassland associated with the central Free State. The top ten can also be linked to the three provinces which experience high fire frequency. The vegetation types listed in Table 3.1 contributed to roughly 60% of all fires between 2003 and 2013 leaving the remaining 57 vegetation types with only 40%, again indicating the high concentration of fires in certain regions of the country.

3.3.1.2 Annual Fire Trends

Acquiring an 11-year dataset made it possible to analyse inter-annual trends in fire frequency. The effect of climate change on fire frequency is not known despite a number of existing scenarios. Figure 3.2 illustrates the total number of fires experienced in South Africa between January of 2003 and December of 2013. While no clear increasing or decreasing trend is visible in Figure 3.2, there appears to be a stabilisation in fire numbers over the last three years beginning in 2011 and continuing through 2013. However, three years of stabilisation does not mean that fires are being better managed or that mitigation efforts are successful and further investigation in the upcoming years will be needed to fully understand the trend, assuming the trend continues.

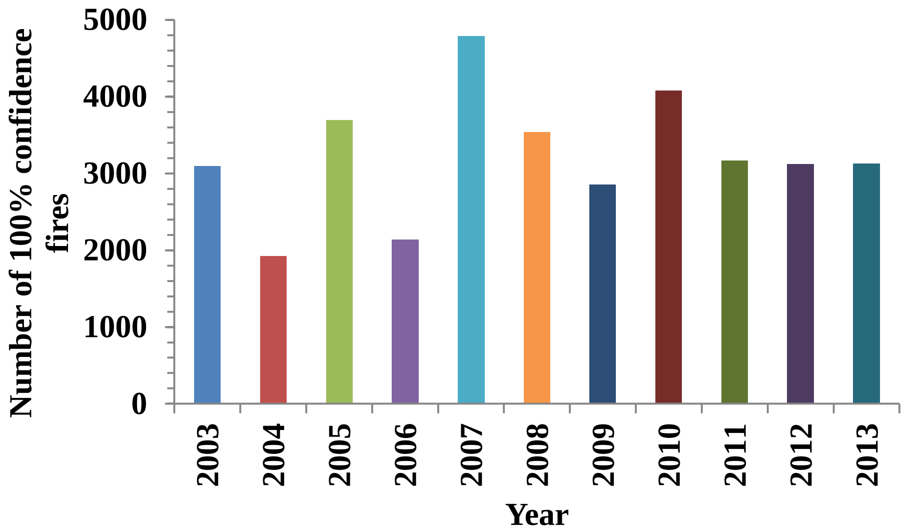


Figure 3.2: Annual fire totals for South Africa

Also of note is the higher than average number of fires in the years 2005, 2007 and 2010. Years 2005 and 2010 have been classified as two of the warmest years in the past decade and the effect of these above average air temperatures seems to have a strong correlation to fire frequency. Year 2006 has also been classified as the warmest La Niña year in the past decade which may explain the high fire frequency in 2007.

3.3.1.3 Monthly Averages

South Africa is known to experience a number of fire seasons due to the variability of the country's rainfall seasons. As the western and south western parts of the country receive winter rainfall their fire season generally occurs in the summer months while the central and eastern portions of the country experience a winter fire season due to a summer rainfall pattern. Totalling the number of fires per month for each year in the dataset and producing monthly averages yielded results which illustrate the months prone to fires. Figure 3.3 illustrates the months which experience the highest number of fires. From the figure it is clear that August and September have dominance in fire numbers which would indicate that the central and eastern regions of the country experience higher fire numbers than the western portions as August and September fall into the dry winter months in the central and eastern regions and the wet winter months in the west. While August and September do have the highest fire numbers, months associated with the western fire season also have relatively high averages.

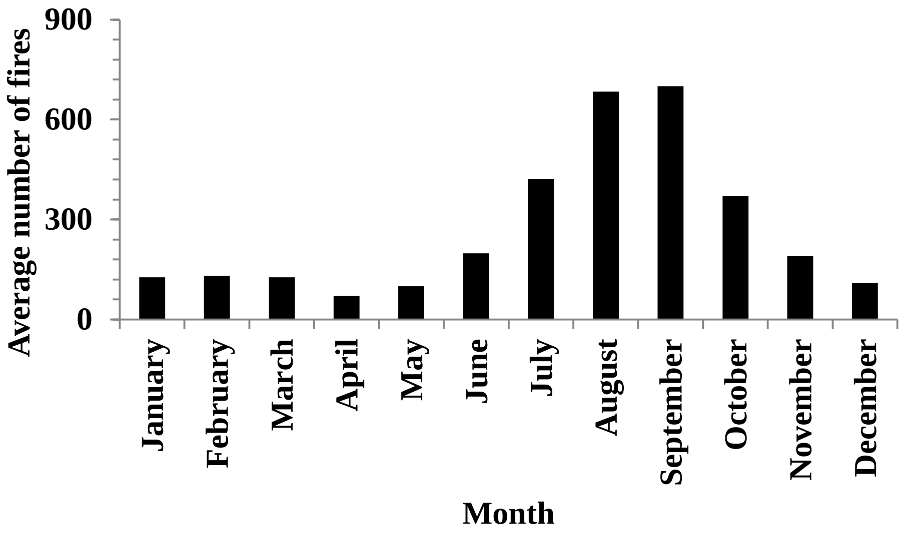


Figure 3.3: Monthly fire averages between 2003 and 2013 for South Africa.

It is important to note that while the winter fire season may appear to have higher fire frequencies, the size of the area is much larger than that which receives winter rainfall. Areas which receive winter rainfall are also largely semi-arid limiting the available fuel to burn during a fire which may limit fire activity. Taking into account the data represented in Figure 3.3, August and September can clearly be identified as the most severe months for fire outbreaks but also proves that fires are possible at all times during the year, which serves as a challenge to land owners and critical decision makers.

3.3.2 Provincial Fire Statistics

The National Veld and Forest Fire Act of 1998 promotes the establishment of regional fire protection association and requires all landowners to be members of a fire protection association. By understanding provincial trends in wild fires these fire protection associations and landowners may be better equipped to mitigate and manage fire outbreaks in their respective provinces. As each province in South Africa has different topography and climatic factors, one cannot expect the management plans of each province to be the same and each province needs to adapt to their own fire season and fire pattern.

3.3.2.1 Annual Trends in Provincial Fire Totals

Using GIS processing the total number of fire spots per province was calculated and plotted over time. The calculations included yearly totals as well as monthly average fire numbers 9figure 3.4). Assessing the trends in yearly fire numbers may provide for better management and the better allocation of funds and resources. All provinces display an increasing or stable trend in inter-annual fire totals, with the exception of the Western Cape which has been experiencing a small decline in fire totals since 2003. While the trend may be indicating a decrease there have still been years where the Western Cape has experienced a significantly high number of fires. The Northern Cape province displays the most noteworthy increasing trend in fire totals from 2003, and while some years have fewer fires than the previous years, the overall trend indicates that fires may be becoming a common problem in the province. Other provinces do not display significant increasing trends and the Eastern Cape province is the only province that appears to have a stable trend in fire totals since 2003.

3.3.2.2 Provincial Variations in Fire Seasons

As stated previously different regions throughout the country experience different fire seasons. Traditionally two main fire seasons have been identified- the dry winter fire season experienced in the central and eastern regions of the country and the dry summer season experienced by the west and south west regions of the country. Analysis of provincial peaks in fire frequency presented in Figure 3.4e to h. indicate slightly more discrete fire seasons. Figure 3.4b to Figure 3.4r indicates four main peaks in fire seasons around the country. The Western Cape experiences its peak in fire numbers in February while the Northern Cape experiences a peak in November. While these two provinces both experience winter rainfall and thus a summer fire season there exists two different peaks in fire season. Mpumalanga and KwaZulu-Natal both experience a peak in fire season in August while the North-West Province, Gauteng, Limpopo, the Free State and the Eastern Cape experience a peak in fire season in September.

While each province can be categorised into a specific fire season it is important to note the severity of each province’s fire season. Mpumalanga, KwaZulu-Natal and the Western Cape have been identified as the three provinces which experience the most severe fire seasons largely due to their native vegetation, topography and climate. KwaZulu-Natal and Mpumalanga have minimum monthly average of roughly ten fires and a maximum of close to 200 fires at their peak in the fire season. The rest of the provinces display similar minimum averages of close to one fire per month and have maximum averages ranging between 30 fires and 120 fires during the peak in the fire season.

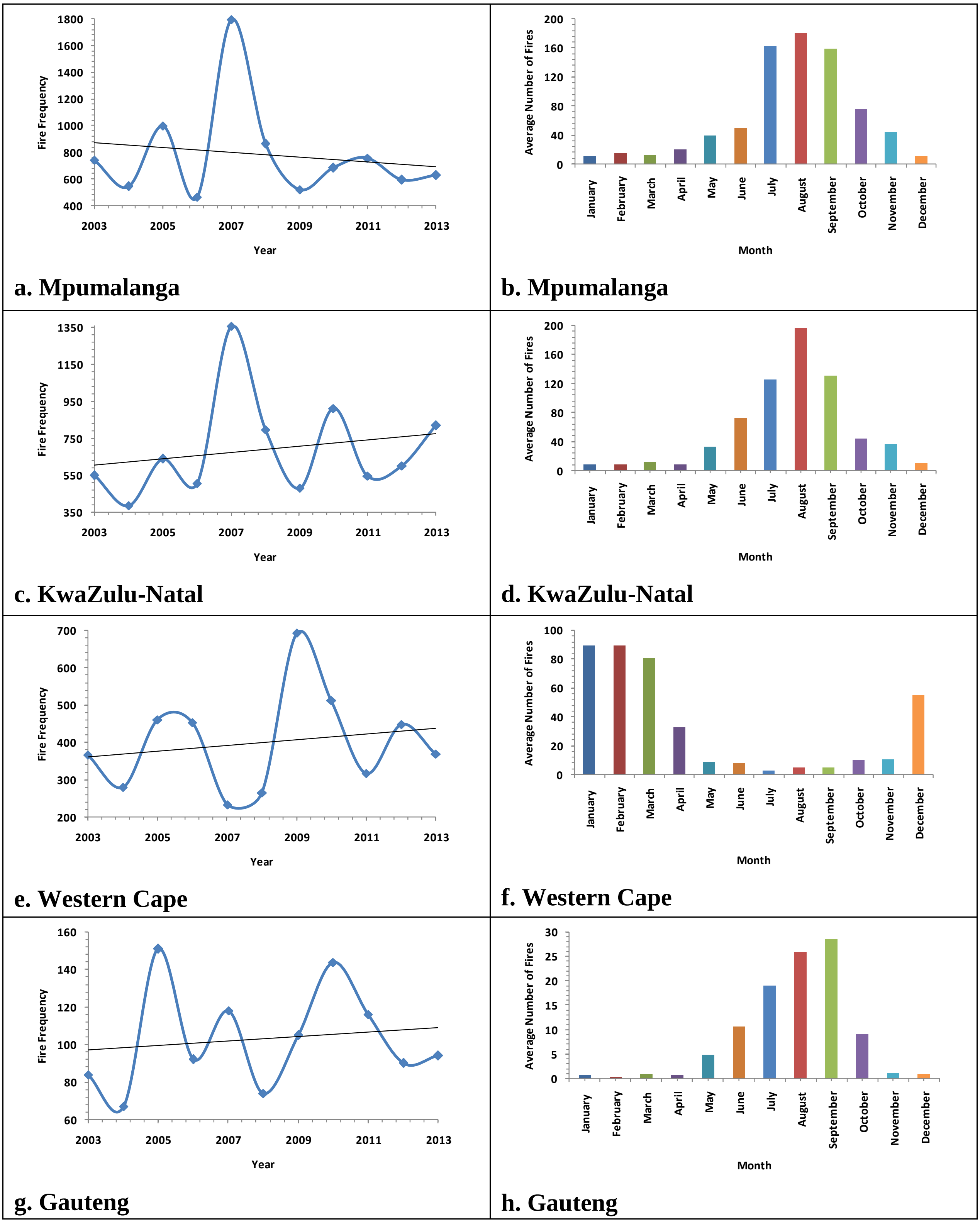
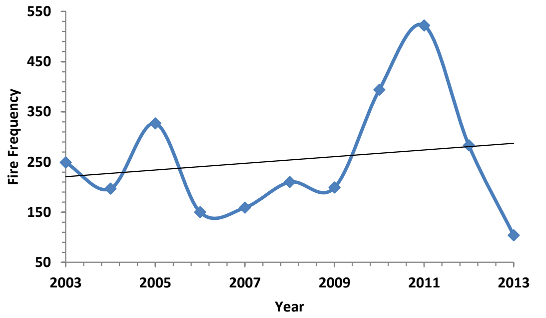
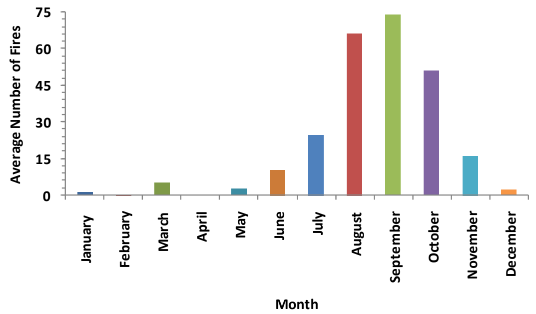


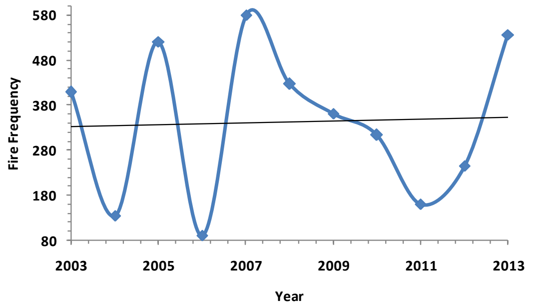
Figure 3.4 a. to h. annual fire totals and monthly fire averages



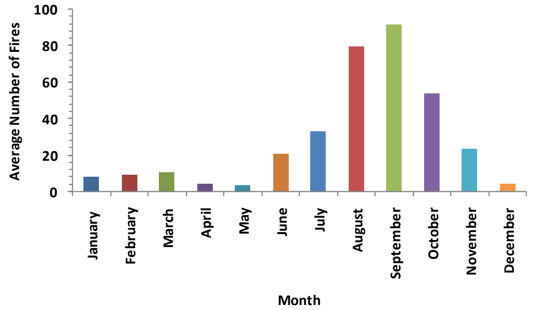
i. North West Province



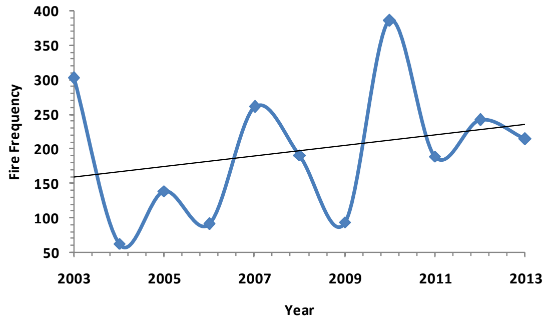
j. North West Province



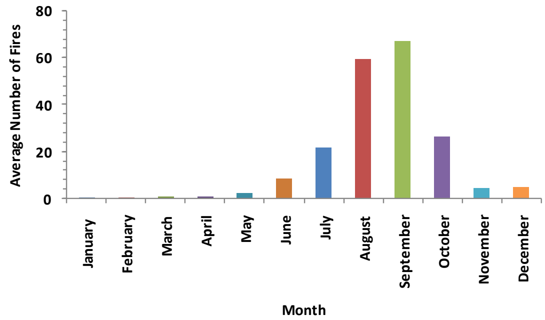
k. Eastern Cape



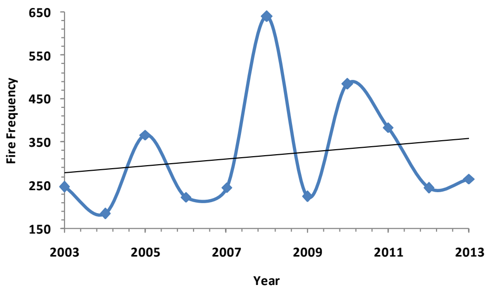
l. Eastern Cape



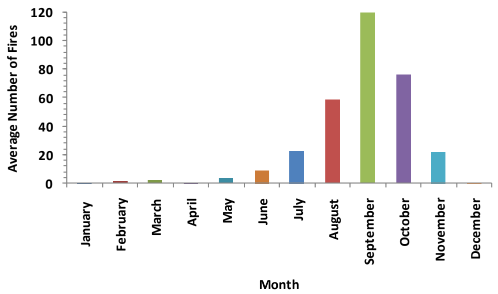
m. Free State



n. Free State

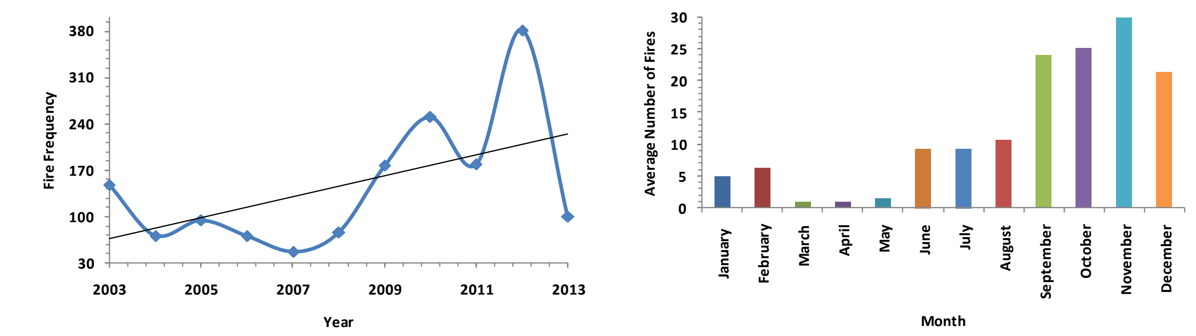


o. Limpopo



p. Limpopo

Figure 3.4 i. to p. annual fire totals and monthly fire averages



q. Northern Cape **r. Northern Cape**

Figure 3.4 Annual fire totals for the nine South African provinces, a. Mpumalanga, c. KwaZulu-Natal, e. Western Cape, g. Gauteng, i. North West Province, k. Eastern Cape, m. Free State, o. Limpopo, q. Northern Cape, and monthly fire averages for b. Mpumalanga, d. KwaZulu-Natal, f. Western Cape, h. Gauteng, j. North West Province, l. Eastern Cape, n. Free State, p. Limpopo, r. Northern Cape

3.4 Discussion

3.4.1 National Distribution of Fires

<u>3.4.1.1 Vegetation and Topographic Influences on Fire Distribution</u>

Figure 3.1 provides a stark indication of the severity of fire occurrences in South Africa over the last 11-years and by analysing the map, one can clearly see why fires result in the number of fatalities on an annual basis. The vegetation types which experience the highest frequency of fires also occur in the north-eastern and eastern regions of the country. Table 3.1 provides a list of the vegetation types most prone to fires. From the table, it is clear that grasslands and bushveld are common fire areas. A number of reasons can be cited for the link between these vegetation types and their high fire frequency. Vegetation like grasslands and bushveld are able to grow rapidly and densely if provided sufficient rainfall. When grasslands and bushveld grow they produce a high fuel load due to the high biomass associated with the vegetation. During the dry season the water content of the vegetation decreases providing a fuel for fires to ignite and spread. The top ten vegetation types all have characteristics conducive for fires to occur. Many are classified as moist or wet indicating an association with an above average rainfall season (either a summer or winter rainfall season). Furthermore many are classified as being mountainous or upland vegetation which is discussed below.

The map provided in Figure 3.1 also provides an idea of the role of topography on fire occurrences. The importance of topography in fire behaviour and fire likelihood is often overlooked by the South African fire community and is not taken into consideration when monitoring or calculating fire danger using the Lowveld fire danger index, evident by the lack of a fire behaviour model. Fire danger indices used by developed countries, such as the Australian McArthur Forest and Grassland Fire Danger Indices and the US National Fire Danger Rating System, generally do consider topography when monitoring fire danger. The concentration of fire points along ranges such as the Drakensberg and Cape Fold Mountains indicate the need for accounting topography as it has a marked influence of fires. Topography can also lead to dry mountain winds, known as Berg winds in South Africa, which have been proven to enhance fire danger. Furthermore, it is believed that fires which originate on mountain slopes and spread up along the slopes may be enhanced due to the local topography-under general meteorological conditions one would assume anabatic winds to prevail during the day, essentially spreading any fire that starts upslope. As a fire moves upslope, the heat emitted by the fire causes the surrounding air mass to warm causing it to rise, providing a ventilation system for the fire. The reasons stated above may explain the high concentration of fires along the major ranges of South Africa. Therefore it is important for landowners, community managers and critical decision makers to be aware of the topography of their area and assess its role on the local fire dynamics.

3.4.1.2 Annual Fire Frequency Trends

The annual fire frequency trends displayed in Figure 3.2 prove to be quite revealing in terms of the impact of climate change and inter-annual climatic variations on fire. As seen in Figure 3.2 the 2005, 2007 and 2010 years experienced the greatest number of fires in the last decade. Years 2005 and 2010 have been cited as two of the warmest years on record in the southern hemisphere compared to a global average (NOAA, undated). One can assume that South Africa's annual average air temperatures would follow that of the rest of the southern hemisphere.

Two possible scenarios have been established for fires under a warming climate. The first scenario states that under warmer air temperatures heatwaves and drought conditions may be more severe which may result in vegetation desiccating at higher rates leading to drier fuel loads resulting in increased fire numbers. The second scenario states that under a warming climate, rainfall may be significantly higher (Intergovernmental Panel on Climate Change, 2013). Higher rainfall totals may lead to increased rates of vegetation growth leading to heavier fuel loads resulting in more available fuel to burn and also increased rates of spread when fires occur. As 2005 and 2010 have been marked as above average air temperature years, they serve well to investigate the possible effect of global warming on South Africa’s fire frequency. As the two years have high fire frequencies, one can assume that the two scenarios are accurate.

While 2007 is not seen as a significantly above average year in terms of air temperature, it still experienced a high fire count. Year 2006 however, has been cited as being one of the warmest La Niña events. La Niña results in increased rainfall over the eastern half of South Africa. As 2006 has been cited as the warmest La Niña event one can also assume that air temperatures were greater than average. Increased air temperatures and increased rainfall may have led to increased vegetation growth which during the 2007 winter (the eastern region’s fire season) could have resulted in higher fire frequencies which would be in agreement with the first possible scenario for fires under global warming. The South African Weather Service has made seasonal rainfall charts available via its website (Figure 3.5). Analysis of these charts confirm that higher than normal rainfall, indicative of a La Niña event, occurred during the summer rainfall season between 2006 and 2007 which may explain the increased fire activity during the 2007 fire seasons. Despite explanations as to why 2007 experienced the greatest fire totals it is clear that global warming will result in increased fires which needs to be taken into consideration by government, landowners and fire protection associations.

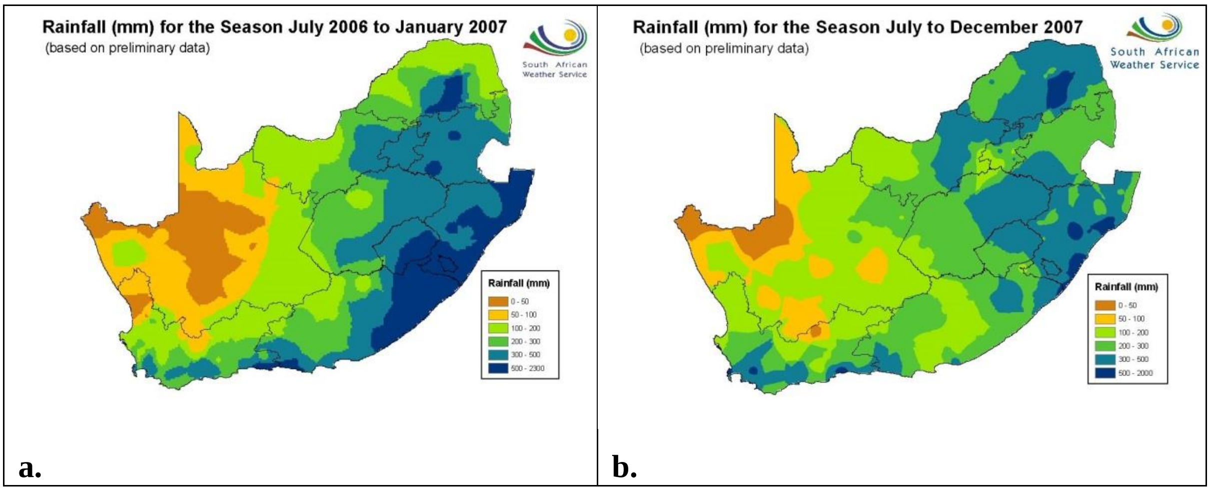


Figure 3.5: Seasonal rainfall prior to and during the 2007 fire seasons with a) indicating the high rainfall totals experienced between July of 2006 and January of 2007 and b) showing the total rainfall experienced between July and December of 2007. The Higher rainfall may explain the high fire totals recorded during the 2007 fire seasons. Charts courtesy of the South African Weather Service.

3.4.2 Provincial Distribution of Fires

3.4.2.1 Variations of Fire Seasons

Traditionally two main fire seasons have been noted- the eastern regions winter fire season and the western regions summer fire season. The variation in fire seasons across the country is largely due to climatic conditions. As evident in the monthly distribution of fires for the various provinces shown in Figure 3.4, there are four main peaks in fire seasons. Mpumalanga and KwaZulu-Natal, both situated in the far eastern regions of the country, experience a maximum in fire activity during August. The Western Cape on the south western seaboard experiences a maximum in February. The maximums of these three provinces have traditionally been identified as the peak of the two main fire seasons. Other provinces such as the North-West province, Free State, Gauteng and Eastern Cape experience maximums in September and Northern Cape in November. While these four distinct peaks occur in the conventional fire seasons, it is still important for landowners and decision makers to take note of the months in which fire activity is at a maximum in their respective provinces so as to ensure the correct timing of resources, and to ensure the efficient provision of resources and infrastructure.

3.4.2.2 Annual Trends in Provincial Fire Activity

As previously stated all provinces with the exception of Mpumalanga display a stable or increasing trend in fire activity between 2003 and 2013. As seen in Figure 3.1, Mpumalanga has displayed a high concentration of fire activity over the past ten years despite the decreasing trend and has been identified as the most prone province to fire activity. The decline in Mpumalanga's fire activity since 2008 may be due, in part, to increased awareness of the dangers of fires and the better management and mitigation of fires by local fire protection associations under the Mpumalanga Umbrella Fire Protection Agency.

The Northern Cape Province has experienced the most notable increase in fire activity since 2008. An increase in fire activity in the Northern Cape came as a surprise as the province is largely classified as semi-arid with mainly succulent Karoo vegetation (Dean *et al*., 1995). Provinces surrounding the Northern Cape have also experienced some kind of increase in fire activity over the last 11 years. As noted before a dataset with a time span of 11 years may not be sufficient to draw viable conclusions but these increasing trends do provide relevant questions.

In the early 1950s, Acocks theorised the spread of desertification and land degradation from the south west into the north eastern regions of the country (Meadows and

Hoffman, 2002). Acocks believed that the grasslands of South Africa were under threat of incremental, progressive and irreversible degradation due to the spread of deserts coupled with the impact of human over-utilization of grasslands (Meadows and Hoffman, 2002). Dean *et al*. (1995) stated that the spread of semi-arid vegetation into grasslands could occur along a front or boundary spreading north-east or could occur due to the coalescence of degraded patches. If Acock's theory were true, then the succulent vegetation of the semi-arid Karoo should have invaded the productive grasslands of the north eastern provinces surrounding the Karoo region (namely the Free State and the North West Province). These two provinces, along with the Northern Cape, have however experienced increases in fire activity over the last 11 years. The succulent Karoo vegetation is believed to be less prone to fire than that of grasslands. The spread of semi-arid regions may have resulted in mixed vegetation communities in which both short grasses and the longer Nama Karoo grasses co-exist which may result in higher fuel loads. A recent study, however, indicates that grasslands have encroached into the semi-arid Karoo landscapes (Masubelele *et al*., 2014), which may explain the increased fire activity in the Karoo regions. As stated by Arthurson (2000), increased human settlement in these regions may have led to increased agricultural activity which is known to alter vegetation structures for livestock grazing. Agriculture brings with it too the use of fire as a management tool which may explain the increasing trend. The increases in fire activity may also be brought about by short term variability in climate such as La Niña or El Niño. The spread of semi-arid regions and the effects on fire activity will require further investigation in the future to assess the role of both climate change and human activity on fire activity.

3.5 Conclusions

Fire has always been a natural part of the African continent which has led to the continent being nicknamed the 'fire continent". Fires do provide services to the environment and are an integral part in the maintenance of the environment but increased fire activity, brought about by anthropogenic activity, has led to adverse effects in the environment. Fires can be classified as South Africa's most common hazard and have often lead to disasters resulting in both loss of human and animal life and loss of property. The study undertaken has provided an insight into the spatial and temporal distribution of fires in the country over the past 11 years and results indicate that the eastern and north eastern regions are most prone to fires. Fire totals appear to be stabilising despite increased fire activity in certain provinces. The role of climate change and short term climate variability has been analysed, and increased air temperatures and events like La Niña have a marked effect on fire activity. In order for fire disasters to be mitigated, landowners and decision makers need to ensure an efficient and effective allocation of resources and manpower to limit the spread of fires and to ensure that fire as a management tool does not result in adverse effects on the environment and society. The results provided in the study make it possible to identify high risk areas. In order for the country to be resilient against fire disasters, we need to better understand the spatial and temporal characteristics of our fire seasons. This study has made way for further investigation into the spatio-temporal characteristics of South African fires.

CHAPTER 4: QUANTIFYING THE EFFECTS OF BERG WINDS ON FIRE DANGER AND THE DEVELOPMENT OF A NEAR REAL-TIME LOWVELD FIRE DANGER INDEX MEASUREMENT SYSTEM

Abstract

Wild fires have been identified as the most frequent disaster, both natural and anthropogenic, to plague South Africa on an annual basis. Increased fire activity can result in adverse effects on the environment. High numbers of human fatalities and large financial loss are also a direct result of fire disasters. Reducing the fatality rate and financial loss brought on by wildfires served as the main motivation for this study. A current issue with the mitigation of wildfires is the lack of proper real-time monitoring and measurement systems which can aid decision makers in the timing of controlled burns. This study included the development of a system for improved monitoring of meteorological conditions conducive to fire. The traditionally used nomogram and lookup table used by Lowveld fire danger index (LFDI) system was replaced by mathematical functions. Near real-time results of the measured LFDI were displayed in a web-based teaching, learning and research system found at:
http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Fire%20danger%20index.
Warm, dry mountain winds, known as Berg winds, have a direct link to fire weather, enhancing the danger of uncontrollable fires. Berg winds are associated with periods of increased air temperature, decreased relative humidity and increased wind speeds, thus increasing the potential for the development and spread of wildfires. An additional aim of the study was to quantify the effects of Berg winds on the microclimate and fire danger. For this purpose historic hourly meteorological data, both local and international, were used together with a fuzzy logic system for determining Berg wind conditions making use of diurnal sinusoidal functions for solar irradiance, air temperature, relative humidity wind speed for various locations.. An additional wind direction measurement was included in the model. Application of the system demonstrated that out of four sites in the KwaZulu-Natal Midlands, South Africa, Baynesfield was the most vulnerable to Berg wind occurrences, followed by Ukulinga (near Pietermaritzburg) and lastly, at a higher altitude, Cedara. Boulder, WY, USA, experienced Berg winds more frequently than Sidney, MT, USA.

KEYWORDS: Lowveld FDI, fire meteorology, fuzzy logic, Berg winds, near real-time monitoring, KwaZulu-Natal midlands, USA, mitigation and monitoring

4.1 Introduction

4.1.1 Fire as a Management Tool in South Africa

Agricultural productivity provides a significant portion of South Africa's gross domestic product but with this intensive agricultural practice arises an increased likelihood of wild fires and fire disasters. According to the Fire Protection Association of South Africa, a large percentage of reported fires occur due to open flames during burning activities associated with agriculture. Fire has always been an important phenomenon in the natural environment and has for decades been utilized as a management tool by the agricultural sector in what is known as 'prescribed burning' which, ironically, is often used to burn fire breaks as a preventative measure against the uncontrollable spread of wildfires (Hodgkinson *et al*., 1984). Hodgkinson *et al*. (1984) describes prescribed burning as the purposeful ignition of vegetation with measures taken to control the spread of the fire with the aim of managing certain components of the land surface.

Prescribed burning plays a crucial role in agricultural management. Hodgkinson *et al*. (1984) noted that prescribed burnings are useful in the control of woody plants and the enhancement of plant growth. According to Fynn *et al*. (2004), prescribed burning promotes the dispersal of seeds from certain fruit species as well as the germination of hard seeds. Removal of ground litter can also increase the amount of solar radiation available to plants and may result in increased soil temperatures. Prescribed burning may increase grass species diversity and also suppress encroachment of alien invasive species in pastoral grasslands (Fynn *et al.*, 2004; Oluwole *et al.*, 2008). Concerning livestock production, prescribed burning is believed to decrease the population of disease-borne vectors such as ticks.

4.1.2 The Lowveld Fire Danger Index

Currently in South Africa, the National Veld and Forest Fire Act (Act 101 of 1998) specifies the prevention of veld, forest and mountain fires through a National Fire Danger Rating System under the responsibility of the Department of Water Affairs and Forestry. A significant portion of fire prevention lies in the monitoring and forecasting of meteorological conditions conducive to the development and spread of fires. Fire danger indices or meters are used internationally to monitor the conditions conducive to fire development and spread. The South African

Weather Service and other interested and affected parties currently use the Lowveld Fire Danger Index as the fire danger index of choice.

The Lowveld fire danger index currently being used is an adaptation of the Zimbabwean 'Fire Hazard Index' which was initially developed in the late 1960s by Michael Laing (Willis *et al*., 2001). The Lowveld FDI is similar to the McArthur Fire Danger Meters, developed in Australia, in that the same meteorological variables are taken into consideration when calculating the fire risk. The Lowveld fire danger index is so named as it has been extensively used in the Lowveld region of South Africa and, historically, has been calibrated to that region of the country (Willis *et al*., 2001).

The Lowveld fire danger index utilizes basic meteorological data to calculate fire danger values. Air temperature and relative humidity are used to calculate a 'Burning Index'. Wind speed is then used to adjust the Burning Index upwards. The adjusted Burning Index is then multiplied by a 'Rainfall Correction Factor' which considers the number of days since the last rainfall event as well as the total rainfall measured during the last event (Willis *et al*., 2001). Calculating the fire danger index has, traditionally, been a manual exercise in which the Burning Index is calculated with the use of a nomogram and adjustment for wind speed and the rainfall correction factor with the use of look-up tables.

4.1.3 The National Fire Danger Rating System

According to Willis *et al*. (2001), the National Forest and Fire Laws Amendment Bill (B-99) requires a national fire danger index to account for both topography and vegetation when calculating the risk of wildfire development. Topography and vegetation observations are frequently used to model fire behaviour characteristics such as forward rates of spread and flame heights. The Lowveld fire danger index currently being utilized in South Africa does not comply with the National Forest and Fire Laws Amendment Bill (B-99) as it does not take into account topography or vegetation observations and does not allow for the modelling of fire behaviour.

An additional limitation of the Lowveld fire danger index is lack of an ignition factor or ignition risk. Fire danger indices such as the U.S. national fire danger rating system (NFDRS) account for ignition risks such as lightning and human sources of ignition. Archibald *et al*. (2009) state that lightning frequency during the South African fire season plays little role in the ignition of fires. Archibald *et al*. (2009) note however that the proportion of lightning-caused fires increases in drier and less populated areas of the country. Furthermore, Archibald *et al*. (2009) state that lightning in South Africa is mostly experienced in association with precipitation during the summer rainfall season. Lightning during the summer months is thought to have a minimal effect on igniting wildfires due to the accompanied precipitation as well as the increased levels of fuel moisture. However, two scenarios are likely to result in increased ignition risk due to lightning activity.

South Africa's central and eastern regions commonly experience thunderstorms during the summer months, when fuel moisture is high and precipitation is common, as stated by Archibald *et al*. (2009). While thunderstorms often result in precipitation, positive lightning (lightning which originates from the anvil region of a storm which does not travel through the storm clouds but rather outside when grounding) may result in the ignition of fuels ahead of the storm where no precipitation has occurred. According to Vavrek *et al*. (undated), lightning has been observed to travel large horizontal distances, with a record of 190 km being observed in the Dallas-Fort Worth area of Texas, U.S.A. While lightning has the ability to travel large horizontal distances, moist fuels during the rainfall seasons may decrease the risk of ignition due to lightning. Deep convective thunderstorm that results in lightning are not limited to summer months. Convection brought on by steep lapse rates due to colder air temperatures in the midlevel of the atmosphere have the ability to result in severe thunderstorms during winter months. Westerly wave troughs and cut-off lows can advect colder air masses through the midlevel of the troposphere resulting in steep lapse rates (Tyson and Preston-Whyte, 2000). According to Gill (2009), the highest lightning ground flash densities are experienced in the northern Drakensberg with the majority of positive lightning occurring during the winter months. June 23rd of 2012 provides an excellent case study of severe winter convection. On the 23rd of June 2012 the Free State province experienced a number of supercell thunderstorms, with tornadoes reported in the town of Bethlehem (Frantz, 2012). The point being made is that lightning producing weather is not limited to summer months. Lightning, associated with severe convection, can and has been documented during winter months. If lightning is experienced during winter months, when fuels may be extremely dry (in the summer rainfall regions of the country), then it is important to account for lightning as an ignition risk, particularly when considering the large horizontal distances that positive lightning can travel.

4.1.4 Humans as a Source of Ignition

According to Archibald *et al*. (2009), increased population densities result in increased urban fire numbers. Furthermore, Archibald *et al*. (2009) state that human sources of ignition are more common in privately or communally owned land compared to commercially used land where fire is managed strictly. Again, other fire danger indices such as the US NFDRS attempt to account for the risk of ignition due to human error. While Archibald *et al*. (2009) consider population density and land tenure as a driver of ignition, South Africa experiences what may be a unique experience of an old phenomenon – arson. While other countries do experience arson, arson in the South African context is not limited to structures such as houses or vehicles. Fire is often used in the agriculture and forestry sector as a revenge tool. Farm workers, when in disagreement with land owners, deliberately set fire to grazing land and plantations in an act of revenge as was the case in early 2013 when farm worker strikes resulted in the burning of vineyards in the Western Cape (Davis, 2013).

The psychology of arsonists has been studied extensively but no study has been found that investigates the use of arson as a revenge tool in the agricultural sector of South Africa. The concept of revenge as a motivational factor in arson has also been studied among convicted arsonists in countries such as the United States of America and Great Britain, but the tools used to develop the psychology of "African arsonists' is highly biased and may not account for cultural differences. According to Labree *et al*. (2010), the motivation for acts of arson are highly diverse with revenge being the most important motivator. Canter and Fritzon (1998) also note the importance of revenge as a motivation for arson. The study by Labree *et al.* (2010) on convicted arsonists provides a number of insights into the psychology of arsonists. According to Labree *et al*. (2010), male arsonists are more likely to have undergone previous psychiatric treatment and display higher levels of alcohol or substance abuse. The results presented by Labree *et al*. (2010) may be biased towards 'European' cultures, a problem that is inherent in most psychological studies, and may not be applicable to the South African context. Labree *et al*. (2010) did however find that arsonists have less control over their impulses which may be relevant in the South African context in which revenge is the driving factor behind arson in the agricultural sector.

4.1.5 Motivation for the Study

Fire disasters have been shown to result in high numbers of human fatalities and extreme loss of property and money. The main motivation of the study is to provide a means to reduce or mitigate the loss of human life and property brought about by fire disasters. While Lowveld fire danger monitoring systems are in place, few provide for the near real-time monitoring of fire danger. Most current systems operate on a daily basis using modelled data rather than actual meteorological data. The proposed system will operate at hourly intervals using meteorological data recorded in near real-time. Additionally, little research has been done to quantify the effects of Berg winds on fire danger as was done in this study. It is hoped that by quantifying the effects of Berg winds on fire danger and by providing a near real-time monitoring system, that mitigation efforts may be improved to reduce the number of fatalities and loss of property.

4.2 Materials and Methods

4.2.1 Materials

4.2.1.1 Datalogger

A CR1000 datalogger (Campbell Scientific Inc., Logan, Utah, USA), was utilized to control the data collection process. The CR1000 is a battery operated datalogger with an operating range between -25 and 50 ^{o}C. The CR1000 has an internal memory of 4 Mbyte as well as a real-time external clock. The datalogger allows for the connection of eight differential channels and two pulse channels. The datalogger is powered by an internal sealed battery that can be connected to a solar panel or other charging source (Campbell Scientific Inc., 2004). For the research project all datalogger batteries were charged by solar panels. The dataloggers are also compatible with communication links. For the study situated on the UKZN Pietermaritzburg campus (South Africa) the datalogger was set to a propriety address protocol with a baud rate of 38400 which allowed for the reliable transfer of data via a RF416 radio communication link. A multiplexer was attached to the CR1000 to expand the number of ports available for sensor connection.

4.2.1.2 Solar Radiation

A Kipp and Zonen CM3 pyranometer (Kipp and Zonen B.V., Delft, The Netherlands) was utilized to measure solar irradiance. The CM3 uses a copper-constantan multi-junction thermopile to detect solar radiation and was positioned to measure incoming or reflected solar radiation. The CM3 has a spectral range between roughly 300 and 2800 nm with a sensitivity of 10 to 35 $\mu V/W\ m^{-2}$. The optimal operating temperature ranges from -40 to 80^{o}C.

4.2.1.3 Air Temperature and Relative Humidity

A Campbell Vaisala CS500 (Vaisala Oyj, Helsinki, Finland) was used to measure air temperature and relative humidity. The CS500 probe contains a platinum resistance temperature detector and a Vaisala relative humidity sensor. The temperature sensor has an optimal range between -40 and 60 ^{o}C and the relative humidity sensor has an accuracy of ± 3% RH between 10 and 90% RH at 20 ^{o}C and ± 6% RH between 90 and 100% RH at 20 ^{o}C.

4.2.1.4 Wind Speed and Direction

This study made use of a R.M. Young Model 03001 wind speed and direction sensor (R.M. Young Company, Traverse City, Michigan, US). The sensor, consisting of a 3-cup anemometer, has a measurement range of up to 100 m s^{-1}. The sensor has an accuracy of ± 0.5 m s^{-1}. Wind direction is measured using a balanced Gill vane which has a 360^{o} range.

4.2.1.5 Rainfall

A Pronamic Rain-O-Matic rain gauge was set up to collect rainfall data. The Pronamic rain gauge utilizes a tipping spoon/bucket mechanism to measure cumulative rainfall. A funnel channels precipitation down into a tipping spoon held in place by a magnet. The magnet's tension allows for the spoon to empty when full and return to its original position. Each tip is recorded as a specific amount of rainfall, usually 1 mm. The rain gauge has a resolution of 1 mm but a model with a resolution of 0.254 mm can be purchased.

4.2.2 Methods

4.2.2.1 Near Real-Time Fire Danger Index Data

Meteorological data were collected at the UKZN Agrometeorology Instrumentation Mast (AIM) site (29^{o} 37' 39.72" S and 30^{o} 24' 09" E, 684 masl) situated on the Science and Agriculture campus in Pietermaritzburg (Savage *et al.*, 2014). The site consists of two main meteorological masts with sensors attached to the mast and other sensors placed around the mast. Additional stations are setup around the two main masts. The main AWS mast, at a height of 8 m, is used for data collection and information display on a web based teaching and learning site. The second mast is used for staff and student research projects. Dataloggers are powered using solar panels. The site is set up at a distance from surrounding buildings and trees, fenced off, and, in general well maintained to comply with the World Meteorological Organisation standards for meteorological sites.

4.2.2.2 Historical Berg Wind Data

Four locations across the KwaZulu-Natal Midlands were selected for the study with historical data for three of the sites obtained from the Agricultural Research Council. Historical data obtained through the UKZN AIM system were also used. Table 4.1 below summarises the relevant details of each study site. The four South African sites range in altitude with Cedara situated the highest above sea level at 1130 m and UKZN being the lowest above sea level at 684 m while the 2 USA datasets range from 613 m (Sidney) to 2165 m (Boulder). All datasets have varying durations with Sidney, MT being the longest.

4.2.2.3 Near Real-Time Fire Danger Index Data

Data were measured by relevant sensors attached to the two masts at the meteorological site. Mast 1 housed the CR1000 datalogger and other sensors used such as the CS500 air temperature and relative humidity sensor and the R.M. Young wind speed and direction sensor. Mast 2 consists of test sensors and check sensors to ensure that the sensors on mast 1 are operating correctly. The two masts' dataloggers are connected via an underground cable with each datalogger having its own propriety address protocol with a baud rate of 38400 for the transfer of data. Data were received every ten minutes via radio communication and selected data were then displayed on the UKZN agrometeorology research and teaching webpage at http://agromet.ukzn.ac.za:5355. All sensors were routinely checked and calibrated if necessary.

The CR1000 datalogger was programmed using Shortcut 9.2 software as well as Loggernet software. The program creates commands which operate various sensors. For the study, the datalogger was programmed to measure variables at a scan rate of 15 seconds and output two tables: an hourly and daily table. The sensors discussed previously were set to measure their specific variables at 15 seconds with the datalogger recording the hourly averages, daily averages, maximum and minimum of the day or in cases such as for relative humidity recordings, the hourly sample, and the daily, maximum and minimum sample. The

Table 4.1: Historical dataset collection locations

Location	Co-ordinates (DMS)	Altitude (m)	Duration of Dataset
UKZN AIM (Pietermaritzburg)	29° 37' 39.72" S , 29° 24' 09" E	684	May 2011 - present
Cedara Agricultural College	29° 31' 60" S , 30° 16' 00" E	1130	September 2002 - May 2010
Baynesfield Estate	29° 46' 00" S , 30° 21' 00" E	758	April 2008 - May 2010
Ukulinga (UKZN Research Station)	29° 40" 09.72" S , 30° 24' 44.24" E	810	January 2001 - May 2010
Boulder, WY, USA	42° 43' 07" N , 109° 45' 11" W	2165	January 2005 - January 2014
Sidney, MT, USA	47° 30' 00" N , 104° 19' 48" W	613	January 2004 - January 2014

number of days since last rainfall and the daily cumulative rainfall total as recorded by the datalogger.

The AIM system was the basis for the hourly FDI calculations. As stated previously the AWS used to calculate and measure FDI had a programmed logger scan rate of 15 seconds and measurements were averaged, sampled or totalled hourly. Measurements included solar irradiance, air temperature, relative humidity, wind speed, wind direction, rainfall and atmospheric pressure. Most measurements were conducted at 2 m above the ground except for rainfall where the rim of the rain gauge was maintained at 1 m above the ground (Strydom and Savage, 2013).

The Lowveld fire danger index (FDI) is based on a nomogram which is utilized to convert air temperature and relative humidity to a burning index (BI). The BI is then adjusted for wind speeds using a lookup table (BIPWS). The BIPWS is always greater than the BI as it is applied only when speed is greater than 2.3 m s^{-1}. The FDI is then calculated using the BIPWS and a rainfall correction factor (RCF). The RCF takes into account the number of elapsed days since last rainfall and the daily total rainfall. The BIPWS is multiplied by the RCF which ranges between 0.5 and 1. The nomogram for BI was converted into an equation using multi-linear regression analysis and the lookup table was replaced by datalogger code eliminating the need for manual calculation of the BI and FDI and allowing for it to be programmed into a near real-time monitoring system (Strydom and Savage, 2013).

4.2.2.4 Berg Wind Data

A fuzzy logic system utilizing diurnal sinusoidal functions for solar irradiance, air temperature, relative humidity and wind speed as well as information on wind direction and atmospheric pressure, was developed to determine conditions characteristic of Berg winds. The sinusoidal functions were centred at noon and used defined values to generate a typical diurnal variation in solar irradiance for Berg wind conditions. Co-sinusoidal functions were used, also centred at noon with a defined value to generate a diurnal curve for RH and wind speeds associated with Berg wind conditions (Strydom and Savage, 2013). The defined values at 13:00 SAST were 25% and 1.5 m s^{-1} respectively. A diurnal curve for air temperature was based on the Parton and Logan (1981) model for variations in air temperature. A maximum air temperature of 27 ^{o}C was defined for noon. For wind direction, only directions between westerly (270^{o}) and north-easterly (45^{o}) were considered as applicable for Berg wind conditions. The fuzzy logic system was applied to historic hourly weather data from four locations in KwaZulu-Natal

(Pietermaritzburg, Ukulinga, Cedara and Baynesfield) (Strydom and Savage, 2013), as well as two locations in the USA (Sidney, MT and Boulder, WY).

4.2.2.5 Analysing Collected Data

Historical hourly datasets were obtained from research stations at Baynesfield, Cedara and the UKZN meteorological site. Near real-time AWS data were also used to "nowcast" Berg wind conditions. This involved using a fuzzy logic system using sinusoidal functions for solar irradiance, air temperature, wind speeds and relative humidity. Further information on the wind direction and the atmospheric pressure was used. This system was applied to the historic hourly data from the aforementioned sites. Various statistical methods were applied to the historical datasets to identify temporal patterns of Berg wind events and fire danger events.

Simple statistics were used to identify the site most vulnerable to Berg wind conditions and thus fire danger. Statistics were also applied to identify the months in which Berg winds are more prevalent. Analysis of micrometeorological conditions prior to and during Berg wind events allowed for the development of a microclimatology of Berg wind events. This was also used to identify microclimates conducive to fire events. Fluxes within the microclimate were investigated to identify ranges at which severe fire danger events can be possible. Near real-time data was analysed to identify diurnal changes in fire danger. Meteorological variables during severe fire danger periods were identified.

4.3 Results

4.3.1 Fuzzy Logic System for Identifying Periods of Berg Winds

4.3.1.1 Most Vulnerable Sites

The fuzzy logic system, developed to identify Berg wind conditions, was applied to historic meteorological data (hourly) obtained from different locations in KwaZulu-Natal and the USA (Table 4.1). The analysis of the historical data indicated that the Baynesfield and Ukulinga sites experienced a higher frequency of Berg wind hours compared to the UKZN AIM (Pietermaritzburg) and Cedara locations. Cedara experienced the lowest temperature conditions required for an event to be classified as a Berg wind event with 1.51 % but had the greatest percentage of high wind speed conditions. Ukulinga had the greatest number of favourable wind direction events (between west (270^{o}) and north-east (45^{o})) with 43% which is a greater percentage than that of Baynesfield (34%) and Cedara (29%). Results of the two international sites indicate that Boulder, Wyoming experiences Berg wind events similar to those recorded at Baynesfield. Sidney, MT, does experience a number of Berg wind events (1.07%) but due to increased relative humidity conditions is not as prone to Berg winds as Boulder, despite the difference in altitude.

Taking into account the data presented in Table 4.2, both Ukulinga and Baynesfield can be identified as the most vulnerable in the KwaZulu-Natal Midlands for fire disasters due to higher frequencies of Berg wind hours. While the Baynesfield site does have a higher percentage of Berg wind hours compared to the Ukulinga site, the Ukulinga site remains vulnerable due to the higher percentage of suitable wind directions. The Cedara site remains the least vulnerable due to reduced significant percentage of winds flowing between 270° and 45° and a lower incidence of high air temperatures despite the high percentage of suitable wind speeds. The data recorded at the USA locations compare well to the South African locations, despite being situated at higher latitudes, and in the case of Boulder, WY, at a higher altitude which should result in different microclimates to those of the South African sites.

Table 4.2: The results of the fuzzy logic system for identifying hourly Berg wind conditions for various locations in KwaZulu-Natal and the USA.

UKZN AIM system	**May 2011 - present**		**Baynesfield Estate**	**April 2008 to May 2010**	
	Duration (h)	**% of Time**		**Duration (h)**	**% of Time**
Berg wind	239	1.57	Berg wind	290	1.91
Air temperature ≥ 30	473	3.12	Air temperature ≥30	385	2.53
Wind speed > 1.5 m s^{-1}	5294	34.88	Wind speed > 1.5 m s^{-1}	6406	42.13
Wind direction ≥ 270 and ≤ 45	3764	24.80	Wind direction ≥ 270 and ≤ 45	5144	33.83
RH ≤ 25	649	4.28	RH <= 25	627	4.12
Record length	15178		Record length	15205	
Record length (days)	632.416		Record length (days)	633.541	
Cedara Agricultural College	**Sept 2002 - May 2010**		**Ukulinga, Pietermaritzburg**	**Jan 2001 - May 2010**	
	Duration (h)	**% of Time**		**Duration (h)**	**% of Time**
Berg wind	403	0.79	Berg wind	1415	1.74
Air temperature ≥ 30	769	1.51	Air temperature ≥ 30	1380	1.69
Wind speed > 1.5 m s^{-1}	27707	54.50	Wind speed > 1.5 m s^{-1}	18870	23.16
Wind direction ≥ 270 and ≤ 45	14860	29.23	Wind direction ≥ 270 and ≤ 45	35385	43.42
RH ≤ 25	2639	5.19	RH ≤ 25	32120	39.42
Record length	50838		Record length	81490	
Record length (days)	2118.25		Record length (days)	3395.416	
Boulder, WY, USA	**Jan 2005 - Jan 2014**		**Sidney, MT, USA**	**Jan 2004 - Jan 2014**	
	Duration (h)	**% of Time**		**Duration (h)**	**% of Time**
Berg wind	1536	1.75	Berg wind	939	1.07
Air temperature ≥ 30	2379	2.71	Air temperature ≥ 30	1958	2.23
Wind speed > 1.5 m s^{-1}	36324	41.35	Wind speed > 1.5 m s^{-1}	67258	76.57
Wind direction ≥ 225 and ≤ 0	42613	48.51	Wind direction ≥ 225 and ≤ 0	37112	42.25
RH ≤ 25	10801	12.30	RH ≤ 25	3036	3.46
Record length	87840		Record length	87840	
Record length (days)	3660		Record length (days)	3660	

In order to identify which months are more prone to significant Berg wind days, monthly averages were calculated. This involved identifying the number of significant Berg wind days per month for each of the years in the locations' respective datasets. The number of significant Berg wind days per month was then averaged by the number of years in each dataset. The results (Figure 4.1) indicate that all local locations, except Cedara, experience the highest number of significant Berg wind days in August and September. Cedara's most vulnerable month is July. Boulder, WY and Sidney, MT experienced the highest significant Berg wind days in the months of July and August. Throughout the various datasets only August and September had significant Berg wind days across all four locations. For the study a significant Berg wind event was defined as an event when Berg wind conditions persisted for three or more hours consecutively.

4.3.1.2 Meteorological Conditions Experienced During Berg Wind Events

The historical meteorological data were analysed to identify significant Berg wind events throughout the datasets of the four locations. For this study a significant Berg wind event was defined as any event meeting the predetermined conditions for at least three hours during a day. The significant days were listed and the meteorological conditions prior to and during the Berg wind events were analysed (Table 4.3). The ranges of conditions were averaged to allow for comparison.

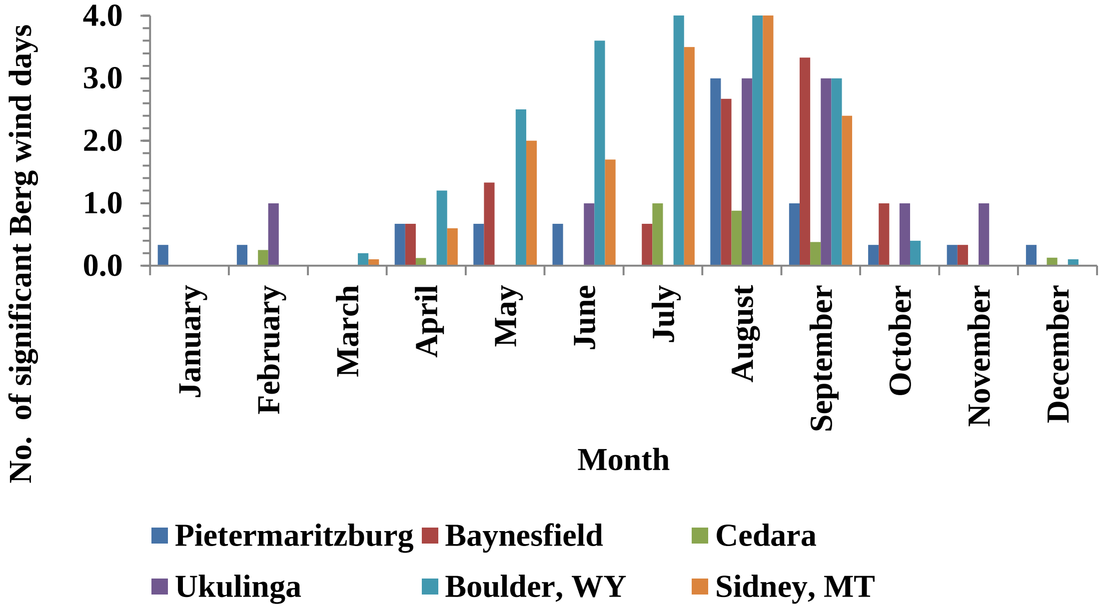


Figure 4.1: The average number of significant Berg wind days per month for the four local and two US locations.

Table 4.3: Ranges of conditions prior to, and during Berg wind events. Results have been averaged for comparison for the recorded data available.

	TAir Before	TAir During	RH Before	RH During	Wind Speed Before	Wind Speed During	FDI Before	FDI During
Pietermaritzburg	26.44	31.46	27.45	15.96	1.39	2.42	48.75	55.62
Cedara	23.19	29.44	33.05	13.97	2.99	4.61	52.93	61.33
Ukulinga	24.39	30.11	28.76	13.90	1.64	2.46	50.99	57.49
Baynesfield	22.82	29.10	34.15	16.37	1.39	2.72	48.48	56.38

Table 4.3 illustrates how conditions change once a Berg wind begins. Important variables such as air temperature, relative humidity, and wind speed as well as fire danger are shown. As indicated by Table 4.3, conditions become warmer, drier and windy during a Berg wind event. While certain events may result in only a small change the average changes are high. Table 4.3 also reaffirms what is previously stated - that is, the most vulnerable sites are Baynesfield and Ukulinga. While the average changes may not seem notable, the significant events from each location that display the significance of Berg winds in changing the microclimate need to be identified.

4.3.1.3 Significant Change During Berg Wind Events

A specific Berg wind event was chosen from each of the four locations that display significant changes in microclimatic conditions at and during the onset of a Berg wind event. The Berg wind day was chosen based on the level of change that occurred as a result of the Berg wind. While each event does display impressive changes, it is important to note that not all Berg winds that have occurred or may occur at a site will result in such significant changes. The reason for this section is to highlight the potential effect sudden Berg winds can have on a location's weather conditions.

4.3.1.4 Air Temperature Changes

Figure 4.2 illustrates the changes in air temperature on four different Berg wind days across the four locations. Locations are differentiated by the different labelled curves. Figure 4.2a runs for an entire day (24 hours). The beginning of the Berg wind event for each location can be easily identified as the air temperature begins to increase drastically. All four sites experience rapid increases in air temperature with the maximum air temperatures occurring around noon or mid-afternoon. The skewing of the curve to the right indicates that Berg winds may result in higher temperatures prevailing into the afternoon and in certain cases into the evening, depending on the duration of the Berg wind event. Of each specific Berg wind day, Baynesfield experiences the highest air temperatures.

4.3.1.5 Relative Humidity Changes

Relative humidity is notable as it is the only variable that should consistently decrease during the onset of a Berg wind. Figure 4.2b illustrates the changes in relative humidity throughout a Berg wind day for the four locations. As with air temperature, relative humidity undergoes a significant change throughout a Berg wind event. A decrease in relative humidity is evident at the start of all four Berg wind events. In rare cases relative humidity values may increase during the Berg wind event although these increases are short lived and do not exceed the threshold of what constitutes a Berg wind. Figure 4.2b illustrates that the lowest relative humidity values occur around midday on a significant Berg wind day, just as the highest air temperature does. With the exception of Baynesfield, the low relative humidity does not extend into the early evening hours but tends to increase in the mid-afternoon with a decrease in air temperature.

Relative humidity across the four locations does not follow a common trend as air temperature does. Topographic variations at each location may be responsible for variations in relative humidity trends after sunset with each location having a varying relative humidity trend around the 21:00 mark with Ukulinga and Pietermaritzburg experiencing a continuous decrease in relative humidity. Cedara and Baynesfield experience an increase.

4.3.1.6 Wind Speed Changes

Wind speed can be highly variable during a normal day but wind speeds during a Berg wind event tend to display an overall increasing trend. As illustrated in Figure 4.2c all four locations experienced increased wind speeds in the early hours of the morning only to decrease again during early morning before increasing again in the mid-morning, continuing to increase to the maximum wind speeds around noon. During a Berg wind event it is common for the wind speeds to remain high for the duration of the event before decreasing during the mid-afternoon. The wind speeds at Ukulinga for its selected day may not seem impressive, with a maximum around 2.5 m s^{-1}, but as displayed in Figure 4.2c a rapid increase in wind speed is experienced at Ukulinga at the onset of the Berg wind. Figure 4.2c is confirmation that Cedara is vulnerable to fire disasters due to the prevalence of high wind speeds conducive to the rapid spread of fires. It is important to note the initial increases in wind speeds as the Berg wind event begins. At the height of the Berg wind event wind speed changes are gradual but remain high and do still pose a risk. The onset of the Berg wind event poses the greatest risk for fires becoming uncontrolled as wind speeds increase dramatically. Fire danger remains high throughout the Berg wind event.

4.3.1.7 Fire Danger Changes

None of the four locations was equipped to measure fire danger in near real-time. Recent additions to the AIM system have allowed for the near real-time measurement of fire danger. A computational model of the Lowveld fire danger index was applied to all four historical datasets. Based on the Lowveld fire danger index, fire danger is dependent on high air temperatures, low relative humidity and strong winds blowing between 270^{o} and 45^{o}. Fire danger is not dependent on Berg wind conditions but will escalate during periods of Berg wind conditions.

Figure 4.2d illustrates the calculated fire danger across all four sites on their respective days. Of note is the fact that the fire danger curves are similar in shape to that of the air temperature curves suggesting a strong relationship between fire danger and air temperature. While the Lowveld fire danger index does not weigh variables against each other, it does have an emphasis on air temperature and relative humidity which may explain the similarities between the two figures' curves. The highest periods of fire danger occur at the times of highest air temperature and lowest relative humidity along with times of high wind speed. Relative humidity's role in fire danger can be seen in the Baynesfield curve of Figure 4.2d in which a sharp decrease in relative humidity at 06:00 causes a significant rise in fire danger before decreasing as relative humidity increases. As with the other variables, fire danger peaks around midday for all locations.

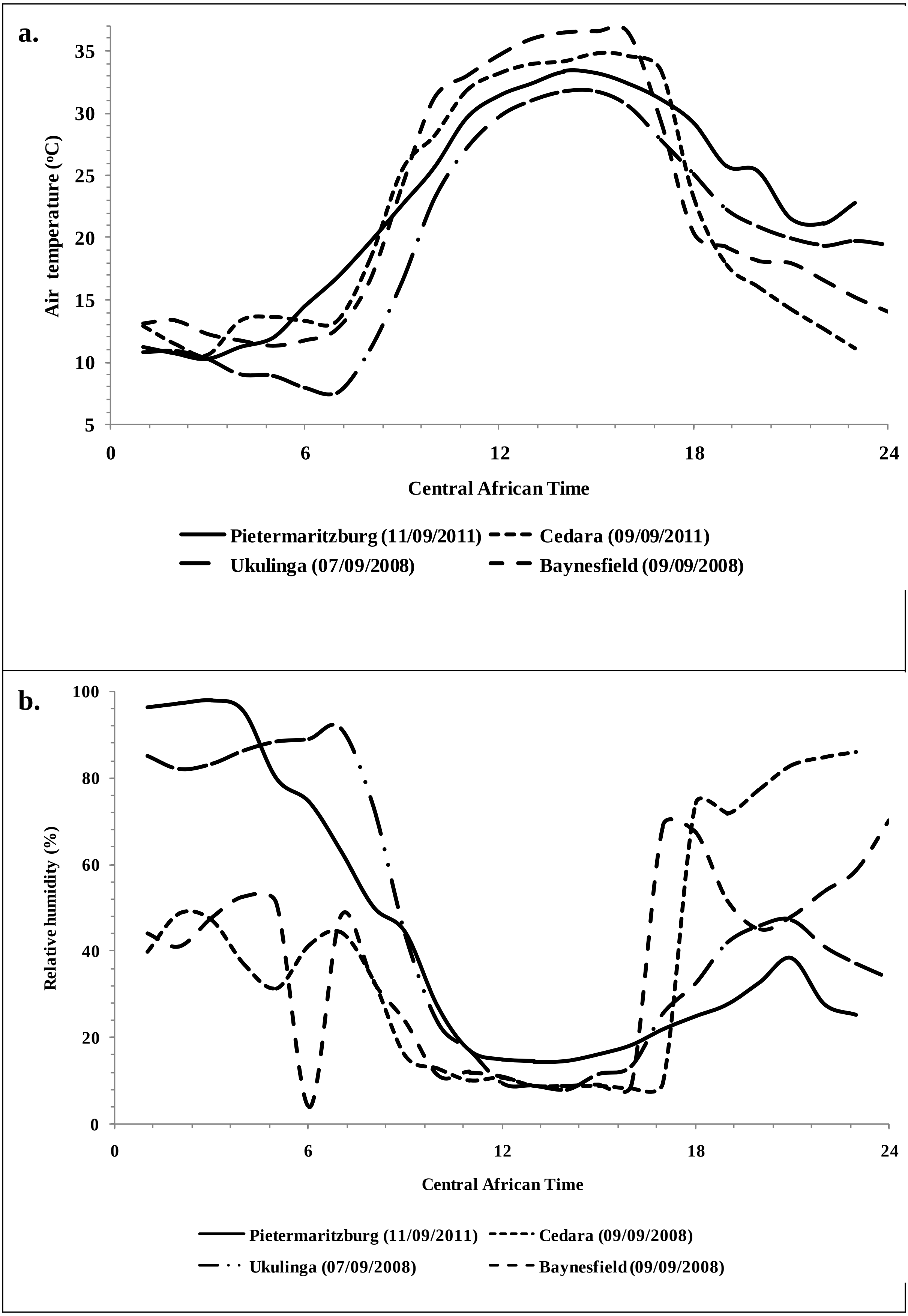


Figure 4.2: Changes in meteorological conditions during Berg wind events for a. air temperature, b. relative humidity

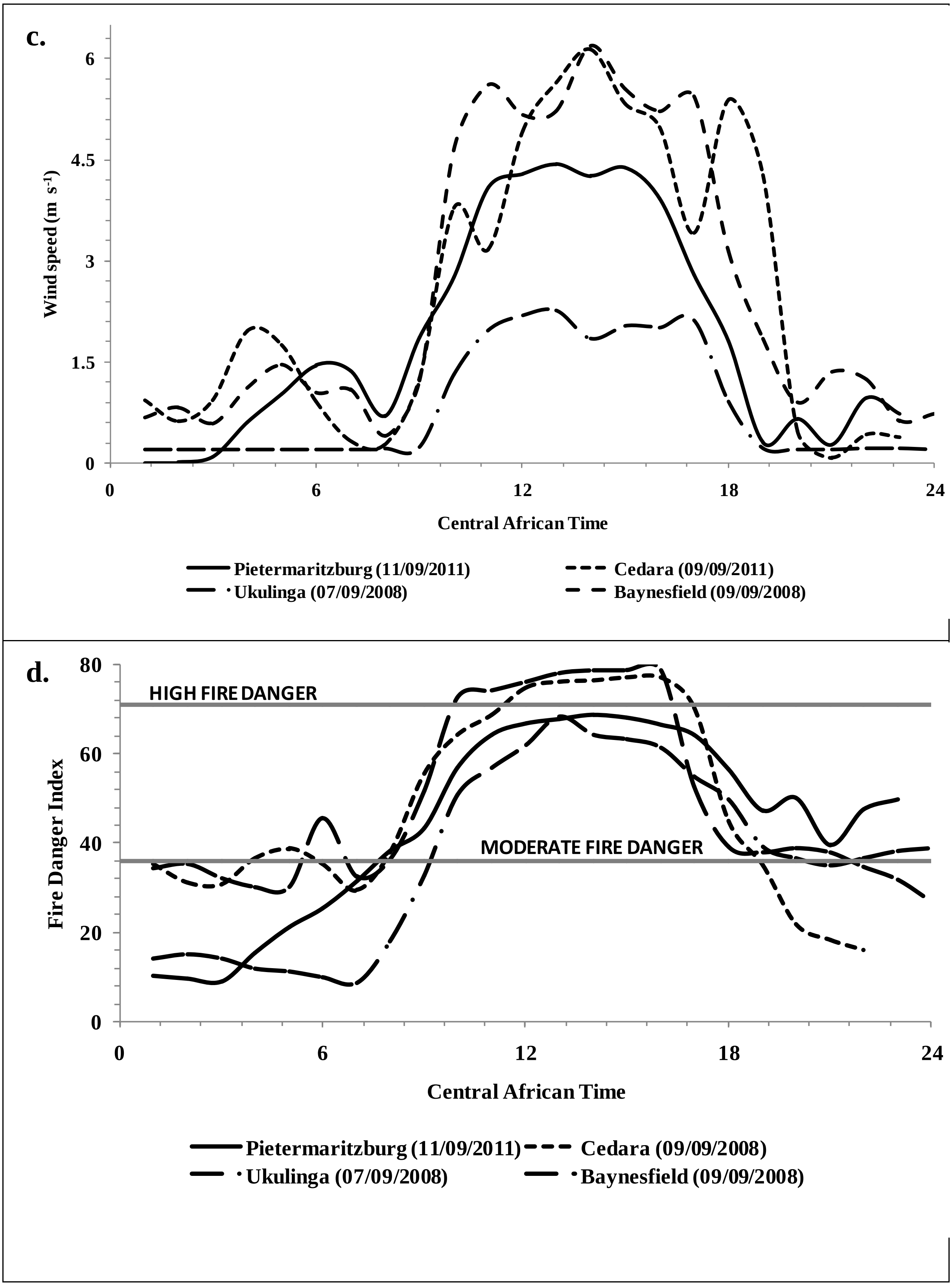


Figure 4.2: Changes in meteorological conditions during Berg wind events for c. wind speed and d. fire danger index.

4.3.2 Near Real-time Lowveld Fire Danger Index Monitoring System

4.3.2.1 Burning Index and Rainfall Correction Factor Functions

Traditionally the Lowveld fire danger index was calculated using a nomogram and look-up tables rendering the entire process manual. In order for the Lowveld FDI to be programmed into a datalogger both the burning index (BI) and rainfall correction factor (RCF) had to be altered into a mathematical function using multi-linear regression techniques. The original BI nomogram was cross-checked with the multi-linear regression function used to replace the nomogram. Cross-checking the mathematical function BI involved simulating environmental conditions ranging between 5 and 35 ^{o}C with relative humidity ranging between 0 and 55%. The calculated BI value was then compared with a manually calculated value obtained from the nomogram. This process was repeated to get a sizeable dataset. Comparison of the two datasets involved plotting them in a regression graph and applying regression data analysis. The results of the analysis are as follows: slope of 1.012, intercept -0.313 BI units, R^2 = 0.999 (Figure 4.3). The comparison analysis yielded results that were highly satisfactory.

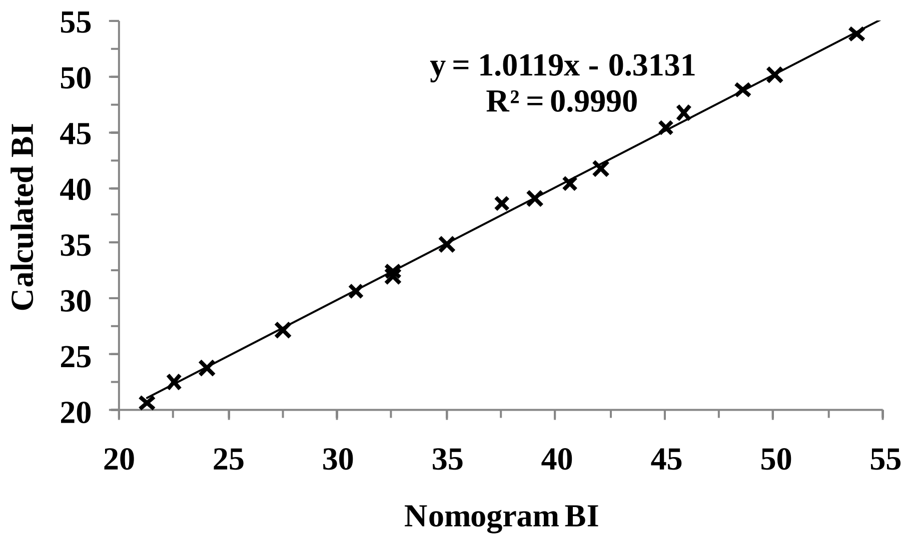


Figure 4.3: Regression plot of the burning index (BI) determined using the nomogram and calculated using a multi-linear regression equation.

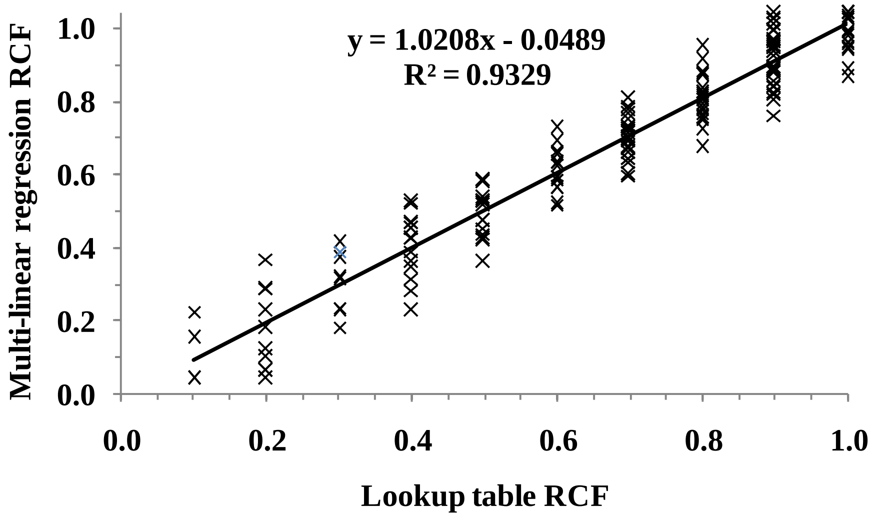


Figure 4.4: Regression plot of the rainfall correction factor (RCF)

Multi-linear regression was again applied to the rainfall correction factor (RCF) lookup table so as to determine a relationship that could be used in near real-time (Figure 4.4). Due to the nature of the RCF lookup table, it is possible to calculate more than one value for a given RCF value in the lookup table and hence different calculated RCF values for the same lookup table RCF value.

4.3.2.2 Near Real-Time Fire Danger Index Platform

Figure 4.5 shows an example of the near real-time display of fire danger index data displayed on the AIM system. The fire danger web screen includes graphics of all relevant variables. The screen also makes use of two FDI graphs - weekly and current day's FDI values. Both graphs include the FDI values as well as the Burning Index adjusted for wind speed (BIPWS) values. Both the weekly graph and the daily graph include the National Fire Danger Rating system thresholds which indicate the category of fire danger ranging from 'Moderate' (FDI between 36 and 70) to 'High' (between 71 and 95) and 'Extreme' (above 95). Data can be obtained from the screen by selecting the tabled hourly values below the daily graph.

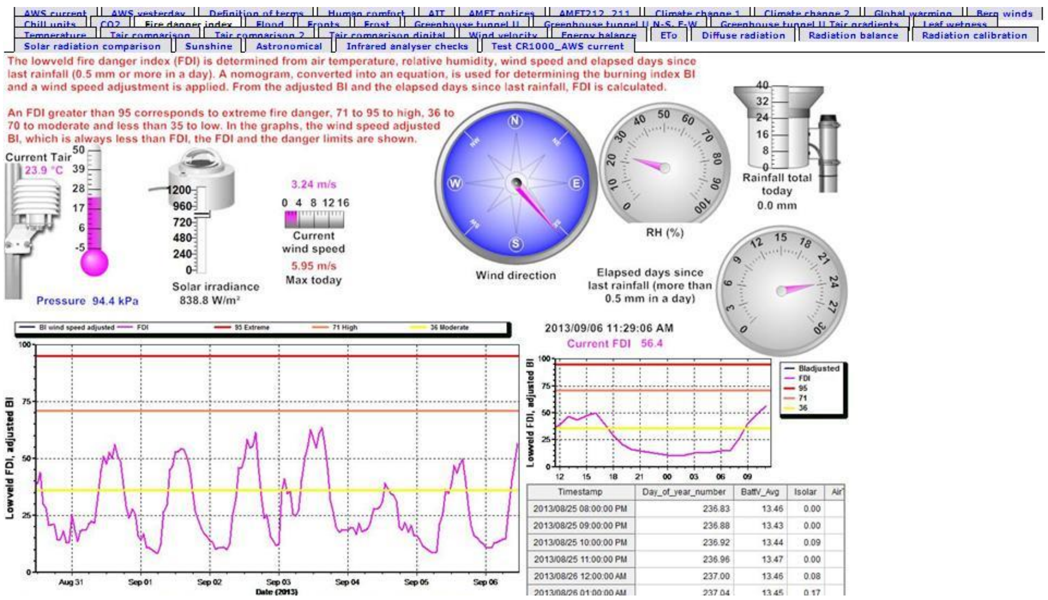


Figure 4.5: Screenshot of the near real-time FDI screen on the AIM system

4.3.2.3 Near Real-Time Fire Danger Data

As the Lowveld fire danger index is mainly based on a location's air temperature, relative humidity, and wind speed along with historical rainfall, analyses focussed on these variables. Additional meteorological variables which are associated with periods of high fire danger were also examined. Figures 4.6 to 4.9 illustrate conditions measured by the UKZN AIM system in Pietermaritzburg beginning on the 24th of August, 2013. A particularly intense cold frontal passage proceeded to pass through the KwaZulu-Natal Midlands, bringing with it the highest FDI values recorded since the initiation of the fire danger index measuring system.

Figure 4.6 illustrates the relationship between air temperature and fire danger. As can be seen periods of high fire danger index coincide with periods of increased air temperatures. As the Lowveld FDI has a burning index component, which takes air temperature into consideration, one would expect to see higher FDI values with higher air temperatures.

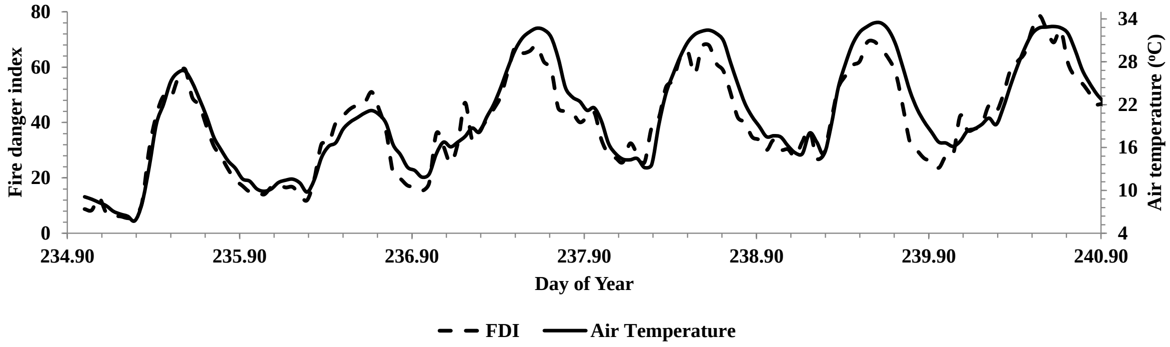


Figure 4.6: Relationship between air temperature and fire danger index for the period 24th to 29th August 2013.

Unlike air temperature, relative humidity does not follow a pattern where distinct periods of low relative humidity coincide with high FDI values (Figure 4.7). Only in certain periods are the lowest relative humidity conditions associated with a peak in fire danger index. Instead it appears as if any general decrease in relative humidity will result in an increase in fire danger index. As the Lowveld FDI takes into consideration the relative humidity of an area one would again expect a decrease in relative humidity to result in an increase in fire danger index although other variables such as wind speed and water vapour pressure may result in lack of associated peaks of fire danger index.

As is the case with air temperature (Figure 4.6), periods of increased wind speed result in periods of increased fire danger (Figure 4.8), with a clear relationship between high wind speeds and high fire danger periods. Peaks in fire danger index during days 236 and 237 which cannot be explained by air temperature or relative humidity can be explained by periods of

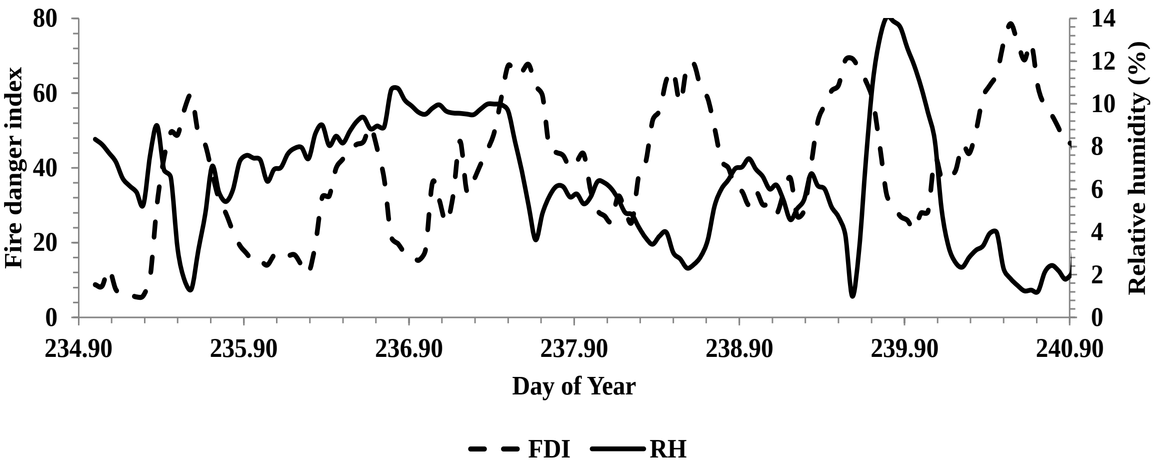


Figure 4.7: Relationship between relative humidity and fire danger index for the period 24th to 29th August 2013.

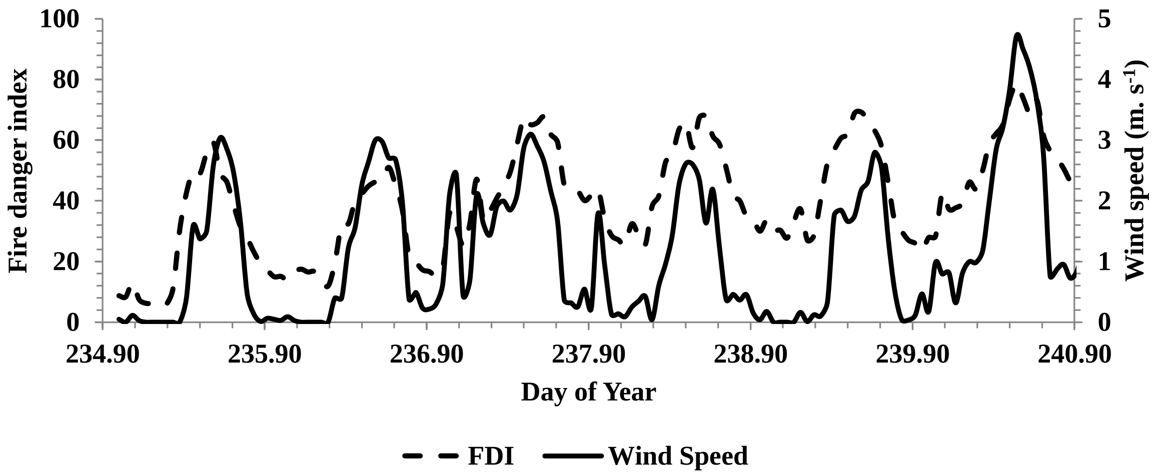


Figure 4.8: Relationship between wind speed and fire danger index for the period 24th to 29th August 2013.

increased wind speeds. These periods experienced sharp peaks of increased wind speed resulting in an increase in fire danger index despite the lack of a significant increase in air temperature or a decrease in relative humidity. Again the Lowveld FDI takes into consideration wind speeds, which are used to adjust the burning index upwards depending on wind speed.

The most notable associated meteorological condition absent from the Lowveld FDI is atmospheric pressure (Figure 4.9). Periods of high fire danger index are often associated with periods of decreasing atmospheric pressure or periods of low atmospheric pressure. In KwaZulu-Natal cold fronts and coastal lows play an important role in the formation of Berg winds. This importance can be seen in periods of high fire danger index.

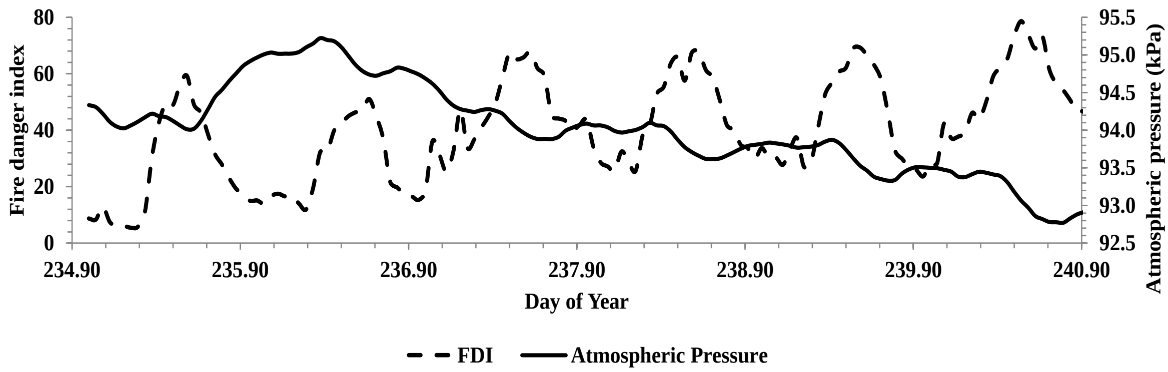


Figure 4.9: Relationship between fire danger index and atmospheric pressure for the period 24th to 29th August 2013

4.4 Discussion

4.4.1 Berg Wind Data

4.4.1.1 Most Vulnerable Sites

It was possible to identify the site most vulnerable to fire disasters by applying simple statistics to all four historical datasets. Data presented in Table 4.2 identified Ukulinga and Baynesfield as being the most vulnerable to fire disasters due to a higher incidence of Berg wind hours along with higher percentage of variables conducive to fires. The fact that Ukulinga displayed a higher prevalence of suitable wind directions, coupled with its high incidence of conducive wind speeds results in it being classified as the most vulnerable site. Due to a lower incidence of suitable wind direction and suitable air temperatures, Cedara was identified as the least vulnerable site. The lower prevalence of suitable air temperatures can be attributed to Cedara's altitudinal location. Cedara's higher altitude moderates air temperatures resulting in a lower annual air temperature average. Similarly, due to altitude, one would expect Boulder, WY to have a lower incidence of air temperatures representative of Berg winds, yet Boulder does have a high incidence of Berg wind hours. Despite the lack of suitable wind direction and suitable air temperatures, Cedara may remain vulnerable due to a high percentage of suitable wind speeds which, when coupled with suitable air temperatures and wind direction, may lead to heightened fire danger. It is believed that the fuzzy logic system for identifying Berg wind conditions can be used internationally, with modifications in the wind direction component of the model, as demonstrated in this study. Topography is a major contributor to a location's Berg wind incidence and should be investigated thoroughly. Katabatic winds and their influence on the microclimate also needs to be investigated to filter out any possible Berg wind false alarms which may be observed due to katabatic winds.

Throughout the four local sites, the months of August and September are the most prone to Berg wind conditions. The exception to this is Cedara, which experiences its highest number of significant Berg wind days during July. The US locations experienced more frequent Berg wind days in July and August. Cold fronts and coastal lows are common features of these months, during the transition from winter to spring and a higher occurrence can lead to an increased number of significant Berg wind days during these months. While August and September have been identified as the most prone to Berg winds, it is important to note that all months experienced significant Berg wind days.

A possible explanation for the high number of fire disasters may be attributed to a decrease in labour capacity. Farmers and other stakeholders who are involved in the use of fire as a management tool as well as the prevention of fire disasters may have limited staff or limited resources during the non-winter months. During the spring and summer months vegetation may be denser. This may lead to fires spreading faster and burning more intensely despite any limitations from summer rains.

4.4.1.2 Meteorological Conditions Experienced During Berg Wind Events

Historical data, analysed by applying the fuzzy logic system indicates that significant Berg winds are not common in Pietermaritzburg and the surrounding KwaZulu-Natal Midlands comprising only a small percentage of data duration hours. Figure 4.1 supports the statement by indicating that the highest average number of significant Berg wind days is less than five days per month in months such as August and September when Berg winds are expected to be more common.

Based on previous studies, Berg winds are expected to increase a location's air temperature, decrease relative humidity, and increase wind speed. Table 4.2 gives an indication of the extent of micrometeorological change during periods of Berg winds. Throughout all four locations air temperature and wind speed increase drastically coupled with a sharp decrease in relative humidity. The maximum changes associated with Berg wind conditions peaks around midday. While the literature provides an explanation for this occurrence, it is believed that this study is the first to actually quantify the phenomena across a larger part of the KwaZulu-Natal Midlands.

The fuzzy logic system of identifying Berg winds is practical for studying temporal changes in conditions associated with Berg winds. A limitation of the fuzzy logic system is that it does not make use of weighted variables. In many cases throughout the historical data, Berg wind periods were not detected due to wind direction being out by only a few degrees. By weighting variables, one allows for slight deviations from the predefined conditions - if wind speed, for example, is high but wind direction is out by a few degrees then it should still be classified as a Berg wind event. Cedara's dataset contained a number of instances where all conditions except wind direction were met. Cases where wind direction indicates onshore flow should not be classified as Berg wind events, but cases where wind direction may be from 260^{o} may still be classified as Berg wind events. Weighting of variables is subjective and should not differ significantly from the predefined conditions associated with Berg wind events.

4.4.1.3 Significant Change During Berg Wind Events

By investigating significant Berg wind events across the four sites it was found that changes in meteorological conditions occur gradually. While the average differences may be high, hourly changes can at times be of such a nature that they would not be perceived by humans. These gradual changes emphasise the need for a near real-time monitoring system. The system would prove vital in the scenario where burning for veld management is being practiced and where changes at the onset of the Berg wind are not noticeable. These slight increases in wind speed, for example, may lead to controlled fires becoming uncontrolled.

It is noticeable in the historical datasets that there are three main types of Berg wind days -firstly the less significant Berg wind days where Berg wind conditions are experienced for less than two hours, secondly a significant Berg wind day where conditions are experienced for more than three hours but rarely over five hours and thirdly, the days where Berg wind conditions are experienced for more than five hours and up to nine hours in some cases in a day. Cedara's dataset was interesting in this respect - while having a fewer number of significant Berg wind days, Berg winds often lasted for more than six hours on days for which they were classified as Berg wind days. Baynesfield on the other hand had a higher occurrence of Berg wind days but for days classified as Berg wind days, the conditions lasted between only three and five hours.

The different scenarios pose an interesting question - which is more of a threat in terms of fire hazards? Berg wind conditions lasting for more than six hours would undoubtedly increase the fire danger but it is believed that on days with a high risk of fire outbreaks, stakeholders will be more prepared and will have staff available to mitigate or combat any fire outbreak. On days where Berg winds blow for a few hours stakeholders may not have staff available and may not be adequately prepared for a fire hazard. Both scenarios are likely to lead to more intense fire hazards but it is believed that in areas where fire awareness and preparation are low (such as in rural communities and rural informal settlements) days with long durations of Berg wind conditions may lead to extreme fire disasters. Berg wind conditions that are more prevalent, but last for fewer hours may not pose a risk in these areas and fire danger will be limited (as the Berg wind hours are not continuous) but may still lead to outbreaks of wildfires.

4.4.2 Near Real-time FDI Data

4.4.2.1 Near Real-Time Fire Danger Index Platform

The AIM web-based system (available at http://agromet.ukzn.ac.za:5355, described by Savage *et al*., 2014) used for near real-time monitoring, early warning and learning provides a number of useful tools. It provides university students and researchers with a means of accessing and visualising data which aids in the understanding of atmospheric processes. The website also provides users with hourly updates of fire danger conditions. Stakeholders, such as farmers and municipal managers involved in vegetation burning practices, are able to monitor conditions in near-real time allowing for some early warning and preparedness. Currently lacking from the website is a predictive function which will allow users to have an idea of possible conditions in the near future. While some subjective forecasting is possible through the system by analysing trends in variables during the morning, a proper predictive function would need to be highly accurate to meet the standards needed for early warning of fires.

The UKZN AIM system can currently send out alerts for predetermined events. Alternatively alert instructions can be included into the datalogger programme which would then email alerts to selected users via a GSM modem. Alerts can be based on changes in air temperature, relative humidity or wind speed. A suitable alert would identify when hourly FDI values increase by 25 and then send out an alert to warn users of the increase in fire danger. An increase of 25 is likely to move fire danger from one danger rating category to the next.

4.4.2.2 Near Real-Time Fire Danger Data

Data collected through the web-based monitoring system indicated that fire danger was generally highest during the late morning and early afternoon which is in agreement with the study by Gaffin (2007) on American foehn wind events. Figures 4.6 and 4.7 indicate that periods of high fire danger are closely related to periods of high air temperature and low relative humidity. The importance of wind speed is also indicated and can be seen by comparing the burning index prior to and after adjustment for wind speed. The burning index adjusted for wind speed (BIPWS) will always be equal or greater than the original burning index (BI). High burning indices with low wind speeds can be just as hazardous as low burning indices with high wind speeds. The complex interaction between air temperature, relative humidity and wind speed again emphasise the importance of a near real-time monitoring system.

A limitation of the Lowveld fire danger index is the rainfall correction factor (RCF). The RCF’s purpose is to take into consideration the amount of soil water available to vegetation. The RCF ranges between 0.5 and 1 and is multiplied by the BIPWS. Prolonged periods without precipitation will result in a RCF of 1. The RCF is used as a proxy to gauge the fuel load and vegetation density. Other fire danger indices such as the McArthur Grassland FDI take into consideration both the fuel load and an ignition risk which is lacking in the Lowveld FDI. Different vegetation communities may have different fuel loads and different ignition risks despite similar rainfall patterns. Ignition risk in South Africa is also a unique situation where fire is used as a revenge tactic by rural communities against farmers and often this type of arson leads to uncontrollable fires.

While air temperature, relative humidity and wind speed are important micrometeorological variables in determining fire danger, certain synoptic features are also associated with periods of high fire danger. Figure 4.9 illustrates the variation of both fire danger and atmospheric pressure in Pietermaritzburg during a week (24th August – 29th August, 2013) leading up to a strong cold front which resulted in floods in the Western Cape along with snowfall on Table Mountain. Snowfalls were also experienced in the Drakensberg and in towns such as Kokstad in KwaZulu-Natal. Peaks in fire danger index, including those explained by high wind speeds coincide with periods of decreasing atmospheric pressure.

Ridging high pressures should theoretically result in calm days, with little or no wind. Despite the lack of a strong wind, fire danger may be increased due to higher than average air temperatures, low relative humidity and prolonged periods of no rainfall. During periods of warm weather associated with high pressure systems, vegetation desiccates more quickly which may enhance fire spread should a fire start. Coastal lows and interior high pressure systems, which have been identified in the literature review as an important component in the establishment of Berg winds and thus high fire danger, can at times result in periods of lower fire danger in the KwaZulu-Natal Midlands.

According to Preston-Whyte and Tyson (2000), it is not uncommon for coastal lows to extend as far as Pietermaritzburg during periods of onshore flow. During such periods fire danger will be moderated due to increased relative humidity and in many cases rainfall. It is thus important to know how synoptic features will influence micrometeorological conditions. Most periods of high fire danger coincide with periods of Berg wind conditions, but can also occur in months where Berg winds are less common.

4.5 Conclusions

Fire disasters result in large financial losses and fatalities every year. A good understanding of conditions conducive to fire danger is integral in improving warning systems. Improved warning systems would aid in reducing damage and limiting loss of life. Mountain wave dynamics and associated mountain winds have been discussed and an investigation into the characteristics of mountain winds was undertaken. In most cases mountain wave activity was dependent on the position and strength of a surface pressure gradient over a mountain range. Strong surface pressure gradients result in air masses being orographically lifted where they cool adiabatically. On reaching the summit peaks of a range the air masses are forced to descend and warm adiabatically. The air masses reach the valley as a warm wind bringing with them increased air temperatures, decreased relative humidity and increased wind speeds. In South Africa a number of synoptic weather events can lead to the development of 'Berg winds'. Common features include a low pressure system along the coastline with an interior high pressure system resulting in surface pressure gradients which flow over the Drakensberg mountain range.

Periods of high fire danger are largely associated with periods of Berg wind activity. To this end, historical data obtained from four different locations in the KwaZulu-Natal Midlands were analysed, using a fuzzy logic system ('if, then' statements) based on diurnal sinusoidal and co-sinusoidal models of relevant variables to identify periods of Berg winds. Analysis of significant Berg wind events indicates that air temperatures across all four locations increase drastically at the onset of Berg winds and at the same time experience a decrease in relative humidity and an increase in wind speed. Two of the four sites (Baynesfield and Ukulinga) were identified as being the most vulnerable to Berg winds and thus fire outbreaks. Historical data also indicated that Berg winds are common in KwaZulu-Natal. August and September were identified as the months most prone to Berg wind activity due to various weather parameters working together e.g., high air temperatures, low relative humidity, above normal wind speeds and wind direction between 270^{o} and 45^{o} as a result of synoptic scale weather systems. Berg winds (known as foehn or chinook winds in the USA) are also prevalent in mountainous regions of the USA as identified by applying the fuzzy logic system to two USA locations in mountainous regions, in states (provinces) known to experience large wildfire disasters.

Fire has played a natural management role in the environment for centuries and despite the incredible social impacts it provides many environmental services, such as seed germination, prevention of alien invasion and nutrient recycling. A number of adverse impacts are also experienced, ranging from adversely impacting on air quality to playing a role in weather modification and climate change to increasing erosion and desertification. The loss of human life and the financial loss served as the main motivation for the research.

Forecasting and monitoring of fire danger in South Africa makes use of the Lowveld Fire Danger Index (FDI) which comprises a nomogram to calculate a burning index (BI) and lookup tables to calculate a rainfall correction factor (RCF) and to adjust the BI for wind speed. The Lowveld FDI system was replaced by multi-linear regression functions which were then programmed into a datalogger. Simulating environmental conditions indicated that the multi-linear regression functions were accurate. Data obtained from the system were displayed on an online web-based platform for learning, teaching and research (http://agromet.ukzn.ac.za:5355).

Data obtained from the system indicated that periods of fire danger peaked around midday and were greatly influenced by air temperature and wind speed and to a lesser extent relative humidity and rainfall. Periods of high fire danger were also observed during periods of decreasing atmospheric pressure. Fire disaster management requires a well-developed near real-time monitoring system. The system described herein provides a platform from which further developments can be made. The system provides a first of its kind open to the general public in South Africa. Further research should focus on developing a system that utilizes remote sensing data such as the Normalized Difference Vegetation Index to feed into the fire danger index. Various other fire danger indices need to be developed into an AWS suitable format to determine the best possible index for South Africa’s varying weather and vegetation zones.

CHAPTER 5: MONITORING FIRE DANGER IN NEAR REAL-TIME USING THE MCARTHUR FIRE DANGER METERS

Abstract

The McArthur Fire Danger Meters (FDM) have been used to monitor and measure fire danger since the 1950s when they were first developed following severe wildfires. The McArthur FDM has traditionally made use of nomograms to calculate grassland and forest fire danger. In the 1980s mathematical descriptions of the McArthur FDM were developed. This allowed for the sub-daily and near real-time measurement of grassland and forest fire danger. While commercial forestry contributes only a small percentage of South Africa's GDP, forest fires have been identified as a common occurrence in commercial forestry plantations and natural forests, which can at times spread to neighbouring grasslands or non-forest vegetation. Forest fire disasters in South Africa are well documented by the mainstream media and it is believed that proper monitoring of forest fire danger, along with grassland fire danger, may mitigate potential wildfire disasters and limit human fatalities and financial loss. The McArthur FDM also provides opportunity to model fire behaviour – a component of wildfire mitigation lacking in the Lowveld fire danger index currently used in South Africa. The study utilized the equations developed to investigate the use of the McArthur FDM in South Africa by applying the equations to historical hourly meteorological data recorded at four locations in the KwaZulu-Natal Midlands, South Africa. Modifications to the McArthur grassland fire danger index (GFDI) were needed and resulted in the development of a method to calculate vegetation curing as a function of micrometeorological variables. Datasets were analysed to investigate seasonal curing at the four locations with results indicating high monthly curing averages in all months. The greatest range of curing averages were experienced in the winter months. Frequency analysis of both the GFDI and the forest fire danger index (FFDI) indicated that lower fire danger ratings are more common than high danger ratings as one would expect. The GFDI and FFDI displayed acceptable sensitivity to changes in the microclimate as observed through conducting sensitivity analysis and by plotting diurnal variations of GFDI and FFDI during Berg wind events. The fire behaviour modelling component of the McArthur FDM did not yield realistic results on steep topography but provided a baseline on fire characteristics on gentler slopes.

KEYWORDS: McArthur, grassland fire danger, forest fire danger, wildfires, fire behaviour, monitoring and mitigation, near real-time measurement, fire meteorology

5.1 Introduction

Australia, as with Africa, experiences a number of fire disasters on an annual basis. A particularly devastating fire disaster in the early 1930s emphasised the need for better management and monitoring of Australian fires (Willis *et al*., 2001). The McArthur Fire Danger Meters (hereafter 'FDM'), commonly referred to as the 'Grassland Fire Danger Index' (hereafter 'GFDI') and the 'Forest Fire Danger Index' (hereafter 'FFDI') were first implemented in the 1950s to improve fire management and monitoring of fire danger. The Lowveld Fire Danger Index (hereafter 'LFDI'), currently used in South Africa is not capable of monitoring forest fire danger and is only suitable for grassland vegetation communities and as such one of the aims of this study was to develop a system, operating in near real-time, that would provide sufficient and accurate measurements of forest fire danger.

5.1.1 Overview of the McArthur Fire Danger Meters

5.1.1.1 The Forest Fire Danger Index

As stated previously, the McArthur FDM was first utilized in Australia to improve fire management and fire danger monitoring in forests (Willis *et al*., 2001; Sharples *et al.*, 2009). The FFDI has been further developed and modified to the current Mk IV version in use today. The FFDI categorizes fire danger into five danger ratings ranging from 'Low' to 'Extreme' fire danger. Inputs of the FFDI include air temperature, relative humidity, wind speed and rainfall data as well as the Keetch-Byram Drought Index (KBDI) which requires inputs of daily maximum air temperature, daily rainfall and the average annual precipitation for the specified location (Keetch and Byram, 1968; Willis *et al*., 2001).Sharples *et al*. (2009) state that the McArthur fire danger meters are based on over 800 observations, albeit unpublished.

5.1.1.2 The Grassland Fire Danger Index

The McArthur GFDI was first developed after the development of the FFDI and is relatively similar in design and operation to the FFDI (Willis *et al*., 2001). The GFDI requires inputs of air temperature, relative humidity, wind speed and rainfall as well as some estimate of vegetation curing to calculate the fire danger level. As with the FFDI, fire danger is categorized into different classes ranging from 'Low' to 'Extreme' (Willis *et al*., 2001). Recent modifications of the Mk IV GFDI have been made to include a measure of fuel availability (fuel load) but it is noted that the inclusion of fuel load does not significantly change the output fire danger rating and as such little use is made of the new Mk V GFDI. While the LFDI does provide accurate measurement of grassland fire danger, it fails to consider certain inputs such as the level of vegetation curing. It is felt that due to the lack of consideration of certain inputs the GFDI is more suitable than the LFDI for monitoring grassland fire danger in South Africa and thus the proposed near real-time measurement system will include the McArthur GFDI.

5.1.1.3 Fire Behaviour Modelling Components

An added benefit of utilizing the McArthur FDM is the option of modelling fire behaviour along with the standard fire danger rating measurements. The McArthur fire behaviour modelling components allow for the calculation of rates of fire spread, spotting distances, flame heights as well as heat and energy components of a fire. The modelling components rely on inputs of fire danger values, topography and fuel loads to calculate the aforementioned fire characteristics (Willis *et al*., 2001). According to Willis *et al.* (2001) some confusion exists concerning the differences between ‘fire danger’ and ‘fire behaviour’. Tolhurst (2010) defines fire danger as the combination of constant and variable factors that influence the ignition, spread and controllability of a fire. Constant factors may include topography and fuel loads while variable factors refer to meteorological factors. Tolhurst (2010) notes that while certain fire danger rating systems do take into account non-meteorological factors, many assume that these non-meteorological factors are constant and do not change significantly to affect fire danger.

5.1.2. Forestry in South Africa

Agriculture and forestry are among those sectors most affected by wildfires. The Lowveld FDI currently implemented in South Africa has been noted for only being suitable for grassland wild fire danger monitoring resulting in minimal monitoring of fire danger in the forestry sector. Grazing - the use of grasslands for agricultural livestock consumption - makes up roughly 68% of South Africa’s land use compared to forestry that contributes only 1% of total land use in the country (Godsmark, 2010). While forestry may not be as spatially intensive as grazing lands, forest fires do still pose a threat to the sector which contributed to R6705 million of the 2009 GDP. Mpumalanga and KwaZulu-Natal have been identified as the top two provinces when considering annual fire totals. In these provinces, forestry accounts for roughly 6% of the total provincial area (Godsmark, 2010). It is important to note that the analysis of South African forestry done by Godsmark (2010) only considers commercial forestry and as such does not include natural forests.

<u>5.1.2.1 South Africa Forest Fire Case Studies</u>

Godsmark (2010) indicates that plantation loss due to fires has increased significantly between the 1980 and 2009 ranging from roughly 7500 ha in 1980 to roughly 70 000 ha due to fires in 2009. The significant increase in losses due to fires may indicate an increasing risk of forestry losses due to fires. The 2008 fire season resulted in one of the worst forest fire disasters the country has ever faced, with media referring to the wildfires as 'forestry's own 9/11' (Gordin, 2008). Wildfires spread through many timber plantations in the provinces of the Western Cape, KwaZulu-Natal and Mpumalanga. In a single week 'forestry's own 9/11' resulted in the destruction of 84 000 ha of timber, a significant increase from the country's 25-year average loss of 14 000 hectares per year due to fires (Gordin, 2008). Of all the fires recorded in plantations during 2009, 5.9% of those fires have unknown causes whereas arson, accidental and natural fires contribute to 17.9, 22.4 and 3.7% respectively leading to a total loss of 19 805 ha (Godsmark, 2010).

5.1.3 Forest Fires and Climate Change

The effects of climate change on forest fires (and wildfires in general) have been well theorized. Most climate scientists agree that the earth's average air temperature is rising. This increase in average air temperatures is likely to increase the risk of forest fires (Dale *et al.*, 2000; Flannigan *et al.*, 2000). Forest fires can also be seen as a positive feedback mechanism for further global warming. As air temperatures rise vegetation desiccates more rapidly, providing more dead and dry fuel for forest fires. Forest fires then release stored carbon when forest biomass is burned (Harmon, 2009). While the burning of biomass associated with forests may lead to increased carbon emissions, Flannigan *et al*. (2000) note that a quarter of atmospheric CO_2 concentrations can be linked to deforestation and not forest fires. It is important to remember that a fire is the result of a number of interactions between topography, weather conditions, ignition risks and fuel loads, and that an increase in air temperature does not guarantee increased fire activity (Flannigan *et al.*, 2000) although no one would argue against taking precautions to increased fire activity.

5.1.4 The Need for an Alternative Fire Danger Index and Motivation for the Study

South Africa's National Forest and Fire Laws Amendment Bill (B-99) requires a national fire danger index to account for both topography and vegetation when calculating the risk of wildfire development (Willis *et al.*, 2001). Topography and vegetation observations are frequently used to model fire behaviour characteristics such as forward rates of spread and flame heights and are considered as constant factors affecting fire danger (Tolhurst, 2010). The Lowveld fire danger index currently being utilized in South Africa does not comply with the National Forest and Fire Laws Amendment Bill (B-99) as it does not take into account topography or vegetation observations and does not allow for the modelling of fire behaviour. It is believed that by using the McArthur FDM, fire disaster mitigation may be improved. Consider the scenario where a wildfire occurs on a mountain with sufficient vegetation to result in a fast moving wildfire. By using the Lowveld FDI the fire danger of the particular mountainous area may be considerably lower, leading to ill-prepared mitigation practices or fire fighting capabilities. By using the McArthur FDM, disaster managers or land owners would have a better insight into how the topography and the vegetation properties of the mountain may increase the risk of a fire becoming uncontrollable. A recent example of the scenario occurred in the Overberg area of the Western Cape on the 25th September 2014 when a lightning-induced fire occurred on the upper slopes of a mountain range leading to severe wildfires which local fire and disaster managers battled to extinguish (Sesant, 2014). Had proper fire danger and fire behaviour monitoring been in place, the risk of wildfires spreading may have been reduced.

5.2 Materials and Methods

5.2.1 Materials

The study utilized datasets of historical hourly meteorological data obtained from the Agricultural Research Council for three locations in the KwaZulu-Natal Midlands namely Cedara, Ukulinga and Baynesfield. In addition to the datasets obtained from the ARC, historical hourly meteorological data collected by the Agrometeorological Instrumentation Masts (AIM) on the Pietermaritzburg campus of the University of KwaZulu-Natal were used. The materials discussed in this section were only used in the collection of the AIM dataset.

5.2.1.1 Datalogger

A CR1000 datalogger (Campbell Scientific Inc., Logan, UT, USA), was utilized to control the data collection process. The CR1000 is a battery operated datalogger with an operating range between -25 and 50 ^{o}C. The CR1000 has an internal memory of 4 Mbyte as well as a real time clock. The datalogger allows for the connection of eight differential channels and two pulse channels. This study made use of a multiplexer attached to the CR1000 to expand the number of channels available for sensor connection. The datalogger is powered by an internal sealed battery that can be connected to a solar panel or other charging source. For this study, batteries were charged by solar panels. The dataloggers are also compatible with communication links. For the study, the datalogger was set to a propriety address protocol with a baud rate of 38400 which allowed for the reliable transfer of data via a radio communication link to a nearby computer server connected to the internet.

5.2.1.2 Solar Radiation

A Kipp and Zonen CM3 pyranometer (Kipp and Zonen B.V., Delft, The Netherlands) was utilized to measure solar irradiance. The CM3 uses a copper-constantan multi-junction thermopile to detect solar radiation and was positioned to measure incoming solar irradiance. The CM3 has a spectral range between roughly 300 and 2800 nm with a sensitivity of 10 to 35 $\mu V/W\ m^{-2}$. The optimal operating temperature ranges from -40 to 80 ^{o}C.

5.2.1.3 Air Temperature and Relative Humidity

A Campbell Vaisala CS500 (VaisalaOyj, Helsinki, Finland) was used to measure air temperature and relative humidity. The CS500 probe contains a platinum resistance temperature detector and a Vaisala relative humidity sensor. The temperature sensor has an optimal range between -40 and 60 ^{o}C and the relative humidity sensor has an accuracy of ± 3% RH between 10 and 90% RH at 20 ^{o}C and ± 6% RH between 90 and 100% RH at 20 ^{o}C.

5.2.1.4 Wind Speed and Direction

This study utilized a R.M. Young Model 03001 wind speed and direction sensor (R.M. Young Company, Traverse City, Michigan, USA). The sensor, consisting of a 3-cup anemometer, has a measurement range of up to 100 $m\ s^{-1}$. The sensor has a sensitivity of ± 0.5 $m\ s^{-1}$. Wind direction is measured using a balanced Gill vane which has a 360^{o} range.

5.2.1.5 Rainfall

A Pronamic Rain-O-Matic rain gauge was utilized to record rainfall events. The Pronamic rain gauge utilizes a tipping spoon/bucket mechanism to measure rainfall. A funnel channels precipitation down into a tipping spoon held in place by a magnet. The magnet's tension allows for the spoon to empty when full and return to its original position. The rain gauge has a resolution of 0.254 mm but a model with a resolution of 0.2 mm can be purchased.

5.2.2 Methods

5.2.2.1 Data Collection Sites

A total of four sites across the KwaZulu-Natal Midlands were selected for the study with data for three of the sites provided by the Agricultural Research Council. The UKZN AIM data was collected as part of a web-based teaching, learning and research system at UKZN (available at http://agromet.ukzn.ac.za:5355 described by Savage *et al*., 2014). Table 5.1 provides the relevant information of each site. The sites are well spread throughout the KwaZulu-Natal Midlands and varying altitudes allow for a wide range of microclimates. The four sites range in altitude with Cedara situated the highest above sea level at 1130 m and UKZN being the lowest above sea level at 684 m. The four datasets have varying durations with Ukulinga being the longest (Table 5.1).

5.2.2.2 The UKZN AIM System

The UKZN Agrometeorological Instrumentation Mast (AIM) was first developed in 2011 as a tool for the near real-time display of micrometeorological information for teaching, learning and research purposes. It has since then been further developed and now consists of a total of five stations. The main mast comprises a 3-m mast extended to 8 m by a pole used onto which sensors have been attached (Savage *et al*., 2014). Data is communicated via a radio link to an in-house server which publishes data and information onto a web-based system. A second mast acts as a backup system and houses sensors used for postgraduate and staff research (Savage *et al*., 2014). Mast 1 acts as a base station with dataloggers at other stations 'piggy-backed' to transfer data to the base station datalogger which then transmits data via an antenna to a receiver on the roof of a nearby building. This study utilizes data collected at Mast 1 of the AIM system.

5.2.2.3 Equations Describing the McArthur Fire Danger Meters

As discussed previously the McArthur fire danger meters have traditionally been calculated using nomograms. In 1980 Noble *et al*. (1980) provided the first set of equations describing the McArthur fire danger meters. These equations, and others were used in the study.

Table 5.1: Historical datasets locations and relevant details

Location	Co-Ordinates (DMS)	Altitude (m)	Duration of Dataset
UKZN AIM (Pietermaritzburg)	29° 37' 39.72" S , 29° 24' 09" E	684	May 2011 - Present
Cedara Agricultural College	29° 31' 60" S , 30° 16' 00" E	1130	September 2002 - May 2010
Baynesfield Estate	29° 46' 00" S , 30° 21' 00" E	758	April 2008 - May 2010
Ukulinga (UKZN Research Station)	29° 40' 09.72" S , 30° 24' 44.24" E	810	January 2001 -May 2010

The McArthur Grassland Fire Danger Index was developed for use in the pasturelands of New South Wales, Australia (Noble *et al*., 1980). Further modifications to the GFDI resulted in a number of versions or “Marks” in use today. As the aim of the study was to measure grassland fire danger in near real-time, the Mark 3 version was selected as it does not require any fuel load input. The Mark 3 grassland fire danger index is described by Noble *et al*. (1980) as:

$$GFDI = 2.0 \times EXP(-23.6 + 5.01 \times LN(C) + 0.0281 \times T - 0.226 \times \sqrt{H} + 0.633 \times \sqrt{V}) \quad \textbf{(5.1)}$$

where *GFDI* is the grassland fire danger index, *C* is curing (%), *T* air temperature (^{o}C), *H* relative humidity (%) and *V* wind speed at 10 m (km h^{-1}). As seen in Eq. 5.1, the McArthur GFDI considers traditional micrometeorological variables with the addition of a curing function (*C*) as well as wind speed at 10 m in km h^{-1} (*V*). No method for measuring curing using AWS technologies exists; as such, a method had to be developed. The Mark 5 version of the GFDI allows for the calculation of fuel moisture content (%) described by Noble *et al*. (1980) as:

$$M = (97.7 + 4.06 \times H)/(T + 6.0) - (0.00854 \times H + 3000.0)/C - 30 \quad \textbf{(5.2)}$$

where *M* is fuel moisture (%). Finding a suitable alternative fuel moisture index (measured in percent), and changing the subject of Eq. 5.2 to *C* made it possible to calculate curing using only micrometeorological variables. An investigation of existing fuel moisture content measurement methods determined that the Vinney (1990) method for calculating fuel moisture to be the most suitable. The equation for calculating fuel moisture using Vinney (1990) is described by Sharples *et al*. (2009) as:

$$M = 5.658 + 0.04651 \times H + 3.151 \times 10^{-4} \times H^{3} \times T^{-1} - 0.1854 \times T^{0.77} \quad \textbf{(5.3)}$$

Vinney’s (1990) method for calculating fuel moisture was identified as the most suitable for two reasons. Firstly it only requires inputs of micrometeorological variables and secondly it provided a wide range of fuel moisture content values when tested against real hourly meteorological data. Using Eq. 5.3 as a substitute for *M* described in Eq. 5.2 and by changing the subject of Eq. 5.2 to *C* resulted in curing being calculated using the equation which yielded satisfactory results when applied to real hourly meteorological data:

$$C = (3000.0 \times (T + 6))/(M + 30 + 0.00854 \times (T + 6.0) - 97.7 - 4.06 \times H) \quad \textbf{(5.4)}$$

The McArthur Forest Fire Danger Index was initially developed for use in Eucalypt forests of Australia (Noble *et al*., 1980). As with the GFDI, the FFDI has undergone numerous modifications. This study utilized the Mark 5 version of the McArthur FFDI described by Noble *et al*. (1980) and Willis *et al*. (2001). The forest fire danger index (*FFDI*) used by Noble *et al.* (1980) is given as:

$$FFDI = 1.25 \times D \times EXP(((T - H)/30) + 0.0234 \times V) \tag{5.5}$$

where *D* is the drought factor, *T* air temperature (^{o}C), *H* relative humidity (%) and *V* wind speed at 10 m (km h^{-1}). Apart from the traditional micrometeorological variables required as inputs, the FFDI also requires a drought factor consideration. The drought factor (*D*) is described by Noble *et al*. (1980) as:

$$D = (0.191 \times (KBDI + 104) \times (N + 1)^{1.5})/(3.52 \times (N + 1)^{1.5} + P - 1) \tag{5.6}$$

where *KBDI* is the Keetch-Byram Drought Index (mm equivalents), *N* time since last rainfall (days) and *P* rainfall (mm). Noble *et al*. (1980) do not provide any equations for the calculation of the Keetch-Byram Drought Index (KBDI). The KBDI is described by Willis *et al*. (2001) as:

$$KBDI = Max\ [(OLDDI - EFFRAIN) + DQ, 0] \tag{5.7}$$

where *KBDI* is the Keetch-Byram Drought Index (mm equivalents), *OLDDI* previous days *KBDI*, *EFFRAIN* effective rainfall (mm) and *DQ* the drought factor. The calculation of the *KBDI* requires a number of other calculations to be done prior to the calculation of *KBDI* such as *EFFRAIN* and *DQ*. Willis *et al*. (2001) describe *EFFRAIN* as:

$$EFFRAIN = Max\ [(P - 5.08), 0] \tag{5.8}$$

where *EFFRAIN* is the effective rainfall (mm) and *P* the rainfall (mm). The value of 5.08 mm is considered a threshold for interception capacity, that is to say, only once rainfall exceeds 5.08 mm will any precipitation reach the forest floor. The equation for calculating the drought factor is described by Willis *et al*. (2001) as:

$$DQ = ((203.2 - OLDDI) \times (0.986 \times EXP(0.0875 \times TMax + 1.5552) - 8.30))/(1 + 10.88 \times EXP(-0.001736 \times RainPA))\ /1000 \tag{5.9}$$

where *DQ* is the drought factor, *TMax* the maximum air temperature (^{o}C), *RainPA* the annual rainfall for the site (mm).

5.2.2.4 Analysis of Historical Data

All analyses of the acquired data was done using the Microsoft Office Excel software package (2010 version). The sensitivity analysis of the McArthur GFDI was done by applying Equation 5.1 to a predetermined set of data which included variables of air temperature, relative humidity, wind speed and curing. By keeping 3 out of the 4 variables constant and changing the remaining variable by a realistic factor allowed for regression plots to be graphed in Excel with the variable on the x-axis and the resulting GFDI on the y-axis. The sensitivity analysis of vegetation curing was conducted by keeping air temperature, relative humidity and wind speed constant while increasing the curing value by a factor of 5%. With air temperature - the curing, wind speed and relative humidity were kept constant while air temperature was increased by a factor of 5 ^{o}C. The same procedure was followed for wind speed and relative humidity with decreases in relative humidity of 5% and increases in wind speed of 5 km h^{-1} selected.

Frequency analysis of the McArthur grassland fire danger index was conducted using historical hourly meteorological data from the four locations previously discussed. The analysis required processing the datasets to exclude missing data. In Microsoft Excel the Histogram function found in the Data Analysis toolpak was used to count the number of hours experienced for selected fire danger rating ranges. The same process was followed for the forest fire danger index with the exception that only recent hourly meteorological data collected by the AIM system were used.

The fire behaviour modelling component of the McArthur fire danger meters allows one to model a wide range of fire characteristics. For this study, only two characteristics-forward rate of spread and spotting distance were selected for investigation as was believed that these two characteristics prove to be the most dangerous when fighting wildfires. Modelling of fire behaviour utilized a similar process to that of the frequency analysis discussed earlier. The equation to calculate the Forward Rate of Spread in km h^{-1} (FROS) is described by Willis *et al*. (2001) as

$$FROS = 0.0012 \times FDI \times FUEL \times EXP(0.069 \times \Theta) \qquad \textbf{(5.10)}$$

where *FDI* is the forest fire danger index, *FUEL* the fuel load (t ha^{-1}) and ϴ the angle of the land surface slope (degrees) from the horizontal. Graphs illustrating the forward rates of spread were plotted for selected slopes. Keeping ϴ and *FUEL* constant while increasing the *FDI* values yielded graphs illustrating the forward rate of spread for the fuel load as a function of fire danger. Each forward rate of spread graph illustrates the *FROS* for different fuel loads as a function of *FDI* and Θ.

The equation for spotting distance in km (*SPOT*) is described by Willis *et al*. (2001) as

$$SPOT = FROS \times (4.17 - 0.033 * FUEL) - 0.36 \quad \textbf{(5.11)}$$

The same principle as used to model the forward rate of spread was used to model the spotting distance with graphs illustrating spotting distances for various fuel loads as a function of *FDI* and Θ.

5.3 Results

5.3.1 McArthur Grassland Fire Danger Index

5.3.1.1 Sensitivity of the McArthur Fire Danger Index to Changes in the Microclimate

As the McArthur Grassland Fire Danger Index (GFDI) has never been operationally used in South Africa, little is known on how the different components of the index may influence the overall fire danger rating. A preliminary sensitivity analysis was conducted to assess the magnitude of change brought about by changes in the microclimate. The sensitivity analysis was also utilized to assess the role of vegetation curing on the index as no method of calculating or measuring vegetation curing automatic weather station technologies was known to exist. Figure 5.1 a – c illustrates the sensitivity to changes in the microclimate considered in the McArthur GFDI. From Figure 5.1, it was observed that air temperature and wind speed have near linear influences on the GFDI with relative humidity and degrees of curing having more exponential or power relationships with the GFDI. The increased level of change in the GFDI due to changes in curing indicated the need to develop a method for representing curing using automatic weather station technologies.

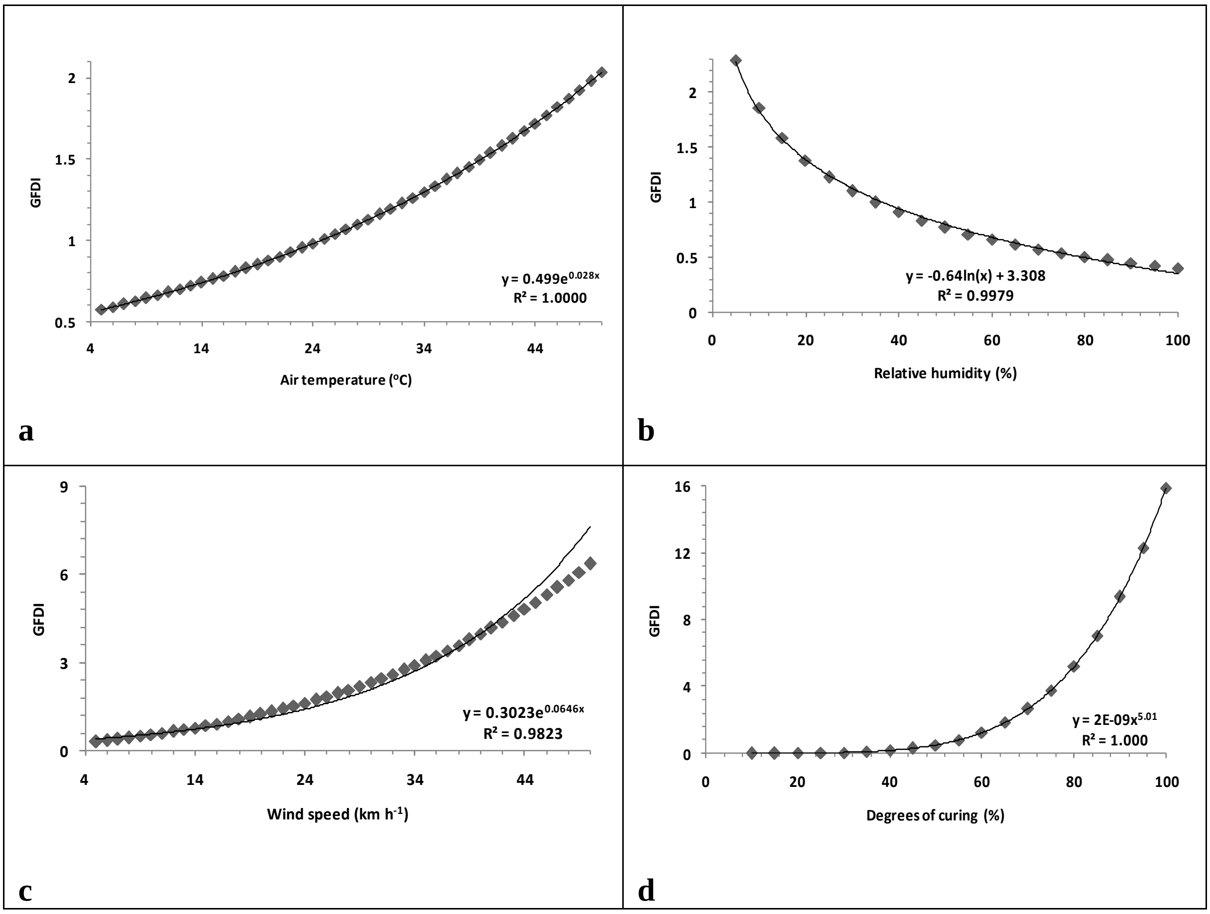


Figure 5.1: Sensitivity of the McArthur Fire Danger to changes in a. air temperature, b. relative humidity, c. wind speed and d. degrees of curing.

5.3.1.2 The Relationship between Fuel Moisture Content and Curing

One of the challenges to the study involved developing an accurate method for measuring or calculating vegetation curing using automatic weather station technologies. Traditional methods for measuring vegetation curing require the collection of vegetation samples which are weighed upon collection, oven dried and then re-weighed to assess fuel moisture. Less quantitative methods include assessing vegetation curing visually based on a level of greenness. As the aim of the study was to develop a near real-time McArthur FDI measurement system, both the traditional and visual methods of assessing curing were unsuitable for use in an automatic weather station system. Modifying the equation for fuel moisture provided by Noble *et al*. (1980) made it possible to calculate curing using microclimate factors as well as a fuel moisture content index. The method for determining fuel moisture developed by Vinney (1990) was selected for the study as it provided the greatest range of values ranging from 1% to 100%. Figure 5.2 illustrates the relationship between fuel moisture content and degrees of curing. As one would expect, increases in fuel moisture result in decreases of vegetation curing and *vice versa*.

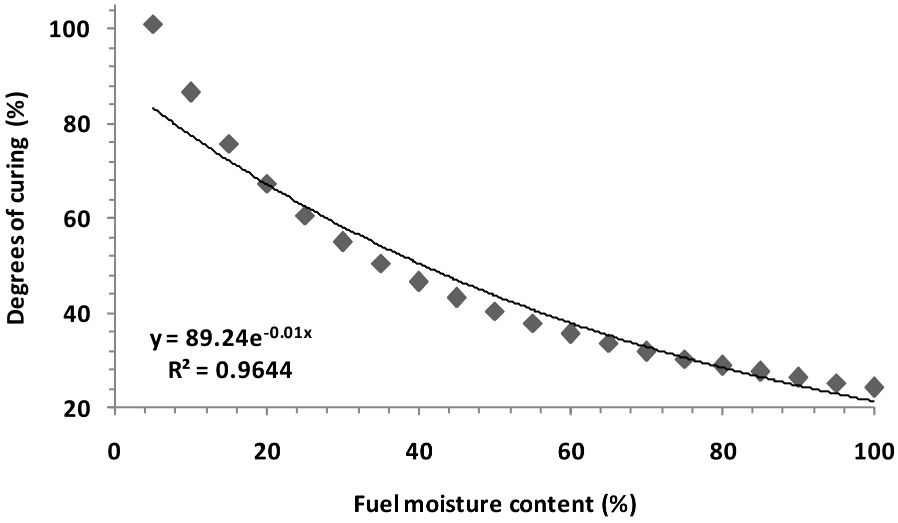


Figure 5.2: The relationship between fuel moisture and vegetation curing calculated using equations developed by Noble *et al*. (1980) and Vinney (1990).

Utilizing Vinney's (1990) method for measuring fuel moisture allowed for the accurate calculation of vegetation curing. It must be noted that the method used in this study to calculate curing utilizes hourly meteorological data and thus may result in curing values unrepresentative of seasonal expectations. For example, curing is expected to be high during the dry winter months yet days which experience cold and wet weather may result in relatively low curing values. However, at a sub-daily timeframe it is felt that the proposed method for calculating curing is accurate and suitable for use in an automatic weather station system.

5.3.1.3 Seasonal Curing Trends in the KwaZulu-Natal Midlands

Historical meteorological data from four sites across the KwaZulu-Natal Midlands were analysed to produce seasonal curing graphs for each location. Figure 5.3 illustrates the seasonal curing graphs for all four locations with average monthly curing as well as monthly maximum and minimum curing values plotted. The maximum curing values for all months across all four locations is 100%. As hourly data was utilized in the production of the graphs, one would expect to find at least one value of 100% in each month, typically associated with warm and dry days which can be experienced throughout the year in the KwaZulu-Natal Midlands regardless of season. Monthly averages were also observed to be high, never going below 90% which may be attributed to the use of hourly meteorological data skewing the results towards higher curing values. Nevertheless some seasonal variation was observed across all locations.

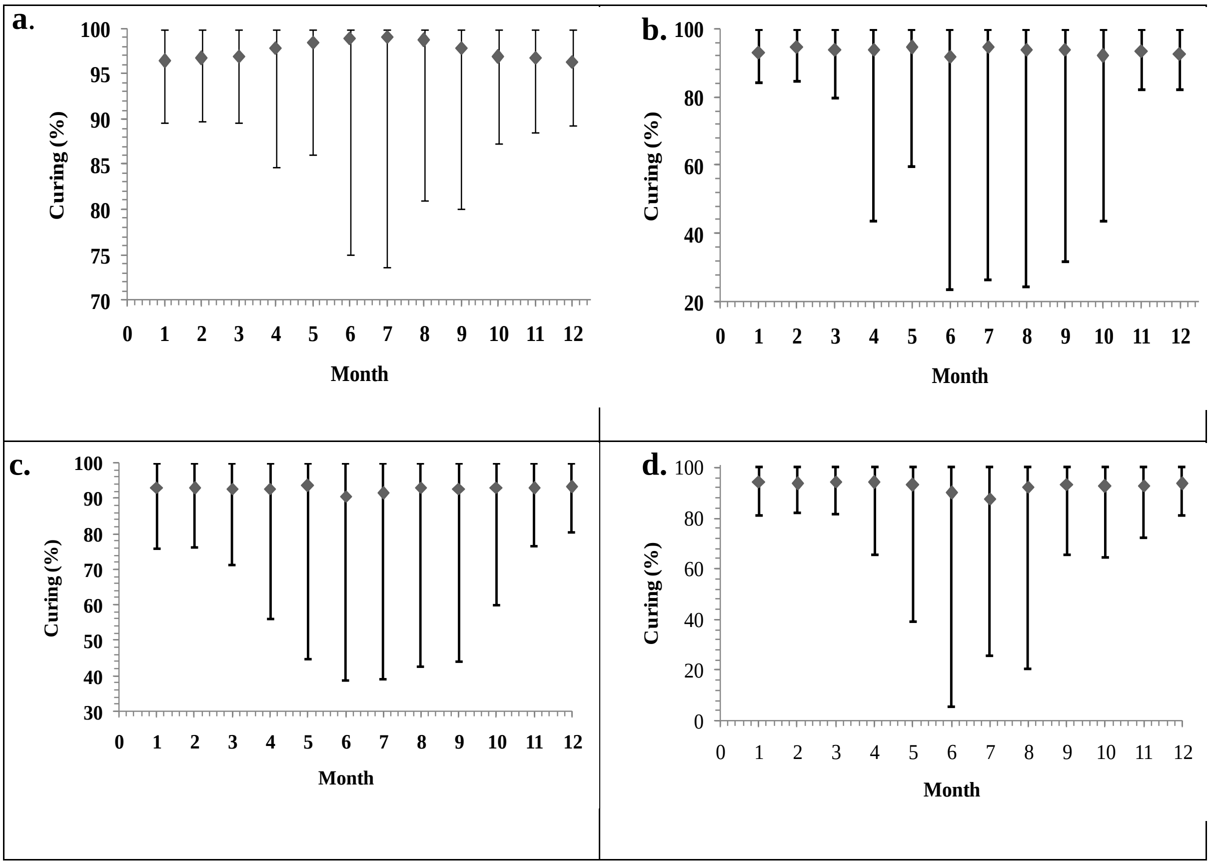


Figure 5.3: Seasonal curing averages for the KwaZulu-Natal Midlands. Points on the graph represent monthly averages and whiskers represent monthly maximum and minimum curing values for a. Ukulinga, b. Baynesfield, c. Cedara and d. Pietermaritzburg.

The monthly minimum curing values provide an interesting and alternative view of seasonal curing. Generally one would assume the minimum curing values to be lower during the summer months compared to winter months. Figure 5.3 illustrates the opposite with lower minimum curing values observed during the winter months. The observed values may be explained by understanding the KwaZulu-Natal Midlands winter weather patterns. While the region is characterized by warm and dry winter months, cold fronts and extending coastal lows may result in cooler air temperatures and higher relative humidity resulting in low curing values. Summer months are characterized by hot and relatively dry weather patterns (thunderstorms are common but not at a frequency which will result in high incidences of increased relative humidity) which may explain the higher curing values observed during summer months.

Table 5.2: McArthur Grassland Fire Danger Index frequency analysis for four locations across the KwaZulu-Natal Midlands

Ukulinga Grassland Fire Danger Index						Baynesfield Grassland Fire Danger Index					
GFDI	*Frequency*	*Percent*	*GFDI*	*Frequency*	*Percent*	*GFDI*	*Frequency*	*Percent*	*GFDI*	*Frequency*	*Percent*
10	57297	88.97	60	101	0.16	10	14621	96.29	60	14	0.09
20	4422	6.87	70	38	0.06	20	408	2.69	70	6	0.04
30	1727	2.68	80	20	0.03	30	88	0.58	80	2	0.01
40	582	0.90	90	8	0.01	40	28	0.18	90	0	0.00
50	201	0.31	100	5	0.01	50	17	0.11	100	1	0.01
Cedara Grassland Fire Danger Index						**PMB Grassland Fire Danger Index**					
GFDI	*Frequency*	*Percent*	*GFDI*	*Frequency*	*Percent*	*GFDI*	*Frequency*	*Percent*	*GFDI*	*Frequency*	*Percent*
10	42006	85.86	60	394	0.81	10	18279	98.29	60	1	0.01
20	2927	5.98	70	311	0.64	20	266	1.43	70	0	0.00
30	1393	2.85	80	234	0.48	30	44	0.24	80	0	0.00
40	818	1.67	90	145	0.30	40	7	0.04	90	0	0.00
50	541	1.11	100	155	0.32	50	0	0.00	100	0	0.00

5.3.1.4 Frequency Analysis of the McArthur Grassland Fire Danger Index

Investigating the frequency of FDI events across a dataset aids in evaluating the fire danger index for operational use. It is expected that lower fire danger ratings will be experienced more frequently than higher fire danger ratings. As shown in Table 5.2, applying the equations provided by Noble *et al*. (1980) made it possible to produce a frequency table for the McArthur Grassland FDI across all four study sites.

From Table 5.2 it is clear that the frequency of each fire danger rating decreases as the rating increases. That is, periods of low fire danger are more frequent than periods of moderate fire danger and moderate fire danger periods are more frequent than periods of high fire danger. All four locations display this trend with the exception of Cedara in which the frequency of GFDIs of 100 is higher than that of 90. It must be noted that the length of a locations dataset may skew data somewhat as seen in Pietermaritzburg’s frequency table. Longer datasets allow for more opportunities for the microclimate to be conducive to higher fire danger ratings.

5.3.1.5 Diurnal Variation of the McArthur Grassland Fire Danger Index

Microclimate factors such as air temperature and relative humidity are expected to follow sinusoidal or co-sinusoidal diurnal trends with peaks or groups in values centred at around 1 PM. As the McArthur GFDI takes into account these factors, and considering the results in Figure 5.1, one would expect the diurnal variation in fire danger to display similar trends. Figure 5.4 illustrates the diurnal variation in GFDI for the month of July, 2014.

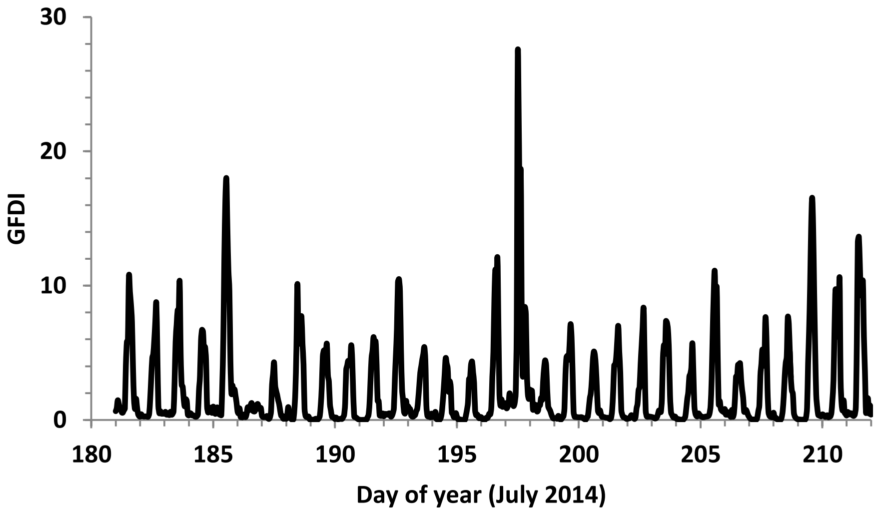


Figure 5.4: Diurnal variation in grassland fire danger recorded in Pietermaritzburg for the month of July 2014.

The diurnal variation follows similar trends to those of air temperature and relative humidity with peaks in fire danger centred at around 1 PM.

While Figure 5.4 does display a sinusoidal trend, smaller fluctuations are still present representing smaller fluctuations in the microclimatic variables used to calculate the GFDI. As seen in Figure 5.4, the maximum GFDI fluctuated daily with the highest value close to 28 and the minimum calculated fire danger close to 0.

5.3.1.6 Wind Speed at Different Height Consideration

The McArthur Fire Danger Meters utilize wind speeds in km h^{-1} at a height of 10 m. The global standard requires anemometers to be positioned at a height of 2 m (as per WMO standards) unless the application calls for wind speed data at a different height. It is important to consider the height of wind in relation to fire danger. Wind speed does play a significant role in fire danger but it is believed that in a region characterized by grassland vegetation, that wind speeds at 10-m will have little influence of the fire danger. As such 2-m wind speeds may be more suitable as these better represent the environmental microclimate of grasslands. As seen in Figure 5.5, wind speed plays a significant role in determining the fire danger rating. However, it is believed that wind speeds measured at 10 m heights may not result in representative fire danger ratings when considering grassland fire danger.

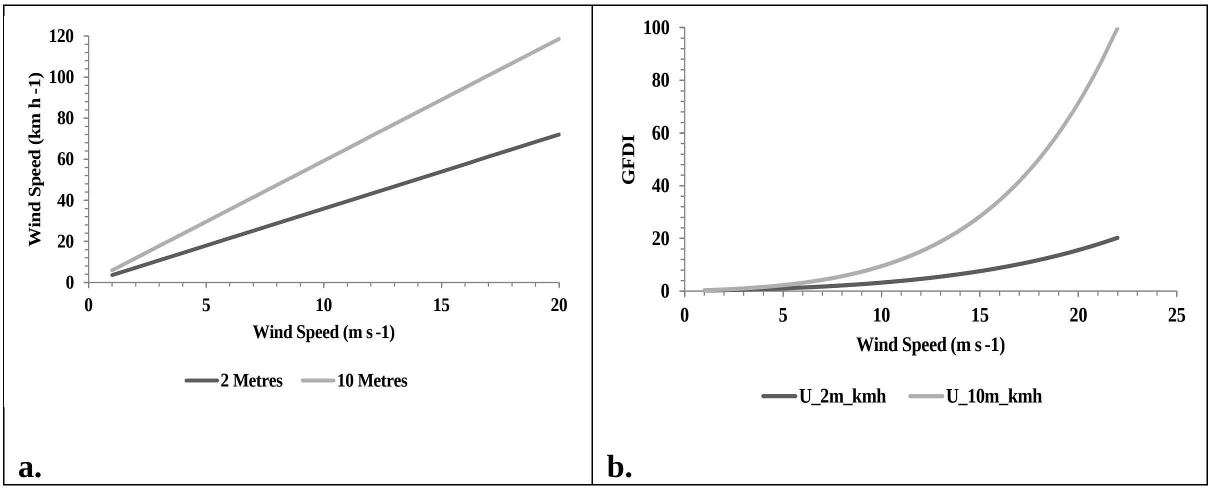


Figure 5.5: The McArthur Grassland Fire Danger Index utilizes 10-m wind speed in calculating the fire danger. The graphs represent the difference observed when using 10m wind speeds and 2-m wind speeds. a. represents the 10-m and 2-m equivalent wind speeds and b. represents the observed changes in the fire danger rating when using 10-m and 2-m wind speeds.

Figure 5.5b illustrates the differences observed in the GFDI when using wind speed measured at 10-m heights. Divergence between GFDI values calculated using 10 and 2-m wind speeds is observed at roughly 6 m s^{-1}. As seen in Figure 5.5b, the GFDI varies significantly when using 10 m wind speeds, particularly when these wind speeds are greater than 15 m s^{-1}. As it is assumed that wind speed will increase with an increase in height, one makes the assumption that 10-m wind speeds will always be greater than 2-m wind speeds.

5.3.2 McArthur Forest Fire Danger Index

The McArthur Forest Fire Danger Index (FFDI) requires a number of additional factors to be considered when calculating forest fire danger such as the Keetch-Byram Drought Index and Effective Rainfall. The index also utilizes daily maximum air temperature resulting in a more complicated analysis of FFDI. The analysis of the McArthur FFDI was done using recent data recorded at the UKZN AIM site. The AIM site is characterized by grassland vegetation which may have resulted in some misrepresentation of forest fire danger, but as the aim of the study was to demonstrate the development of a near real-time McArthur FDI measurement system any representation errors are inconsequential. It must be noted that a forest microclimate differs from that of a grassland microclimate – air temperature and relative humidity differences are most notable in the context of calculating the McArthur FFDI.

5.3.2.1 Frequency Analysis of the McArthur FFDI

As with the GFDI, it is expected that lower forest fire danger ratings will be experienced more frequently than higher forest fire danger ratings. Again the equations provided by Noble *et al*.

(1980) were applied to the data collected at the AIM site to produce a frequency table for the McArthur FFDI. The frequency of forest fire in Pietermaritzburg between January and August of 2014 is illustrated in Table 5.3. As observed with the GFDI frequency analysis the FFDI frequency indicates that lower forest fire danger rating values were experienced in Pietermaritzburg, with the frequency of events decreasing towards the higher forest fire danger ratings exceptions observed in the 70 and 80 ranges where frequencies are higher than those observed for the 60, 90 and 100 ranges.

5.3.2.2 Diurnal Variation of the McArthur FFDI

An alternative method was adopted when analysing the diurnal variation of the McArthur FFDI – instead of plotting a monthly graph of diurnal change, a single day was selected for analysis. Figure 5.6 illustrates the diurnal variation observed on the 5th of July 2014. The greatest FFDI values occurred at roughly midnight, decreasing drastically before increasing again during the morning hours and fluctuating further throughout the day. Of note is the lack of a sinusoidal or co-sinusoidal trend evident in the diurnal variation graph for the McArthur GFDI (Figure 5.4). The lack of this trend can be attributed to the fact that the FFDI equation does not only consider the basic factors that quantify the microclimate but is also influenced by a drought index and drought factor which does not follow a sinusoidal diurnal trend. Furthermore, the FFDI considers the current daily maximum air temperature, whereas the GFDI considers hourly air temperature averages.

Table 5.3: McArthur FFDI frequency analysis for Pietermaritzburg, KwaZulu-Natal over a period beginning in January 2014 ending in August 2014.

FFDI	*Frequency*	*Percent*	*FFDI*	*Frequency*	*Percent*
10	3213	70.99	60	98	2.17
20	412	9.10	70	152	3.36
30	220	4.86	80	9	0.20
40	172	3.80	90	68	1.50
50	113	2.50	100	69	1.52

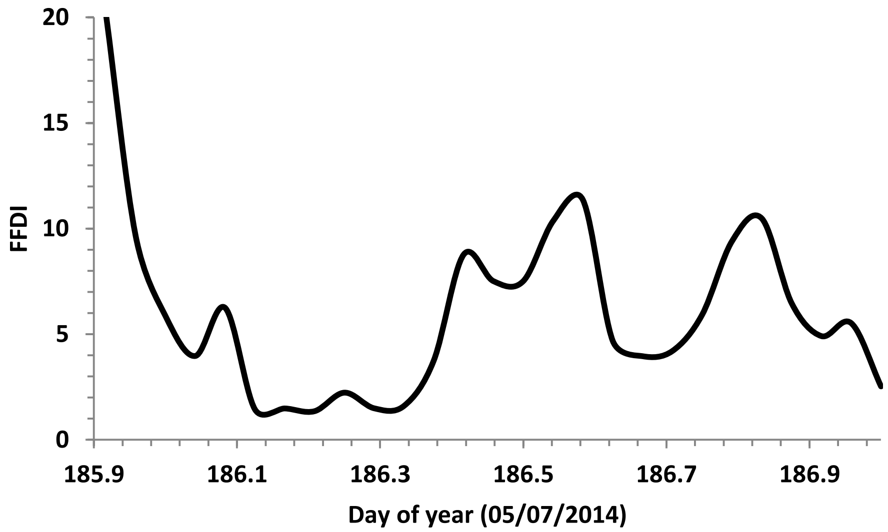


Figure 5.6: Diurnal variation in the McArthur FFDI recorded at the UKZN AIM site on the 5th of July 2014.

Further analysis of hourly meteorological data points to the occurrence of a night time Berg wind event on the 4th of July 2014 (DOY 185) lasting past midnight into the 5th of July 2014 (DOY 186). The Berg wind event may explain the increased FFDI in the early hours of the 5th of July as these winds are associated with increased air temperature and decreased relative humidity. Berg winds are also associated with approaching cold fronts which may explain the precipitation recorded. Any precipitation will result in a decreasing drought index and drought factor decreasing the overall FFDI. Cooler air temperatures and increased relative humidity associated with the passage of the cold front will also result in the lowering of the FFDI observed on the day.

5.3.3 The Near Real-time McArthur Fire Danger Meter Measurement System.

Figure 5.7 shows a screenshot of the near real-time McArthur GFDI display on the AIM system. The McArthur fire danger web screen includes graphics of selected variables such as the current air temperature, current RH and current wind speed, as well as a count of the number of days since the last rainfall event. The screen includes temporal graphs, one for hourly and another for the daily display of the GFDI and one for the daily display of the GFDI. Both graphs include the fire danger rating system thresholds used by the McArthur fire danger meters which indicate the category of fire danger ranging from ‘Low to Moderate’ (FDI between 0 and 11) to ‘High’ (between 12 and 24), ‘Very High’ (between 25 and 49), ‘Severe’ (between 50 and 74), ‘Extreme’ (between 75 and 99) and finally ‘Catastrophic’ (100+). Data can be obtained from the screen by selecting the tabled hourly values below the daily graph.

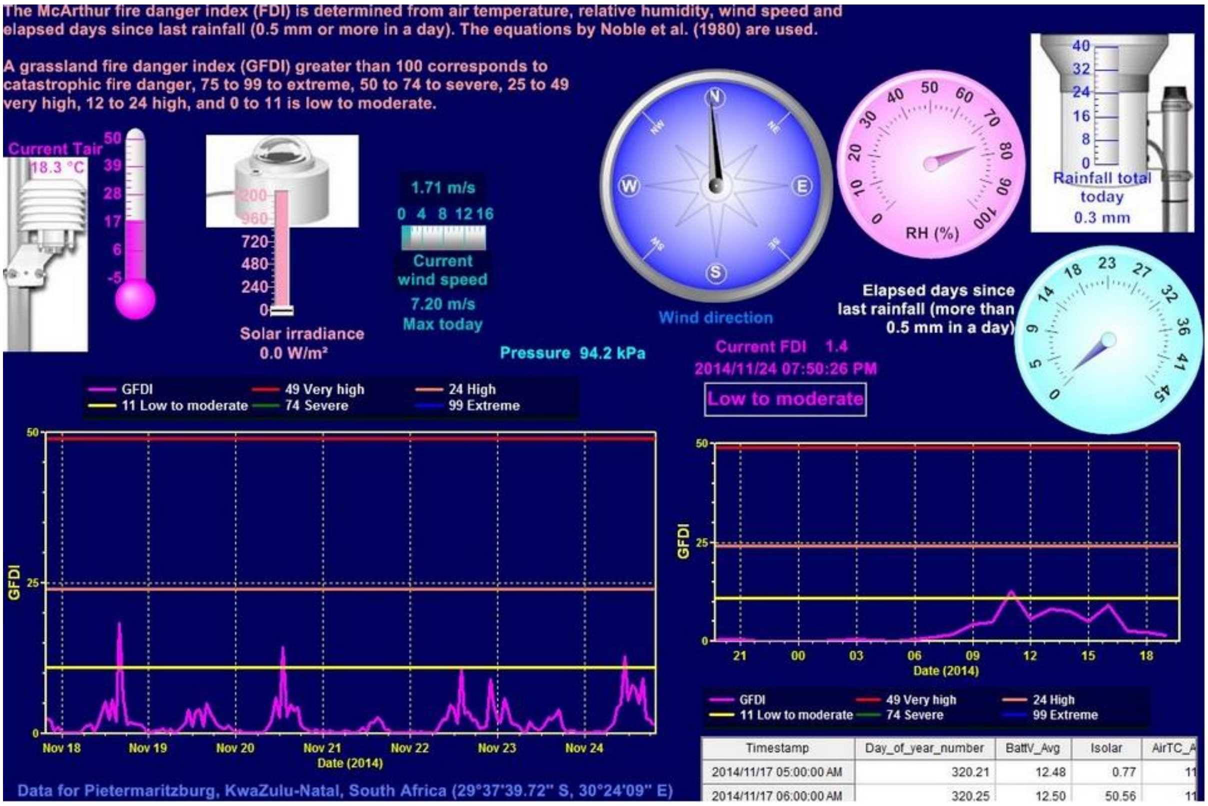
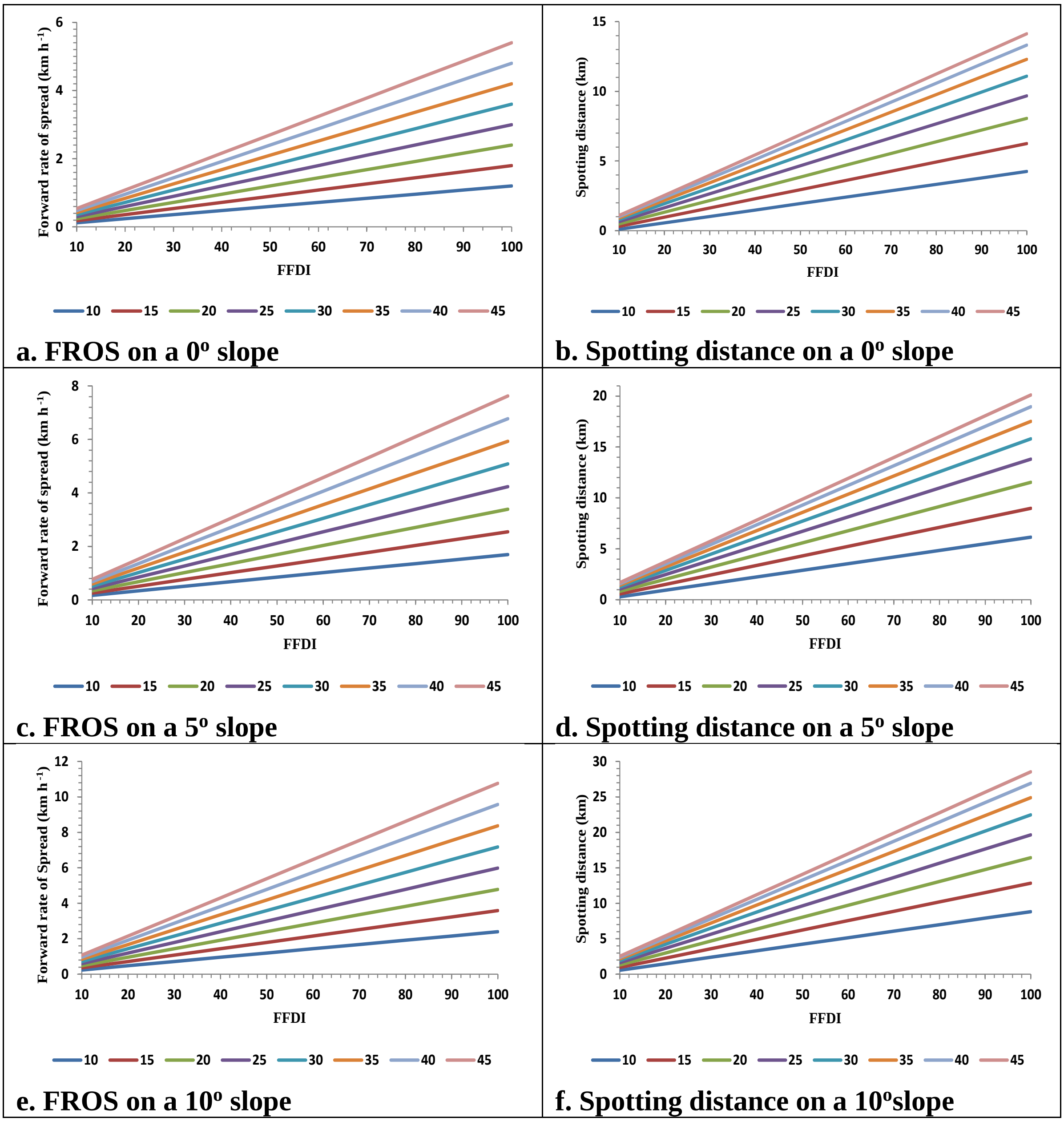


Figure 5.7: Screenshot of the McArthur fire danger near real-time screen displayed online at http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Fire_McArthur

5.3.4Fire Behaviour Modelling

An important aspect of utilizing the McArthur FFDI is the opportunity to model fire behaviour based on topography and vegetation fuel loads and the overall forest fire danger rating. The current fire danger index utilized in South Africa does not provide for any fire behaviour modelling. Thus it is believed that the use of the McArthur FDIs in South Africa for modelling fire behaviour alone makes it highly favourable compared to the existing Lowveld FDI. The study only considered the "Forward Rate of Spread" (FROS) and "Spotting distance" fire behaviour characteristics. A benchmark of 45 t ha^{-1} fuel load was selected based on anecdotal evidence as well as literature on average fuel loads of forests. Slopes of 0, 5 and 10^o were selected for further analysis and preliminary analysis indicated that the fire behaviour model did not yield plausible results with slopes greater than 10^o, suggesting that the model is only suitable for modelling fire behaviour on gentle slopes which is a definite limitation of the model. Figure 5.8 illustrates the FROS and spotting distances for predetermined fuel loads at each class of slope. As expected, higher fuel loads will have increased FROS and spotting distances while lower fuel loads will result in 'manageable' fire behaviour even in environments of high fire danger. In comparing the FROS graphs, an increase of roughly 2 km h^{-1} was observed for higher fuel loads when increasing slope by a factor of 5^o.



a. FROS on a 0º slope

b. Spotting distance on a 0º slope

c. FROS on a 5º slope

d. Spotting distance on a 5º slope

e. FROS on a 10º slope

f. Spotting distance on a 10ºslope

Figure 5.8: Fire behaviour for varying fuel loads (t ha^{-1}) on different classes of slope with a. and b. representing the forward rate of spread and spotting distances on a slope of 0º, c. and d. for a slope of 5º and e. and f. for a slope of 10º.

5.4 Discussion

5.4.1 Sensitivity Analysis of the McArthur GFDI

The sensitivity analysis of the McArthur GFDI (Figure 5.1) shows the general changes in the fire danger rating value brought about by changes in the microclimate. As seen in Figure 5.1a air temperature has a relationship with the GFDI best described by an exponential trend with a coefficient of determination (R^2) of 1. Increases in air temperature will result in an increased fire danger value with a likely maximum increase of 2.5 of GFDI. Relative humidity has a logarithmic relationship with grassland fire danger, best described by a logarithmic trend line with a R^2 of 0.9979. As with air temperature, decreases in relative humidity are likely to result in a maximum increase of 2.5 of GFDI. The relationship between wind speed and grassland fire danger is also best explained with an exponential trend line with a R^2 of 0.9823. Increases in wind speed from 5 to 50 km h^{-1} are likely to result in a maximum increase of 9 in the GFDI. Degrees of curing displays a power relationship with the GFDI, with a R^2 of 1 observed. Changes in degrees of curing are also likely to result in the largest increases of grassland fire danger. The results of the sensitivity analysis indicate that more emphasis is needed on the influence of air temperature and degrees of curing when planning controlled burns and when monitoring fire danger as these variables are well correlated with GFDI.

Traditionally, wind speed has been emphasized when monitoring fire danger. Changes in wind speed do have a significant effect on GFDI (Figure 5.1c) but using wind speed alone as an indication of fire danger has likely resulted in many controlled fires becoming uncontrolled. Furthermore, without any method for monitoring fire danger in real time, land owners and disaster management personnel may have to rely on what would essentially be a 'best estimate' obtained by visual assessment. Hourly meteorological data are available from relevant agencies and institutes which maintain networks of automatic weather stations, but data are not available in near real-time or requires the purchasing of the data.

5.4.2 Seasonal Curing Trends

Finding an alternative method to measuring vegetation curing was challenging. While the method used in this study appears to function well, it must be emphasized that the method is experimental and for the purposes of this study works well. No other method for calculating vegetation curing using AWS sensors appears to exist. As such, it is expected that further work will be done on perfecting the method. The relationship between fuel moisture and vegetation is logical, this made utilizing Vinney's (1990) method for calculating fuel moisture content appealing. In fact, the simplicity of Vinney's (1990) equation means that it can be used in the field by farmers, landowners and managers to infer curing as opposed to a visual assessment of vegetation curing.

Analysis of seasonal curing across the KwaZulu-Natal Midlands yielded interesting results, with the average monthly curing never decreasing below 90% across all locations. A curing value of 90% is admittedly very high, even when considering the climate of the KwaZulu-Natal Midlands. Inadequate inputs may be a limitation of the method described to calculate curing, as some experts believe that soil water content is significant to fuel moisture.

The use of hourly data may also distort estimations although little difference between using a daily curing average and hourly averages was observed. McArthur's FDM were developed to be daily calculations of fire danger and use at a sub-daily time interval may have resulted in the high monthly curing values observed. While the method used may not accurately represent seasonal curing it is believed that the method represents the sub-daily changes in the microclimate which influence fuel moisture well, thereby influencing fire danger. For example, grassland vegetation may have a reduced ignition risk when the microclimate is highly saturated coupled with low air temperatures. The method utilized in this study is representative of the microclimate and will output a low curing value. Traditional curing values only consider the 'seasonal' curing environments – i.e. if curing for the month of August is observed to be 90% then the calculation of the McArthur GFDI will input a curing value of 90% when in reality the microclimate environment may be best described by a lower near real-time curing value. For example, early morning precipitation such as frost or dew in winter may contribute to increased fuel moisture and lower hourly curing values, i.e. the fuel is wet despite the traditional seasonal curing value (dead grass that is wet is not going to ignite). Be this as it may, some experts state that plant physiological characteristics are still as important as micrometeorological characteristics but do note the importance of micrometeorological considerations of curing in the context of fire danger monitoring and prevention

5.4.3 Frequency Analysis of the McArthur Fire Danger Meters

The frequency analysis of the McArthur GFDI at the four locations indicated that lower fire danger ratings are more prevalent than high fire danger ratings. The results presented in Table 5.2 are in agreement with previous research done on Berg wind events in the KwaZulu-Natal Midlands that suggests Ukulinga and Cedara are more prone to high fire danger periods compared to Baynesfield or Pietermaritzburg. Low to moderate fire danger across the KwaZulu-Natal Midlands is common but extreme to catastrophic fire danger events have been observed. Of interest is the high frequency of low fire danger events despite the high monthly curing as previously noted. Even with high monthly curing observed at all four sites, the frequency of large GFDI is low, which emphasizes the point made previously – fire danger needs to be understood in terms of the microclimatic variables utilized to describe fire danger. Emphasis on only one or two of the variables is likely to result in further fire disasters.

The McArthur Forest fire Danger Index provides the first opportunity to measure forest-specific fire danger in South Africa. Due to the limited natural forest coverage in South Africa, little consideration is given to forest fire danger, with most forest fire danger monitoring being done by the commercial forestry industry. Forest fires have been documented to occur in the country (as highlighted earlier in this chapter) and it is felt that more attention should be given to monitoring forest fire danger. Forestry, particularly commercial forestry, is often situated in agricultural settings including grasslands, with plantations either bordering or being surrounded by commercial agriculture activity. As such, any fire that may originate in the plantation or forest is not limited to the plantation or forest and has a good chance of spreading into the agricultural land – a scenario which alone should warrant efforts into forestry fire danger monitoring.

As expected, the FFDI frequency indicates that lower forest fire danger rating values were experienced in Pietermaritzburg, with the frequency of events decreasing towards the higher forest fire danger ratings as was the case with the analysis of the GFDI for Pietermaritzburg. Of interest is the increased frequency of high FFDI events. While Table 5.3 still presents a decreasing trend similar to that of the GFDI, the upper forest fire danger ratings have a higher frequency than that of the grassland fire danger index for Pietermaritzburg despite datasets of different duration. The frequency analysis indicates that Pietermaritzburg may be moderately vulnerable to forest fire conditions due to the higher frequency of extreme forest fire danger events.

Due to the short length of the AIM site dataset, one needs to practice caution when assuming that the general forest fire frequency trend will exactly as that illustrated in Table 5.3. It is recommended that the equations be applied to a dataset with a longer duration to fully understand the frequency trend of the McArthur FFDI. Emphasis is also needed in noting that the microclimate of the AIM site differs to the microclimate of a forest or plantation. The idea of a fire season needs to be reviewed too as high fire danger environments are not likely to be limited to specific seasons. The results presented in this study should provide enough evidence to suggest that short term variations in the microclimate are just as influential (if not more) as seasonal variations, at least in the KwaZulu-Natal Midlands.

5.4.4 Diurnal Variations in McArthur Fire Danger Meters

The diurnal variations in the GFDI for Pietermaritzburg presented in Figure 5.4 illustrate the expected diurnal variation. As explained in Section 5.4.1, the GFDI utilizes micrometeorological inputs which tend to follow sinusoidal and co-sinusoidal trends, explaining similar trends in the variation of the GFDI. While the diurnal variation is expected to peak around midday, increases in fire danger have been observed in the morning and afternoon hours. Thus Figure 5.4 should not be misinterpreted to mean that fire disaster mitigation efforts should only be in place at midday, but rather that fire danger can be higher than expected at times other than midday depending on the microclimate.

Figure 5.6 illustrates the versatility of the McArthur FFDI when used to calculate fire danger in near real-time in an environment of changing weather. The likely Berg wind event seen in Figure 5.6 resulted in an increased FFDI being recorded in the early hours of the morning. The occurrence of precipitation (decrease in air temperature and an increase in relative humidity) decreased the FFDI with further smaller peaks occurring throughout the day. The diurnal variation of the FFDI illustrated in Figure 5.6 indicates an instantaneous response of the FFDI to changes in the microclimate. As the FFDI includes calculations such as the Keetch-Byram Drought Index, one would not expect it to display sinusoidal or co-sinusoidal trends consistently as observed in the GFDI.

The sinusoidal or co-sinusoidal trends followed by inputs for the McArthur Fire Danger Meters may allow for the development of a nowcasting or very short range forecasting model which would utilize near real-time micrometeorological data to forecast fire danger, although consideration for non-traditional measurements such as curing and drought index would be needed. A suitable forecast model could easily be programmed into a datalogger program, in which case an hourly forecast of grassland fire danger would be possible. If successful, the datalogger program could be added to the current AWS network operated by various institutes and entities which may allow for a wide spatial fire danger forecast model as well as monitoring.

5.4.5 Wind Speeds at Different Heights

The McArthur FDM utilizes wind speed measurements taken at a height of 10 m. As seen in Figure 5.5a, wind speeds increase with an increase in height. This is of particular importance when considering the McArthur GFDI and the differences between wind speed measurements at 2-m and 10-m heights. World Meteorological Standards suggest wind speed measurements be conducted at a height of 2-m unless the application of the data requires data at different heights. The standard practice in South Africa is to measure wind speeds at 2-m height, and in some cases additional wind speed data is collected at 10-m. As wind speed is expected to be faster at 10-m heights, using 10 m wind speed measurements is likely to increase the overall fire danger rating as is seen in Figure 5.5.

If wind speed at 10-m heights are faster than that of 2- m heights, and if this difference is likely to increase the overall fire danger value calculated, should the use of 10-m wind speed data be re-evaluated? When considering fire danger above grassland, one would not expect wind speeds at 10-m heights to significantly influence surface processes driving surface fire development and spread. Wind speeds at 2 m are likely to have a greater influence on grassland fire danger compared to 10 m wind speeds. All things being equal, the use of 10-m wind speeds has likely resulted in an over-estimation of grassland fire danger. Alternatively, many may consider an over-estimation to be better than an under-estimation as any under-estimation may lead to uncontrollable wildfires while an over-estimation will result in increased mitigation and preparation. Overall the kinematics of atmospheres conducive to grassland fire development and spread should be investigated to assess the role of wind speed at different heights on overall fire danger and behaviour.

5.4.6 Fire Behaviour Modelling

Fire behaviour modelling has been absent from South African fire danger monitoring activities due to the utilization of the Lowveld fire danger index which does not provide any behaviour modelling components. Drawing from the case studies presented in the introduction of this study, it is clear that modelling of fire danger is critically needed, particularly in mountainous regions such as the Cape Fold Mountains and the Drakensberg which have been identified as fire prone regions in earlier research. Figure 5.8 describes two important fire behaviour characteristics – the forward rate of fire spread and the spotting distance of an existing fire. Topography appears to have a greater influence on the two characteristics than that of fuel load (Figure 5.8). As fuel loads approach 40 t ha^{-1} the spotting distances plateau, while increased slopes consistently results in increased forward rates of spread. One of the limitations of the McArthur fire behaviour model is its apparent difficulty in modelling fire behaviour on steep slopes. This limits any modelling activity to relatively gentle slopes which, at face value, may not seem beneficial. The use of the McArthur fire behaviour model can however provide a baseline for assessing fire behaviour. If a land owner knows the slope of the land is 20^{o} then Figure 5.8 would indicate that the FROS or spotting distance will be greater than or equal to that of a 10^{o} slope (a slope greater than 10^{o} yields unrealistic characteristics), and as such any necessary precautions can be made with the assumption that the best case scenario will be that FROS and spotting distance will be that of a 10^{o} slope.

Mountainous regions provide difficult fire mitigation and fighting environments and this has led to extreme wildfires as discussed early. It is believed that by implementing a fire behaviour model, the losses resulting from uncontrolled fires in problematic environments could be reduced. The study provides an insight into the response of the McArthur fire behaviour model to different topography and fuel load schemes. While the McArthur model has been used extensively worldwide, further research into a model that resolves topography better is needed, as no rational-minded person would disagree that a fire behaviour model is critical in preventing fire disasters that appear to be becoming more common.

5.4.7 Near Real-time Measurement System

The AIM McArthur fire danger meters web-based system screen (available at: http://agromet.ukzn.ac.za:5355/?command=RTMC&screen=Fire_McArthur) used for near real-time monitoring, early warning, learning and research provides a number of useful tools. It provides university students and researchers with means of accessing and visualising data which aids in the understanding of atmospheric processes. The screen also provides users with hourly updates of grassland fire danger conditions for Pietermaritzburg. Stakeholders, such as farmers and municipal managers involved in vegetation burning practices, are able to monitor conditions in near-real time, with a multitude of devices such as PCs, cellphones and tablets allowing for some early warning and preparedness. As with the Lowveld FDI screen, the McArthur screen lacks a predictive or nowcasting function which will allow users to have an idea of possible conditions in the very near future. Analysing trends of the two hourly graphs as well as the relevant variables throughout the day may allow for some subjective forecasting.

The UKZN AIM system can currently send out SMS and email alerts for predetermined events although this function has not been programmed into the code for the McArthur fire danger meters. Alerts can be based on changes in air temperature, relative humidity or wind speed. A suitable alert would identify when hourly grassland values increase by predetermined factor which would then send out an alert to warn users of the increase in fire danger via email or SMS using a GSM sim card. The current aim of the screen, however, is to provide near real-time monitoring. Future research will investigate forecasting of fire danger and early warning using the AIM system.

5.5 Conclusions

Australia experiences its fair share of fire disasters on an annual basis. The McArthur Fire Danger Meters, comprising the Grassland Fire Danger Index and the Forest Fire Danger Index were developed to improve monitoring of fire danger and fire management in Australia. The aim of this study was to develop a near real-time fire danger index measurement system using the McArthur Fire Danger Meters as the Lowveld fire danger meter currently utilized in South Africa does not consider forest fire danger and does not provide any fire behaviour modelling component. The McArthur Fire Danger Meter equations provided by Noble *et al*. (1980) were applied to historical hourly meteorological data collected at four sites in the KwaZulu-Natal Midlands. Analysis of the calculated curing values was used to plot seasonal vegetation curing graphs for the four locations. Analysis of the seasonal curing graphs indicated that monthly curing averages remained high while monthly ranges in curing increased during the winter months as daily weather patterns become more diverse. Additional analysis involved investigating the frequency of grassland and forest fire danger ratings across the four sites. Findings of the frequency analysis indicate that both the GFDI and the FFDI experience higher frequencies of lower fire danger at all four locations with only a few instances of high fire danger, despite the high monthly curing averages calculated at the four locations. Furthermore, the study investigated the diurnal variations observed in grassland and forest fire danger. Analysis of diurnal variations of the GFDI indicated sinusoidal trends as the inputs of the GFDI follow sinusoidal patterns. The diurnal variation of the FFDI does not follow clear sinusoidal trends due to non-sinusoidal inputs. Both the GFDI and the FFDI appear to be sensitive to changes in the microclimate. The study also demonstrated the use of the McArthur fire behaviour modelling component. While fire behaviour was successfully modelled under different topographic and fuel load schemes, the model does not perform well on steep slopes and may only be useful as a baseline measurement on steep slopes.

CHAPTER 6: OVERALL CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Conclusions

Fire has always been a natural component of the earth system, providing agro-environmental regulatory services such as nutrient recycling, combating alien invasive species and regulating climate. Anthropogenic activity has, however, resulted in intensive utilization of fire which has led to fire impacting adversely on the environment, resulting in increased vegetation loss, increased soil erosion and sedimentation as well as increasing greenhouse gas concentrations influencing climate negatively. Wildfires are also considered hazards or natural disasters. The African continent has been identified as the "fire continent" due to its high fire frequency. Fire disasters have resulted in numerous human fatalities and financial loss on an annual basis. The aims of this study, outlined in Chapter 1, included investigating the spatio-temporal variations of South African wildfires, quantifying the effect of warm mountain winds known as Berg winds on fire danger, and developing two near real-time fire danger index systems using the Lowveld FDI as well as the McArthur fire danger meters. The motivation and belief of the research is that these aims will result in an improved understanding of fire danger and lead to improved monitoring and mitigation measures.

A review of relevant literature is provided in Chapter 2 (Literature Review). Chapter 2 provides an investigation into the theoretical background of fire meteorology. This includes a review of the dynamics at synoptic and microclimate scales of mountain waves in the USA, Antarctica, Australia and South Africa. Chapter 2 also investigated the effects of fires on the environment, economy and society. A review of current fire danger monitoring and forecasting techniques is also provided.

The material covered in Chapter 3 (spatio-temporal analysis of South African fires) provides the first known investigation into the spatial and temporal variations in South African fires using an 11-year dataset obtained from remote sensing platforms. Results of the study indicate that fire numbers are increasing in all provinces of South Africa, but Mpumalanga, although a relatively stable national trend has been observed for the last three years. Mountainous regions such as the Drakensberg in KwaZulu-Natal and the Cape Fold Mountains appear to have the highest fire activity, most likely due to complex vegetation, topography and microclimatic schemes. Summer rainfall regions experience the highest fire frequencies in the winter months, while winter rainfall regions experience higher fire frequencies in the summer months. However, all months in all provinces have experienced some fire activity. Grasslands, bushveld and fynbos vegetation zones were identified as being the most prone to fire activity. Climate change is theorised to have a marked influence on fire activity. The study provides an insight into the likely effect of changing climate indicating that fire frequency is likely to increase in a changing climate, determined by studying two of the ten warmest years on record and by investigating the role of seasonal climate events such as La Niña on fire frequency. It is hoped that the study will provide relevant parties insights to focus on mitigation strategies where fire activity is more likely. Furthermore, with improved knowledge on the location and timing of fires, mitigation efforts can reduce the loss of human life and property.

Warm mountain winds, known as Berg winds in South Africa, are warm and dry winds often associated with wildfires and fire disasters. The research presented in Chapter 4 (Berg winds and the Lowveld FDI) is believed to be the first attempt at quantifying the effects of Berg winds on the microclimate and fire danger in detail. The development of the fuzzy logic system for identifying periods of Berg winds is certainly a first for South Africa. Results of the research are in support of the theory that high periods of fire danger coincide with periods of Berg winds. An analysis of Berg winds at four locations across the KwaZulu-Natal Midlands suggests that Baynesfield and Ukulinga are the most vulnerable to periods of Berg wind conditions and thus high fire danger. While analysis indicates that Berg winds are more frequent in August and September, Berg wind conditions and associated increases in fire danger have been observed in all months, with varying duration. The development of the near real-time fire danger index measurement system using the Lowveld fire danger index has provided further steps in sub-daily and hourly monitoring of fire danger. The research has illustrated the relationships between micrometeorological variables and the Lowveld fire danger index. As with Chapter 3, it is hoped that the research presented in Chapter 4 will result in improved and early monitoring of fire danger, thereby resulting in better mitigation strategies and reduced human fatalities.

Australia, like South Africa, experiences a number of wildfire related disasters on an annual basis. The McArthur fire danger meters were developed in Australia to improve management and monitoring of fire danger. The use of the fire danger meters has traditionally been done using nomograms. Noble *et al*. (1980) provide the first set of equations describing the McArthur fire danger meters which were used in this study (Chapter 5: McArthur FDI). An additional benefit of using the McArthur fire danger meters is the inclusion of a fire behaviour model for forest conditions. Anecdotal evidence suggests that improved monitoring of forest fire danger and behaviour is needed in South Africa, despite the limited contribution of commercial forestry to the South African GDP. Challenges of the study included developing a method for calculating vegetation curing using micrometeorological variables. Such a method was developed using a fuel moisture index and by altering certain equations provided by Noble *et al*. (1980). Fire frequency analysis of the McArthur fire danger meters suggests that the meters may be suitable for use in South Africa although the fire behaviour model appears to be limited to gentle slopes. Regardless of any limitations of the fire behaviour model, it can still be utilized as a baseline for judging fire behaviour which may improve fire fighting capabilities and mitigation efforts in light of the results presented in Chapter 3 regarding fire frequency in complex topography. It is believed that a near real-time FDI measurement system using the McArthur fire danger meters may improve mitigation efforts. The study provides the first attempt in South Africa to measure fire danger using the McArthur fire danger meters in near real-time at a sub-daily time interval.

6.2 Recommendations for Further Research in Fire Meteorology

Research in the field of fire meteorology is of great importance due to the devastating effects of fire disasters - even more so in light of climate change. The research undertaken for this dissertation is by no means dead-end research as the near real-time measurement systems can always be improved upon and modified. As years pass, the spatio-temporal study can be updated to include longer datasets and the SADC region to truly understand the long-term effects of climate change on fire frequency.

The spatio-temporal analysis presented in the study (Chapter 3) was limited by available data. Future research should incorporate some type of ground truthing of fire events to overcome any limitations arising from the use of only reliable data obtained from remote sensing platforms. South Africa does not currently have a national wildfire database to keep record of the spatial and temporal variations of wildfire activity. In order to truly understand the spatial and temporal variations of wildfires in South Africa, future research should investigate the development of an online national wildfire reporting system in which landowners and fire managers submit fire event reports of fire events that are made immediately available to other land users.

The Lowveld fire danger index does not currently give much consideration to vegetation properties. Thus, future research could investigate adapting the Lowveld FDI to include a more direct measure of fuel load and fuel moisture. The fuzzy logic system for determining periods of Berg winds (Chapter 4) only considered day-time Berg wind conditions. Future research could investigate the occurrence of night-time Berg wind events and how these events influence the microclimate – particularly fire danger. This system could also be applied to other regions of southern Africa.

The McArthur fire danger meters have never been used in a near real-time measurement system. As such, the research presented (Chapter 5) is seen as experimental. Future research should investigate alternative methods for estimating or calculating vegetation curing using only meteorological variables. It is believed that a fire behaviour model is desperately needed in South Africa to improve mitigation and fire fighting efforts. Future research should investigate alternative fire behaviour models or investigate the limitations of the McArthur fire behaviour presented in this dissertation with the aim of overcoming these limitations. This model could also be extended to other regions of southern Africa.

An area of research that may be fruitful but has not been directly studied for the presented research is the use of remote sensing platforms to derive vegetation curing. Current vegetation indices include the Normalised Difference Vegetation Index, the Visual Greenness Index and the Enhanced Vegetation Index, used to assess vegetation health and moisture content. Further research should investigate the integration of remote sensing data into fire danger indices such as the McArthur FDM. Remote sensing also allows for greater spatial monitoring of near real-time conditions and is likely to further improve on mitigating fire disasters if integrated with ground-based agrometeorological measurement systems.

A second avenue of research that has not been considered in the presented research is the role of CO_2 as a result of vegetation fires in modifying the microclimate, particularly the radiation balance. Current research has focussed on the concentrations of CO_2 released during vegetation burning with little research investigating how this CO_2 release effects the radiation balance. Research into the effect of CO_2 on the radiation balance and other micrometeorological conditions has direct consequences for climate change studies. Agrometeorological measurement systems provide the perfect platform for monitoring the effects of vegetation fires in releasing CO_2 and how this release influences the radiation balance.

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