MODELLING THE IMPACTS OF INCREASED AIR TEMPERATURE ON MAIZE YIELDS IN SELECTED AREAS OF THE SOUTH AFRICAN HIGHVELD USING THE CROPSYST MODEL

By

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Declaration

I, Jonathan M. Pasi hereby declare that:

i. the pictures, graphs, data, results or other information contained in this thesis are from my original work except where acknowledged;

ii. the thesis has not been submitted in full or in part for any degree or examination to any other University;

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ABSTRACT

The Agricultural sector has the potential to eliviate food security problems that many countries experience. However, challeges associated with agicultural production limits its potential to meet food demands. Climate change is a major culprit that has affected various crop yields worldwide. Therefore, the need to develop tools (such as modelling) to manage soil, plant and atmospheric systems in order to increase agricultural production should be prioritised. The ability of crop simulation models to predict yields from a set of described weather, soil, plant and management parameters in a changing climate has provided some insights into improving yields. This study describes the influence of increasing air temperature on the maize crop in selected areas of the Highveld Eco-region of South Africa. The CropSyst model was used to simulate maize yields and the CLIMGEN stochastic weather generatorl was used to generate synthetic data. The selected Highveld locations were Lichtenburg, Bothaville (western half of the Highveld), Bronkhorstspruit, Marble Hall (eastern half) and Cedara, a location outside of the Highveld region.

Missing values in the climate data were patched using models. Daily solar irradiance was generated well at all locations since initial climate data files had none. A model used to generate relative humidity underestimated minimum relative humidy values. Rainfall and air temperature were patched using stations in close proximity to the driver station. Missing wind speed values were patched with 2.0 m s^{-1}. Each location had a different record length. The longest dataset analysed was from Cedara with record length from 1970 – 2010, the shortest from Bronkhorstspruit and Bothaville with record lengths 1988 – 2010 and 1980 – 2004, respectively. Lichtenburg and Marble Hall had record lengths of 1978 – 2004 and 1981 – 2011, respectively.

The air temperature was analysed to determine temperatures trends in the selected locations. Annual trends showed negative maximum air temperature trends (T_x) of -0.08 and -0.02 ^{o}C/decade for Lichtenburg and Bothaville and positive minimum air temperature trends (T_n) of 0.24 and 0.18 ^{o}C/decade, respectively. As a result, negative annual diurnal temperature range trends (DTR) were noted for both locations. For Bronkhorstspruit and Marble Hall, annual T_x trends were positive (0.19 and 0.001 ^{o}C/decade) and negative T_n trends of -0.18 and

-0.35 °C/decade, respectively. Cedara showed negative trends for both T_x and T_n (-0.1 and -0.05 °C/decade, respectively.

Positive DTR range of 0.37 and 0.35 °C/decade were found for Bronkhorstspruit and Marble Hall (eastern half) respectively whilst negative trends of -0.19 and -0.32 °C/decade were noted for the locations from the western part (Bothaville and Lichtenburg).

Prior to simulation using the CropSyst model, scenarios were created by changing baseline conditions. The conditions involved: increasing current CO_2 concentration of 390 to 700 μL L^{-1}, increasing rainfall by 10 and 20 % and increasing air temperature by 2 and 4 °C. The scenarios were based on increases in CO_2 concentration without changes in air temperature and rainfall, an increase in [CO_2] and rainfall with no air temperature increase and an increase in CO_2 concentration, rainfall and air temperature.

Increasing [CO_2] increased average yields at all locations of the study. The influence of rainfall increments by 10 and 20 % increased yields by 5 and 8 %, respectively. Air temperature increments decreased yields across all locations with more reductions noted for the 4 °C increments. With reference to baseline conditions, increasing both CO_2 concentrations and air temperature by 2 °C increased yields. However, the benefits of CO_2 concentration enrichment were masked under 4 °C increments since yields were found to have decreased below yields for the baseline conditions.

With air temperature increasing, the need to consolidate food security in future depends on current agricultural approaches and responses to changes in the environment. Having studies such as this one provides a basis from which decisions can be made at the management level in order to maintain or increase output in maize production or any other crop. This would result in an increase in human life expectancy and reduction in poverty related diseases, ensuring an improved livelihood for many.

1. INTRODUCTION

1.1 Motivation

Over 800 million people are malnourished globally and yet future predictions state that agriculture must provide for an additional 3.5 billion people (Cairns *et al.,* 2013). This is a major shortfall in the plight to fight global food insecurity as the challenges faced in agricultural production escalate. Lack of arable land, implementation of improper agricultural practices, frequency of droughts, scarcity of water, pests and diseases are some of the major issues that have affected agricultural production (Benhin, 2006). However, even though the severities of some of the impacts of these issues are great, most studies investigating agricultural production in the more recent past have been devoted to climate change. The studies have revealed that agricultural production will largely be negatively affected by climate change and this will impede the ability of many regions to attain food security (Lobell *et al.,* 2008).

The greatest impacts on agriculture due to climate change are expected to be in the tropics and sub-tropics, with sub-Saharan Africa (SSA) particularly vulnerable due to multiple stresses and low adaptive capacity (Mendelson *et al.,* 2000). As a result, agricultural production has been limited to crops that can be easily farmed as well as survive hot and dry conditions. Maize is the most popular crop and is the staple food for large parts of the SSA. In South Africa, maize is grown extensively in the Highveld Eco-region yet the country experiences semi-arid conditions. Currently, South Africa is the world's ninth maize producer and contributes 50 % of maize in the Southern African Development Community (SADC) making it a major source of food for the region (FAO, 2012).

According to the mid-2013 estimates from Statistics South Africa, the country's population stands at 52.98 million, up from the census 2001 count of 44.8 million. Population growth is at almost 2 % every year and at this rate, the population is projected to grow up to 82 million by the year 2035. This will pose a major challenge to the already increased food insecurity in the country. In order to account for the population growth, agricultural production, particularly maize, should be increased by at least 6 % per annum before 2015 with more focus on rural areas since they experience high population growth rates with greater food demands than supply (van Rooyen and Sigwele, 1998; Inocencio *et al.*, 2003). With a low standard of living in rural areas, maize production has proved to be a more reliable food source over many years mainly because of its ease to farm. However, maize production in these areas still fails to address food security issues due to the influence of other factors such as climate change, minimal arable land and unskilled farming methods (Walker and Schulze, 2006).

Economically, maize production in South Africa has a farm-gate value of R9.4 billion per annum making it a vital contributor both locally and in the SSA region (Behin, 2006). However, sensitivity analyses of maize yields have shown that increase in air temperatures by 1 – 4 °C and rainfall reduction by 10 – 20 % will decrease yields (Engelbrecht, 2005). Statistical evidence, although limited, shows that South Africa has been getting hotter over the past four decades. Kruger and Shongwe (2004) showed that the country's average yearly air temperatures increased by 0.13 °C/decade between 1960 and 2003. Unfortunately, maize production or any other agricultural crop depends on these climate variables and therefore changes thereof may affect sustainability of livelihoods.

The gap between understanding future climate changes and the impacts on maize production has been bridged by modelling. This has allowed users to effect future plausible changes in climate on maize production which has since provided a platform to develop management and operational strategies aimed at improving current yields and also ensuring supply in the future. Various studies of this nature have been conducted in South Africa with most having relied on the CERES-Maize model (du Toit, 1993; du Toit, 1994, Walker and Schulze 2006).

Most studies regarding the maize crop in South Africa have focused on the phenological and genetic aspects of the plant. Even though there is always a link between the influence of climate parameters and maize production, the subject is not well explored. In fact, only a few studies have been conducted: (a) Walker and Schulze (2008), who investigated climate change impacts on agro-ecosystem sustainability across three climate regions in the maize belt of South Africa using the CERES-Maize model, (b) Walker and Schulze (2006), who assessed the suitability of maize production under different climatic scenarios for small holder agro-ecosystems in KwaZulu-Natal using the CERES-Maize model, (c) Abraha and Savage (2006), who by means of the CropSyst model investigated the potential impacts of climate change on maize in the Midlands of KwaZulu-Natal. This study is similar to the one Abraha and Savage (2006) conducted but focuses on a larger scale with areas representative of key areas of the Highveld Eco-region and also, the study uses longer and more up-to-date input climate data for the CropSyst model.

In essence, there is a need for more robust investigations on the influence of changing air temperature on maize production in the Highveld region. Ideally, all locations within the region should be investigated. This would increase precision in results and aid in correctly diagnosing the problems causing yields to reduce or increase at slower rates seasonally as the climate changes.

1.2 Aims

- The primary aim of this study is to assess the impacts of changes in climate to maize yields and on yield variation in five selected areas in the Highveld Eco-region in South Africa. Two key climatic variables associated with climate change that affect crop production are air temperature and rainfall.
- This study also attempts to determine whether parts of the Highveld region are cooling or warming by comparing annual trends in mean maximum and minimum air temperatures for selected areas of the Highveld Eco-region.

1.3 Objectives

- Gather and document a literature review regarding climate change and modelling its influence on the maize crop.
- Statistically analyse using Microsoft Excel the annual air temperature averages for the entire record lengths of the measured data-sets for the selected locations in the Highveld Eco-regions.
- Generate synthetic data from measured data using the CLIMGEN weather generator.
- Compute the coefficient of variation as a measure of yield variation using Microsoft Excel at all locations selected.
- Use the synthetic data as input into the CropSyst model to simulate maize yields based on plausible future climatic changes.

1.4 Thesis structure

Chapter 1 introduces the study, giving an overview of the need to investigate the impacts of changing climate on maize production in the Highveld region.

Chapter 2 is a review of the literature which encompasses climate change, impacts on crops and specifically details of the maize crop. The chapter also includes a section on modelling as it is vital in understanding future climatic influences on maize.

Chapter 3 outlines the methodology employed in the study. It includes descriptions of the study sites and some of the modelling exercises done in the project. Also, the chapter contains descriptions of the models used in and outlines the scenarios applied onto the climate data.

Chapter 4 is the results and discussion section of the study. Divided into two sections, the first describes an analysis of the air temperature trends for the measured climate data for each study site. The second reports on the results and discussion of changes in maize yields after modelling under various plausible future changes.

Chapter 5 concludes the study.

Chapter 6 is the references used in the study

2. LITERATURE REVIEW

2.1 Climate change

Past climatic records show a variation in the global climate. This is due to various natural processes that occur within the ocean, atmosphere, geosphere, cryosphere and biosphere continuum (Hardy, 2003). Energy from the sun facilitates the interactions within the spheres and stands as a main influence to climate variations. Various factors, known as forcings, collaborate with solar energy to influence the climate through input and output modifications (Parry *et al*., 2007). The role played by solar energy, the earth's orbit, forcings, and geological processes causes a natural influence to climate change (Parry *et al*., 2007). There may also be consequential impacts, such as alterations to the outgoing and returned infrared fluxes which in turn may alter surface temperatures.

However, studies have revealed an exterior factor that propagates climate change at a much higher rate. Studies indicate a strong direct proportionality between changes in climate and the inception and development of industrialisation (Rosenzweig and Hillel, 1998; Ding *et al*., 2001; Le Treut *et al*., 2007). The detrimental effects of industrial by-products have been felt both on land and in the atmosphere. Although both the land and atmosphere are impacted negatively, the magnitude of the impact on atmospheric constituents far out-weighs that of land because the impact spans a larger scale for longer periods of time (Parry *et al*., 2007). However, this should not encourage ignorance on land conservation practices since they play a significant role in protecting and sustaining ecosystems (Chan *et al*., 2006).

The atmosphere includes various chemical and physical compounds that; sustain life on earth, act as a conduit for transportation of extra-terrestrial energy and regulate temperature on the planet (Hardy, 2003). The role played by the atmosphere in regulating energy transmission in and out of the earth is vital and if altered, the energy balance across the land, atmosphere and space continuum becomes effected (Hardy, 2003). Without energy, life would cease. One major function that has been distorted as a result of anthropogenic activities is the atmosphere's ability to regulate temperature (commonly known as the greenhouse effect) (Rosenzweig and Hillel, 1998; Le Treut *et al*., 2007).

2.1.1 The greenhouse effect

The magnitude of the incoming solar radiation into the earth's atmosphere is reduced by: clouds through reflection, absorption by atmospheric constituents and reflection on the earth's surface (as shown in **Figure 2.1**). The radiation absorbed by the earth's surface is then re-radiated back into the atmosphere as infra-red radiation. The infra-red radiation occurs in two distinct radiation fields. The first originates from solar energy consisting of shortwave radiation, which is in the visible and ultraviolet regions. This energy constitutes about 32 % of the energy received on the earth's surface (17 % direct and 15 % scattered by clouds). The second field emanates from the heated earth's surface to the atmosphere in the infra-red region (Parry *et al*., 2007; Le Treut *et al*., 2007). The radiation is then absorbed by gases and re-radiated back into the earth, resulting in warming (Rosenzweig and Hillel, 1998). The warming is known as the greenhouse effect. **Figure 2.1** shows this phenomenon as well as other radiation exchange components between the atmosphere and the earth's surface.

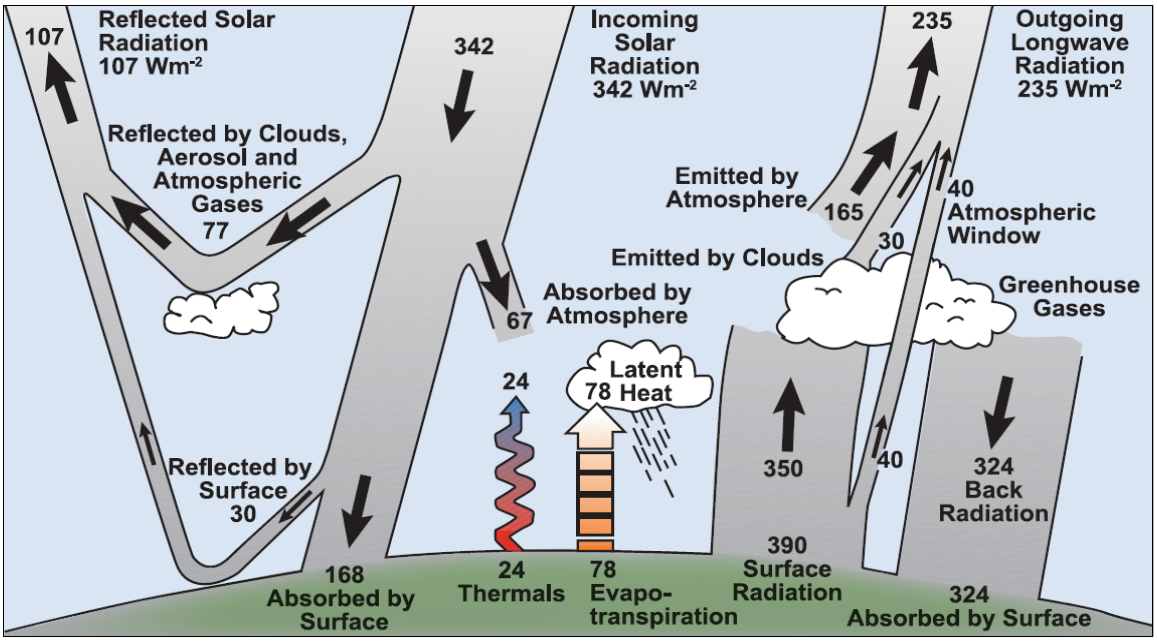

Figure 2.1 Radiation (W m^{-2}) exchange in the atmosphere and at the earth's surface (Parry *et al*., 2007).

Without the earth's greenhouse effect, average temperatures would plummet below the freezing point of water and could reach temperatures of -18 ^{o}C (Rosenzweig and Hillel, 1998). Atmospheric constituents responsible for the warming include water vapour, carbon dioxide, methane, nitrous oxide, ozone, aerosols halocarbons (a group of gases containing fluorine, chlorine and bromine) and sulphur hexafluoride (Boadi *et al*., 2002). Water vapour is the most important greenhouse gas. However, minimal direct influences are experienced due to human activities that worsen the effect of other atmospheric constituents to levels that pose an immediate danger to life-forms on earth (Rosenzweig and Hillel, 1998; Le Treut *et al*., 2007). In essence, contribution by humans in elevating the concentration of atmospheric water vapour is predominantly indirect. Anthropogenic activities that enhance the greenhouse effect encourage more evapotranspiration from water bodies thus adding more water vapour to the atmosphere (Parry *et al*., 2007; Hardy, 2003). Also, when methane (CH_4) is oxidized in the stratosphere, it releases water vapour (Parry *et al*., 2007; Hardy, 2003). Carbon dioxide (CO_2) is the second most important greenhouse gas and due to its direct influence on climate change, it is considered to be the main culprit of changes in climate (Rosenzweig and Hillel, 1998). Methane, nitrous oxide, ozone, aerosols and halocarbons also exert influence on the radiation balance within the earth but to a lesser degree. This influence, called radioactive forcing is increased as the concentration of the gases increase. Among the greenhouse gases, carbon dioxide has caused the greatest forcing since the beginning of the industrial era (Parry *et al*., 2007; Hardy, 2003).

2.1.2 Gases of concern

The three most important gases associated with agriculture are CO_2, CH_4 and N_2O (Snyder *et al*., 2009). Plants use CO_2 for photosynthesis thus reducing the atmospheric content. The same plants release CO_2 during respiration, but in lower quantities. CO_2 is released in small quantities through the decomposition of plant and animal tissue. Larger quantities are released when burnt especially when previously fossilized over time (Le Treut *et al*., 2007). Cement manufacturing and other goods, building heating and cooling, and deforestation also contribute to CO_2 releases into the atmosphere (Le Treut *et al*., 2007). Contribution to the atmospheric CH_4 is mainly from agricultural practices, natural gas distribution and landfills with some quantities being released from wetlands (Rosenzweig and Hillel, 1998; Le Treut *et al*., 2007). Fertilizer applications and fossil fuel combustions releases N_2O while naturally, N_2O is released when chemical processes in the soil and ocean release amounts into the atmosphere (Hardy, 2003).

As shown in **Figure 2.2**, concentrations of CO_2, CH_4 and N_2O were fairly constant for the first 1600 years and then changed in the year 1750 when concentrations suddenly rose exponentially. The rise in concentrations coincides with beginning of the industrial era. In the years leading up to 1750, CO_2 concentrations ranged from 275 - 285 µLL^{-1} with CH_4 and N_2O concentrated within 620 - 650 nL L^{-1} and 650 - 800 nL L^{-1} respectively (as shown in **Figure 2.2**). However, post-1750 saw a CO_2 concentrations increase of about 100 µL L^{-1} and in 250 years concentrations reached up to 379 µL L^{-1} (by 2005) and is expected to double by the year 2050 (Rosenzweig and Hillel, 1998; Le Treut *et al.*, 2007). Current carbon emissions are approximated to be at 9.4 G ton of carbon with 7.9 G ton of it from fossil fuel combustion and industrial processes. About 1.5 G ton is from land use change, mainly from land clearing (Lal, 2004; Raupach *et al.*, 2007; Le Treut *et al.*, 2007). Almost half of the CO_2 persists for longer periods while the rest is absorbed by the ocean and forests. This worsens climate change and if measures to mitigate change are not implemented, it is hypothesized that generations yet to come will experience life under harsher climatic conditions (Ledley *et al.*, 1999).

Methane concentrations increased post-1750 and stabilised at about 1774 nL L^{-1} by 2005. However, concentration rates have since decreased in the last two decades. With N_2O, accumulation in the atmosphere occurred at slow rate with concentrations reaching only up to 44 nL L^{-1} between 1750 and 1998 (Rosenzweig and Hillel, 1998).

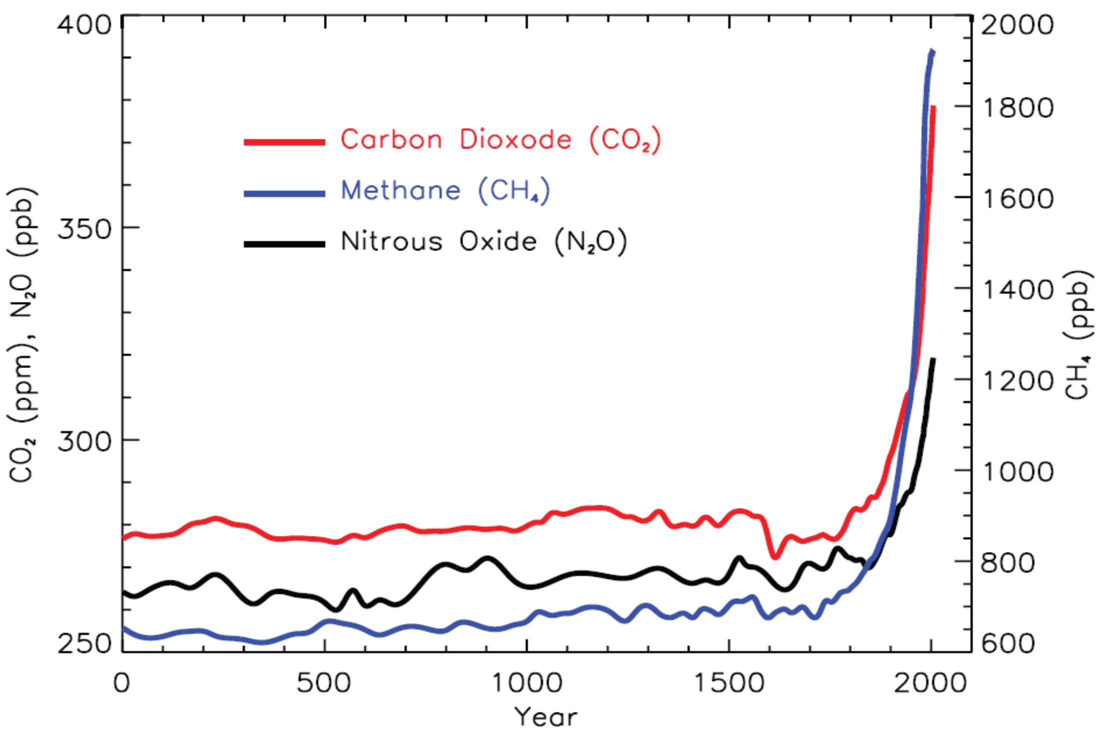

Figure 2.2 Concentration of greenhouse gases CO_2, CH_4 and N_2O from the year 0 – 2005 (Parry *et al.*, 2007).

2.1.3 Warming

Warming is a result of the enhanced greenhouse effect. The global average temperature has increased by 0.74 ^{o}C when estimated by a linear trend over the last 100 years (1906 – 2005). The rate of warming over the last 50 years (0.13 ^{o}C) is almost double the rate over the last 100 years (0.07 ^{o}C) (Parry *et al.*, 2007). In 1997, analysis of global records showed the five warmest years had occurred during the 1900s, with most occurring after 1980. However, in the 21st century, even higher average temperatures were recorded (Cubasch *et al.*, 2001). According to the National Aeronautics and Space Administration (NASA), 2009 and 2010 are the hottest years since 1880 (globally) (Foster and Rahmstorf, 2011). By the year 2100, average temperatures are expected to increase by 3.5 ^{o}C from the beginning of the 20th century (Parry *et al.*, 2007). Other more recent model predictions reveal an even greater rate of increase of up to 5.8 ^{o}C (Cubasch *et al.*, 2001).

Surface air temperature increases differ from region to region. The Northern Hemisphere (NH) experiences greater air temperature increases compared to the Southern Hemisphere (SH) (Mann and Jones, 2003). An analysis of monthly average maximum and minimum temperatures and the diurnal temperature range – DTR (difference between mean monthly maximum and minimum air temperatures) at 5400 observing stations around the world revealed the difference in the rates of air temperature increase between the NH and SH (Easterling *et al.*, 1997). As shown in **Table 2.1**, the rates of increase from both maximum and minimum air temperatures are greater for the NH. Higher DTR rates of decrease in the NH than that of the SH was also found. The differences are attributed to larger land area in the NH than the SH and the advancement in the industrial sectors in the NH (Hughes and Balling, 1996) (Trenberth *et al.*, 2001)

Table 2.1 Annual trends from 1950 – 1993 for maximum and minimum air temperature and DTR for the Northern Hemisphere and Southern Hemisphere (Easterling *et al.*, 1997).

Hemisphere	**Air temperature (^{o}C/100 years)**		
	Maximum	**Minimum**	**DTR**
NH	0.87	1.84	-0.89
SH	0.84	1.80	-0.60

Even though the rates of increase in the NH exceed that of the SH, studies have shown trends of minimum air temperatures in the SH to soon catch up with that of the NH. The contribution of the increasing tropospheric aerosols (although still lower than the NH) in increasing minimum air temperatures is less when compared to the NH (Mann and Jones, 2003). As a result, other factors such as increased cloudiness, direct absorption of infra-red portions of incoming solar irradiance and water vapour feedbacks, contribute to the steady increase in DTR in the SH (Easterling *et al.*, 1997). Also, since the soil heats up faster than water and with more landmass than water in the NH, higher air temperature increases are expected (Mann and Jones, 2003).

However, large parts of the world, particularly in the tropics and the continent of Africa are still unaccounted for due to either lack of digitally or publicly available weather data or have sparse data coverage (Easterling *et al.*, 1997; Frich *et al.*, 2002; Lamptey *et al.*, 2009; Collins, 2011). The lack of infrastructure and delayed weather data collection in most African countries has resulted in numerous locations having shorter record lengths, with poor quality data (Hughes and Balling, 1996). The establishment of weather station networks across the continent has been significantly hindered by the technological and scientific underdevelopment prevalent in many African nations (Lamptey *et al.*, 2009).

However, studies assessing the degree of global warming have been conducted and reliable results have been observed (Collins, 2011). Collins (2011) reported findings by Hulme *et al.*, (2001) who found that Africa warmed at an average rate of 0.5 ^{o}C/century throughout the 20th century. Studies conducted on the basis of shorter periods within the 21st century were found to contradict the trends found by Collins (2011). For instance, King'uyu *et al.*, (2000) investigated trends in mean surface maximum and minimum air temperatures (1939 – 1992) from 19 countries located on the eastern part of the African continent and extending from the Southern Sudan extending southwards to Botswana, Zimbabwe and Mozambique. They found a general warming in minimum temperatures in the latter years of the study period at several locations in east Africa. Contradictory trends were noted in the coastal zones and inland locations near water bodies such as large lakes and rivers where minimum air temperature trends either showed no changes or cooling trends (King'uyu*et al.*, 2000). Hulme *et al.*, (2001) also found that Mediterranean coastal countries in north-western Africa and inland southern Africa warmed at 2 ^{o}C/century and that there was a general cooling trend in a few regions that spread across Nigeria, Cameroon, Senegal and Marituana.

Studies conducted on a smaller scale, such as in South Africa for instance, have proved less reliable due to larger natural climate variability. However, trends obtained from such studies can still be trusted to depict current changes in climate (Collins, 2011). Various studies (in South Africa) have shown an increase in mean monthly air temperatures or a decline in the DTR as a general trend over the past several decades (Karl *et al.*, 1993; Easterling *et al.*, 2000). Other studies in South Africa have found either no real evidence of overall changes in mean monthly maximum air temperature, or significant increase in mean annual air temperatures (Karl *et al.*, 1993; Kruger and Shongwe, 2004). Advances in understanding of uncertainties as well as external forces that influence air temperature on a smaller scale will improve analyses in the future (Collins, 2011).

2.1.4 Adaptation and mitigation

As the air temperature increases, it affects other climatic variables such as rainfall variability and amount, solar irradiance and relative humidity (Hardy, 2003). Due to the influence of these climatic variables on the livelihoods of humans, understanding the changes thereof is important in ensuring a sustainable life. Various efforts to curb the increase in air temperatures, either individually or cooperatively are already on-course. However, individual attempts are futile since the task is too challenging to be tackled individually or a handful of nations.

An initiative called the Kyoto Protocol treaty set a platform for parties (countries) to reduce greenhouse gas emissions in an attempt to reduce warming (den Elzen *et al.*, 2011). An international environmental treaty is the only regime available to combat climate change. The treaty, working with the United Nations Framework Convention on Climate Change (UNFCC), involved binding obligations on industrialised countries to reduce emissions of greenhouse gases (den Elzen *et al.*, 2011). The treaty separates the parties into two:

- Annex 1 countries – developed countries that are required to implement legally binding greenhouse gas emission reductions under the UNFCC,
- Non-Annex 1 countries – a group of developing countries that have signed and ratified the UNFCC. They have no binding emission targets (den Elzen *et al.*, 2011).

Many developed countries (excluding the United States of America and Canada) agreed to legally binding reductions in their emissions of greenhouse gases within two commitment periods: the first applied to the reduction in emissions within the period 2008 - 2012 and the second from 2013–2020 (den Elzen *et al.*, 2011). With the first commitment period over and with minimal progress made, focus has now turned to the second commitment period (den Elzen *et al.*, 2011). At the last Congregation of Parties (COP 17) in Durban, South Africa, it was concluded that deeper reductions in global emissions are to be enforced in order to curb the rising average global surface temperature to below 2 ^{o}C by 2020 (target set at Copenhagen Accord in 2009). A new protocol was birthed, that aimed at involving more countries to implement greater legally binding emission reductions (Boyle, 2011). Even though it is an upgrade of the Kyoto Protocol, the disadvantage to this new treaty is that it is set to be completed by 2015 and implemented by 2020, delaying the progress in reducing climate change (Boyle, 2011).

Various scientific groups have modelled estimates of global emissions in 2020 using trajectories based on the Copenhagen Accord (surface temperatures below 2 ^{o}C) (van Aardenne *et* al., 1999; Meinshausen *et al.*, 2009; Rogelj *et al*., 2009; Rogelj *et al*., 2010). Due to the differences in results obtained by the various groups, uncertainties as to whether current binding pledges to reduce emissions are sufficient to meet the 2020 targets have increased. In fact, many have predicted a gap, i.e. the gap between the set 2 ^{o}C climate target by 2020, and the emission levels projected if all parties adhere to reduction pledges (den Elzen *et al.*, 2011). The 2010 Emissions gap and the 2011 Bridging the emissions gap reports indicated a possibility of a gap in 2020 that is larger than anticipated (Rogelj *et al.*, 2011). As a result, the United Nations Environment Program (UNEP) convened a group of 55 scientists and experts for 43 scientific groups across 22 countries to a third emissions gap report that gives a comprehensive assessment of current and projected (2020) national emission levels consistent with current pledges (The report is still in progress).

Involvement by more countries (especially developed countries) in the Kyoto Protocol would assist in meeting the future emission target. Day-to-day activities that contribute to greenhouse gas emissions will not be eliminated overnight. However, adhering to the mitigation attempts to limit emissions is an improved approach rather than adaptation (Rogelj *et al.*, 2011).

Global climate change has already had a negative impact on the environment. Glaciers have shrunk from the poles, ice on rivers and lakes are breaking up earlier, plant and animal ranges have shifted and trees are flowering faster than times in the past (Parry *et al*., 2007). The impact on individual regions will vary over time and forecasters predict:

- increased releases of CH_4 from previously frozen arctic and Antarctic regions,
- an increased rate of reduction of the snowcap in the western mountains of North America,
- a gradual replacement of the tropical forest by savannah conditions in Eastern Amazonia risking loss of biodiversity,
- increased risk of flash floods, more coastal flooding and increased erosion from storms as well as rising sea levels in southern Europe,
- more exposure to increased water stress in Africa, which in turn affects agricultural production, and
- a decrease in freshwater availability in Central, South, East and Southeast Asia by the 2050s. Increased flooding and droughts are also expected in some regions (Parry *et al*., 2007).

Temperature responses to an increase in greenhouse gas forcings is thought to be larger in the polar than equatorial regions (Graverson *et al*., 2008). The Polar Regions are covered in ice that has been melting at faster rates with increases in temperatures. Ice has a high albedo reflecting most of solar irradiance. Over the years, the ice has melted as a result of increases in temperatures revealing a darker underlying surface which reflects less and absorbs more of the solar irradiance (lower albedo) (Curry *et al*., 1995). This process is known as arctic amplification and has caused near-surface warming to be almost twice as large as the global average over more recent decades (Graverson *et al*., 2008).

Due to the problem of food insecurity in Africa, climate change poses a major threat to agricultural production hence the need to find solutions that will enable farmers to better adapt to the changing conditions (Schlenker and Lobell, 2010). Many Africans depend on agricultural production for sustainability. Therefore, studies aimed at understanding the impact of climate change on a crop or any other plant that contributes to the well-being of Africans are necessary.

2.2 Potential impacts of climate change on crops

The extent of growth and yield in crops influenced by higher CO_2 concentrations depends on the photosynthetic pathway (Allen and Prasad, 2004). Three distinct photosynthetic pathways exist: C3, C4 and *crassulaecean acid metabolism* (CAM). C3 photosynthetic plants are those that fix carbon through the process of photosynthesis where CO_2 reacts with five carbon compounds called Ribulose-bisphosphate (RuBP), producing a three carbon-compound molecule called Phospho-glyceraldehyde (PGA) (Edwards and Walker, 1983). Examples include small grain cereals (wheat, rice, barley, oat and rye) grain legumes or pulses (soybean, peanut, various beans and peas), root and tuber crops (potato, cassava, sweet potato, sugar beet, yams) and fibre crops (Allen and Prasad, 2004). Plants that undergo the photosynthesis process which involves a reaction of CO_2 with four-carbon compound called Phospho-enolpyruvate (PEP) to form two molecules of a three carbon compound molecule are known as C4 plants (Edwards and Walker, 1983). Examples of C4 plants include maize, sugarcane, sorghum and millet (Allen and Prasad, 2004). The CAM pathway occurs in many epiphytes and succulents from very arid regions, for example, pineapples. This photosynthetic pathway has limited photosynthetic distribution with minimal contribution to the global cycle (Ehleringer *et al.*, 1997).

Crops with different photosynthetic pathways are affected differently by climate change (Rosenzweig and Hillel, 1998). Due to the large scale production of C3 and C4 crops, focus has been on these two photosynthetic pathways and how they are affected by climate change.

C4 plants include some of the most important crops in the world, i.e. maize, sorghum, millet, forage and a range of grasses and noxious weeds (Brown, 1999). Although C4 plants cover approximately 4 % of the world’s plant species, their contribution to the global primary productivity is about 18 – 21 % (Ghannoum *et al.*, 2000). However, this is inclusive of the high productivity from grasslands masking the contribution by crops.

2.2.1 Crop response to CO_2 enrichment and air temperature increase

Increased atmospheric CO_2 concentrations tend to steepen the gradient between the external air surrounding the leaf and the inside of the leaf stomata. This encourages increased absorption of CO_2, which in-turn increases the rate of photosynthesis (Ehleringer *et al.*, 1997).

Generally, C3 plants respond markedly to increased CO_2 concentrations compared C4 plants (Rosenzweig and Hillel, 1998). The greater response from C3 plants is attributed to the ability to photo-respire. Photo-respiration is photosynthesis reversed (Rosenzweig and Hillel, 1998). During this process, the C3 plants re-oxidise some of the carbon that was initially reduced from CO_2 and fixed into carbohydrates, releasing chemical energy, which then decreases the net photosynthesis to below that of C4 plants (as shown in **Figure 2.3**) (Rosenzweig and Hillel, 1998). This occurs only under current CO_2 concentrations of 390 μL L^{-1}. Doubling of current CO_2 concentrations reduces photosynthetic efficiency in C4 plants causing the C3 rate to exceed that of C4. The increase in net photosynthesis in C3 plants can reach up to 30 – 50 % (Allenand Prasad, 2004). Therefore, C4 crops such as maize are vulnerable to competition posed by C3 weeds under a CO_2 enriched atmosphere (Rosenzweig and Hillel, 1998).

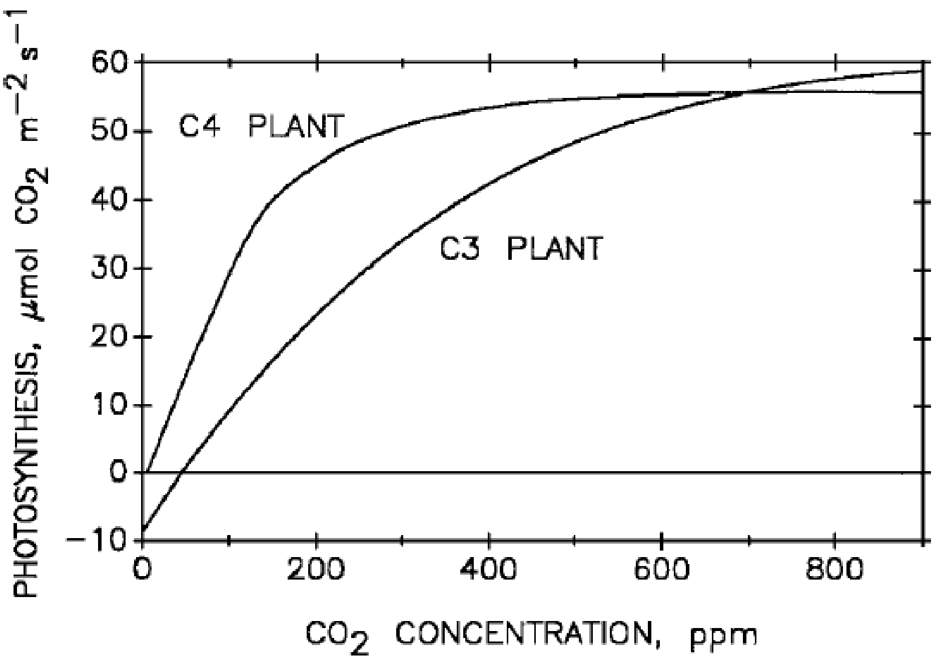

Figure 2.3 Typical leaf photosynthetic rate response of a C3 and a C4 plant to CO_2 concentration when measured under non-limiting (high light) conditions (Allen and Prasad, 2004).

Generally, the C4 photosynthetic pathway is not affected by elevated CO_2 concentrations because CO_2 within plant cells are already at high concentrations. Concentrations can rise up to 3 - 6 times higher than the concentrations in the atmosphere (Leakey *et al.*, 2006). At current atmospheric CO_2 concentration, the cells are already saturated, reducing CO_2 assimilation (Ghannoum *et al.*, 2000). As a result, the stomata close, reducing transpiration, thus improving water use efficiency. At the same time, photosynthesis increases, resulting in a positive response to elevated CO_2 concentration (Drake *et al.*, 1996). However, closure of the stomata for extended periods can cause plants to heat up. Heat causes biochemical processes within cells to slow down or cease if temperatures exceed the optimum temperature threshold that a plant can bear (Amthor *et al.,* 1992).

Increased CO_2 concentration can affect respiration in plants both directly and indirectly. Direct impacts occur during a short term change in CO_2 concentration and may cause changes in enzyme activity and the diffusion rates of CO_2 thereby reducing respiration (Thomas and Griffin, 1994; Baker *et al.,* 2006). A study done by Bunce (1990) found short-term inhibitions of increased CO_2 concentration on respiration, whilst Amthor *et al.,* (1992) found a reduction of 25 – 30 % in respiration after doubling [CO_2]. Other studies have shown direct impacts of elevated CO_2 concentration (Bunce, 1990; Amthor *et al.*, 1992)

Indirect effects involve prolonged growth of plants under elevated CO_2 conditions. This causes an increase in respiration due to increased rates of photosynthesis, growth rates and substrate levels (Bunce and Ziska, 1996). This is substantiated by the notion that greater biomass require a higher energy supply for maintenance and growth, and hence the increase in respiration (Rosenzweig and Hillel, 1998).

At increased air temperatures, the rate of respiration increases significantly. The magnitude of increase can double for every 10 ^{o}C increase (Amthor *et al.*, 1992). However, increases are limited by acclimation i.e. the ability of an organism to adapt under new environmental conditions (Rosenzweig and Hillel, 1998). Greater air temperatures encourage CO_2 assimilation by increasing the CO_2 saturation point within cells, leading to an increase in photosynthesis. However, this is only a reality for slight temperature increases. Once the temperatures increase beyond the plant's optimum temperature for photosynthesis, stress begins to set in (Amthor *et al.*, 1992). A decline in photosynthesis is then experienced, leading to losses in yields. Furthermore, the plants suffer oxidative damage to cells, modifications in membrane functions, denaturing of proteins, reduced pollen germination ability and reduced kernel growth rates (Barnabás *et al.*, 2008).

2.2.2 Economic impact

The agricultural sector is vulnerable to climate change, both physically and economically (Gbetibouo and Hassan, 2005). As the problem of climate change worsens, agricultural supply, especially agricultural food prices will be affected, eventually affecting economies and trade relations between countries (Deke *et al.*, 2001). Numerous empirical studies have been conducted around the world on the impacts of climate change on the agricultural sector (Rosenzweig and Hillel, 1998; Jones *et al*., 2003, Abraha and Savage, 2006; Behnin, 2006; Walker and Schulze, 2006; Kalra *et al*., 2007; Benhin, 2008; Walker and Schulze, 2008). Models have been a major part of the studies and assessment of economic imbalances experienced in countries as a result of climate change have been found (Cline, 1996; Darwin, 1999; Mendelson, 2001; Gbetibouo and Hassan, 2005). Two major approaches have been used to study the interaction between climate, water and agriculture: (a) the Agronomic-Economic approach – calibrated agronomic models that can predict outcomes of economic simulations. (b) The Cross-sectional approach – compares choice and performance of existing farms that are facing different climate and soil conditions (Gbetibouo and Hassan, 2005).

Quantifying the benefits of major crops on the economy of any country is important. This can only be achieved when proper methods that encompass all factors which contribute to the increase and decrease of the crop yields in response to changes in climate are considered. Gbetibouo and Hassan (2005) used a simple empirical approach known as the Ricardian method to study the sensitivity of agricultural production to climate change based on cross-sectional data. The study was conducted in South Africa and their results revealed that the percentage change in net revenue per hectare will increase up beyond 30 % in the Free State and Northern Cape whilst the North West, Limpopo and the Western Cape falling short of the 20 % increase mark. Gauteng, KwaZulu-Natal and Mpumalanga experienced less than 20 % reductions in net revenue per hectare. The study included all South African field crops.

The simplistic approach of the Richardian method has been the most preferred approach amongst researchers mainly because of its ability to account for farm level adaptations and assessment of the relationship between crop performance and climate (Kumar and Parikh, 2001). However, other studies have also raised concerns on the validity of the results obtained using the method (Cline, 1996; Darwin, 1999; Mendelson, 2001):

- Adaptation costs are not considered,
- Analysis makes forecasts based on current farming practices without considering possible future changes that could affect agriculture,
- Does not take into account water supply and availability. If ignored this can affect credibility of the results especially in a country such as South Africa were water in a scarce and precious commodity,
- Treats prices as constant.

In spite of the drawbacks in using the Richardian method, it has gained popularity and has been used worldwide (Kabubo-Mariara and Karanja, 2007; Molua and Lambi, 2007; Kurukulasuriya, 2008; Amiraslany, 2010; Thapa and Joshi, 2010). Other more sophisticated approaches such as the Hydrological-Economic model and the Economic General-Equilibrium model require more robust input information which can be tedious process yet could produce more realistic results (Mendelson, 2001; Deke *et al*., 2001)

2.3 Important crops grown globally

According to Leff *et al.*, (2003), crops were grouped into categories based on distinct biochemical, phenological and food resource characteristics. The categories are shown in **Figure 2.4**.

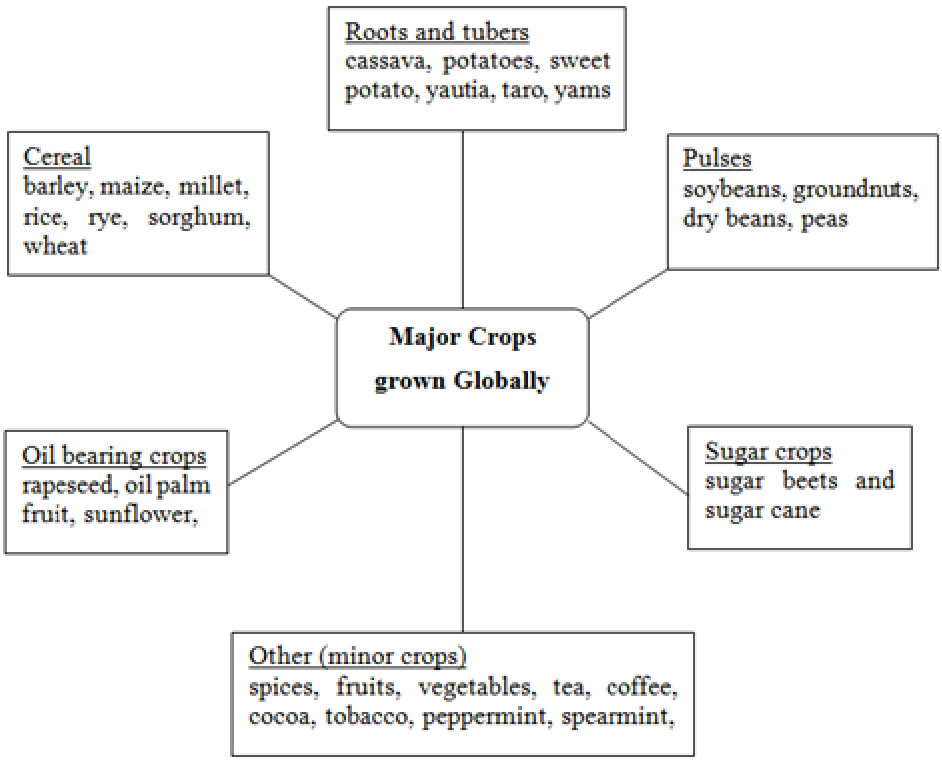

Figure 2.4 Categorized major crops grown on a global scale (Leff *et al.*, 2004).

Of all the crop groups, cereals are the most important direct source of food to humans for consumption and indirectly since there are also used in livestock production. Maintaining supply is therefore fundamental in order to ensure a sustainable livelihood for all. For decades, cereal production has been on the rise. Since the mid-1960s the world has managed to raise cereal production by almost a billion tons (Hengsdijk and Langeveld, 2009). However, the increase in production is expected to slow down over the period 2015 – 2030 due to expected slower population growth and the levelling off of food consumption (Hengsdijk and Langeveld, 2009).

Regional analysis showed that in developing countries, the demand for cereals has grown faster than the supply, forcing many countries to import (Hengsdijk and Langeveld, 2009). Reports suggest that global dependence on imported cereals is likely to increase in the future and predictions are that imports will reach as high as 250 million tons annually (14 % of their cereal consumption) (Hengsdijk and Langeveld, 2009). The most dominant cereal crops in terms of the developing world and large spatial coverage globally include: maize, wheat and rice (Hengsdijk and Langeveld, 2009).

2.3.1 Maize

Maize forms part of the coarse grains produced globally (Hengsdijk and Langeveld, 2009). Other crops include sorghum, barley, rye, oats and millet. About 55 % of the world's coarse grains are used for animal feed mostly contributed from developed countries. Where food security is a problem, such as the sub-Saharan Africa, 80 % of the production is directly consumed by humans (Hengsdijk and Langeveld, 2009). With consumption on the rise, experts predict a faster rate of increase than that of wheat and rice (FAO, 2013).

Maize is known to have originated in America. Its popularity spread throughout the world as its nutritional value gained recognition from developed to developing countries. In the developing African continent, its introduction came through the eastern and western coasts by the Americans as a ration with the slave trade (Smale *et al.*, 2003). This resulted in the replacement of millet and sorghum as staple foods for most sub-Saharan African countries. The crop's widespread gain in favour was attributed mainly for its ability to sustain livelihoods especially in communities located in rural areas where famine proliferates (Byerlee and Heisey, 1996). Other factors that fuelled gains in popularity include its minimal production cost, minimal need of technical skill, agronomic suitability, the broad British starch market and rise in milling technology (Pingali, 2001).

However, despite the crops extensive growth throughout sub-Saharan Africa, its contribution to the world maize production has been low. In the 1970s, the share of maize in total cereal production (includes sorghum, wheat rice and millet) had risen to 40 % from 35 % previously recorded in the 1950s (Byerlee and Heisey, 1996). By the 20th century, production had dropped to a low of 36 % (FAO, 2013) which still proved the crops dominance over the other cereal crops. However, in a world context, sub-Saharan African only contributed 7 % of the world maize production compared to 39 % from the United States of America and 14 % from China (FAO, 2013). Wrong implementation or lack of various practical and theoretical skills has contributed to the low maize production for years. Such studies broaden the knowledge on improving maize production on marginal areas, which is where most African maize is found (Byerlee and Heisey, 1996). As a result, low maize yields are obtained seasonally.

The dominance of non-arable land is not the only factor that reduces maize yields; climate and poor agricultural methods also contribute extensively as well. The latter can be improved through acquiring knowledge while the former is virtually beyond human control because of its natural variability. This instability (changes in natural climatic patterns) has been gravely aggravated by human activities that release by-products which alter the composition of the components found in the atmosphere, distorting their functions. Therefore, factoring in the impacts of climate change in maize production is critical.

In the African continent, maize is mostly grown in the western and eastern belts, with small pockets of maize production within the central areas as well. Maize production flourishes in these areas because of high rainfall and optimum temperature ranges. Most of the remaining land is non-arable, thus need for skills that will enable transformation of the vast non-arable to arable land in the continent. For instance, in the Southern African Development Community (SADC), the presence of the Kalahari Desert in southern Africa aggravates the lack of arable land. Its vast area, which extends through Botswana, Zimbabwe, Zambia, Angola, Namibia and South Africa respectively reduces arable areas forcing farmers into low yielding marginal (Singletary *et al.*, 2003). In spite of this, large scale maize production is practiced within the SADC region. Maize covers 58 % of the total crop production land in the SADC region with approximately 50 % of production contributed by South Africa alone. Therefore, South Africa is a major source of maize in the region (Benhin, 2008).

2.3.2 Other major crops

Wheat and Rice are also major crops grown globally. Wheat is the most widely produced crop after maize and rice in terms of dietary intake otherwise, as a main food source, world wheat production is second to rice (FAO, 2013). In developed countries, wheat is mostly used for animal feed, which constitutes 19 % of the world wheat production. About 70 % (which is increasing) of the crop is used for consumption and is mostly from developing countries of which most is imported (Hengsdijk and Langeveld, 2009). Rice is an important global crop since it is a staple food for more than half the world's population. More recently, the crop has gained popularity in various African countries such that it has also become a staple crop (Hengsdijk and Langeveld, 2009).

2.4 Crop modelling

Success in crop production depends on an ability to manipulate physical, chemical and biological processes surrounding crop growth. Execution of practices that improve production requires prior knowledge of the medium and conditions favourable for optimum growth: the soil-plant-atmosphere continuum and their management (Sinclair and Seligman, 1996). Although complex, progress in understanding of either realm has been made through scientific research and application of which modelling has played a key role.

Modelling is the application of a model to a system. Prior to application, an understanding of the physical, chemical and biological processes is required. This aids in acquiring experimental outcomes that are a true reflection of environmental processes under study (Murthy, 2004). A model is applied to a system, which is defined as a part of reality that contains inter-related elements. It can be distinguished from its surrounding environment by physical or conceptual boundaries (Savage, 2001; Murthy, 2004). The differences in systems command different models used for different functions.

2.4.1 Model types

Essentially, various models exist and are grouped into numerous categories. Three significant types are described:

- Empirical models or regression models: These depend on observed quantitative interrelations between variables, whilst ignoring their functional operations (Murthy, 2004). These have been used widely in agriculture because of their black-box approach despite the associated uncertainty. Furthermore, use in extrapolation spatially and temporally is discouraged thus prompting many scientists to choose other model types.

- Deterministic models: these models are upgraded empirical models. Empirical limitations are corrected by incorporating mathematical descriptions of the processes known to occur in the soil, plant and atmosphere (Murthy, 2004). Models of this nature are mainly physically based and are therefore more accurate (Savage, 2001). Processes are clearly defined and the behaviour of elements based on physical laws controlling mass and energy flow within a system are accounted for (Savage, 2001). Deterministic models can either be mechanistic or functional models:

    - Mechanistic models: incorporate rates of processes, enhancing the accuracy in modelling processes as well as providing a link to other processes such as the transport of chemicals and their reaction with time in soils (Savage, 2001; Murthy, 2004).
    - Functional models: usually based on capacity parameters and fixed time intervals. These use the same process as mechanistic models but do not claim to adhere to the fundamental mechanisms (Savage, 2001; Murthy, 2004).

- Stochastic models are characterised by probability elements attached to the outcome. These models define yield at a given rate (Murthy, 2004). Variability within the system is accounted for by giving statistical credibility to the input conditions and model predictions (Murthy, 2004). The probability calculations can then be used to determine future events based on certain criteria (Savage, 2001).

- Parameter models are usually used in hydrological modelling since they deal with the development and analysis of relationships between hydrological components within a system (Savage, 2001).

2.4.2 Crop simulation models

A crop simulation model is a quantitative scheme for predicting growth, development and crop yields given a set of genetic coefficients and environmental variables (Sinclair and Seligman, 1996). This is achieved by simulating crop growth on a computer with all soil, plant and atmospheric parameters, as well as management strategies affecting growth (Uehara and Tsuji, 1998). Application of crop simulation models has been successful mostly through interpretation of results by modifying management strategies to maximize the output (Hodges *et al.*, 1986). As a result, these types of models are used to depict the soil-plant-atmosphere continuum in order to assess and implement management strategies that would improve yields. However, models should not be a replacement for field experiments, but rather they should validate them.

Crop simulation models are used across the globe with the aim of improving yields. Performance and use of the models largely depends on the model's ability to depict the soil-plant-atmosphere continuum as well as frequency of use. It is easier for a user to choose a model that has been previously used within the region of study or neighbouring regions since these models have already been validated and calibrated.

Examples of crop simulation models include CERES-Maize, CropSyst, DSSAT, APSIM and WOFOST. Some are an upgrade of other models while others use similar modelling mechanisms within models. For instance, APSIM and DSSAT have similarities since they were both created by the International Benchmark sites network for Agrotechnology Transfer (IBSNAT) (Corbeels *et al*., 2011). Models created by IBSNAT differ from ones made by other institutions such as, the School of de Wit crop models such as the BACROS, WOFOST and LINTUL models (Bouman *et al*., 1996). This school is part of an Agricultural University, Wageningen in the Netherlands. However, similarities do exist in models across institutions.

2.5 Maize crop modelling in climate studies

In order to fully assess future climatic impacts on the maize crop, scenarios that adequately represent future changes in climatic variables are important. Scenarios are generated from General Circulation Models (GCM). GCMs are physically based tools used for investigating large-scale climate changes (Bates *et al*., 1998). The models deliver projected meteorological variables in fine time resolution and are usually course spatial grid (50 – 500 km) (Bocchiola *et al*., 2013). Although GCMs perform well in simulating synoptic atmospheric fields, shortfalls have been found in the ability of the models to accurately reproduce historical records at the smallest spatial scale. As a result, downscaling is required and is advantageous in that climate series that are consistent to locally measured data can be obtained (Groppelli *et al*., 2011). However, biasness is common to all GCMs particularly in areas where coarse model resolution cannot resolve complex mountains and coastlines such as Meso-America (Ruane *et al*., 2013).

The scenarios created using GCMs can be used in crop simulation models. Popular crop simulation models such as the CERES-Maize and CropSyst have been used to simulate maize growth under a climate that has changed globally. At present, knowledge on improved farming and management strategies aimed at increasing maize yields in-light of the changes in climate are available in literature. Some of the studies that have enhanced progress in maize production on a global scale are discussed in section 2.5.1.

2.5.1 Global examples

Use of various models in climate studies has improved the adaptive capacity of farmers in a changing environment. Modelling maize production in light of the current and future climate change has been studied. Different crop simulation models have been used for different purposes; either to improve model functionality, develop genetically modified seed that withstand harsh climatic conditions or improve management strategies.

Applying proper management strategies is key to ensure that yields are kept high. However, as the climate changes, adapting to new management practices are also necessary depending on the magnitude of impacts imposed by climate change. For instance, Stockle *et al.*, (1997) evaluated the benefits of irrigation south-western France using the CropSyst model. They found that irrigation not only increased yields but also reduced weather related variation in yields. Also, Bergez *et al.*, (2002) identified optimal thresholds for several maize irrigation strategies in the South-eastern USA. Net returns and irrigation amounts were determined for each growth stage using the growth simulator CERES-Maize model. This improved yields as well as conserved water. Other management operations that have been studied in relation to climate change include: changing of planting dates, benefits of reduced plant densities, application of manures and fertilization, conventional tillage versus no-tillage practices (Kern and Johnson, 1993; Sangoi *et al*., 2002; Lal, 2004; Tao *et al*., 2006).

Studies on the impacts of climate change on maize yields have also been done. Using the CERES-Maize model, Pfeifer *et al*., (2000) studied the consequences of the future climate change and its variability on maize yields in the mid-western United States of America (USA) and found that, a lengthened growing season with high daily maximum temperatures inhibited maize yields. They also found that climate variability reduced maize yields significantly. On the contrary, Finger and Schmid, (2007) found that yield variability decreased with changes in climate after conducting study on the impacts of climate change on mean variability of Swiss corn production using the CropSyst model. It is common to find contradicting findings of similar studies conducted at different locations. However, this does not discredit one from the other but shows diversity in the field of study and allows comparisons between methodologies, models and the differences in results per location.

Generally, the CERES-Maize model has been popularly used to evaluate management and cropping strategies, predict yield, assess impacts of climate change on growth and yield, assess drought severity, and model the effects of irrigation, drainage, water flows and solute transportation as well as, nitrogen uptake, fertilizer impacts, root growth and pests (Du Pisani, 1978; Hodges *et* al., 1989; Popova *et al*., 2004; Saseendran *et al*., 2005; Walker and Schulze, 2006; Soler *et al*., 2007; Fang *et al*., 2010).

Other similar studies have used other models such as the APSIM-Maize and Hybrid-Maize models. Hook (1994) used the SOYGRO and PNUTGRO models to plan water withdrawals for irrigation in drought years. In the US-corn belt in North America, the CERES-Maize model was applied in order to assess the accuracy of the model to predict annual fluctuations in maize production (Hodges *et al*., 1986).

In Egypt, the CropSyst model has been used extensively. It has been used to assess the vulnerability of wheat to climate change allowing for adaptation strategies to be enforced, also assessing various adaptation strategies to increase water use efficiency in maize under climate change conditions (Khalil *et al.*, 2009; Ouda *et al.*, 2009). The model has also been used to model different crops in various other countries, such as Mexico, China, Switzerland, USA, Italy, India, Cameroon and South Africa, to model diverse crops such as maize, wheat, sorghum, alfalfa, barley, millet, dry beans, rice and sugar cane (Pannkuk *et al*., 1998; Abraha and Savage, 2006; Jalota *et al*., 2006; Wang *et al*., 2006; Finger and Schmid, 2007; Sommer *et al*., 2007; Tingem *et al*., 2007; Confalonieri *et al*., 2009).

In Southern Africa, the CERES model has been used to model agricultural productivity and its response to climate change. For example, In Zimbabwe, the model has been used to plan wheat irrigation strategies, assess the impact of the El Nino/Southern Oscillation (ENSO) and seasonal rainfall patterns on maize yield (MacRobert and Savage, 1998; Phillips *et al.*, 1998). South African applications of the CERES-Maize model include assessing potential impacts of climate change to maize yields, assessing and optimising planting dates of maize cultivars to improve yields, assessing yield differences within the Highveld region in light of changes in climate (du Toit *et al.*, 1994; De Jager *et al.*, 1998).

2.5.2 South African examples

Most of the work done in South Africa regarding modelling maize under climate change conditions focused mostly in model calibration. This type of work vital since it is a required that a model be calibrated and validated prior to application. Therefore, the work done by du Toit (1994a); du Toit, (1994b); du Toit, (1994c) and (Tsuji, (2002) modified or performed validation procedures of certain input variables (related to the maize crop) according to South African conditions. For instance, Tsuiji (2002) reported a calibration that was done on inputs e.g. genetic coefficients, crop phenological parameters and management strategies on maize grown from the Potchefstroom area. Furthermore, du Toit (1994a) showed that genetic parameters and the subroutines of the CERES-Maize model revealed a significant difference between observed and optimised genetic coefficients. He also optimised the planting date of various cultivars as well as calibrated the different growing stages which improved phenological predictions of the model and the models systematic reduced errors.

Studies that investigate the impacts of climate change on the maize crop in South Africa are few: Schulze *et al*., 1993; du Toit (1994); Walker and Schulze, 2008; Abraha and Savage, 2008). Schulze *et al*., (1993) investigation of agricultural productivity and its response to climatic changes which revealed a large dependence of production and yield on seasonal and annual rainfall. In a similar and more recent study, Walker and Schulze, (2008) showed that maize yields are affected by rainfall increments and decrease as well as increase in air temperature using the CERES-Maize model. They also found that maize yields decrease from the eastern to the western part of the Highveld-Eco region following the rainfall pattern. The western half was found to be more vulnerable to decline in maize yields as opposed to the eastern part and thus needs more immediate attention. Du Toit and Prinsloo (1998) incorporated the effect of the El-Niño/Southern Oscillation of which also affected yields negatively.

Walker (2005) investigated three selected areas of the Highveld region and modelled the impacts of climate change on maize using the CERES-Maize model. The yields were simulated according to scenarios that comprised of a combination of possible future changes in carbon dioxide, air temperature and rainfall. Areas chosen were representative of dry, intermediate and wet parts of the region. The findings showed that yields were higher for wetter parts of the region than the drier parts.

Abraha and Savage (2008) used the CropSyst model to investigate the impacts of climate change on maize in Cedara. They found that changing air temperature by 2 and 4 ºC reduced maize yields but an increase in rainfall by 10 and 20 % had no effect on yields under an increased carbon dioxide atmosphere. They concluded that even though increased carbon dioxide benefits yields, the rise in air temperature by 2 and 4 ºC is high enough to reduce yields.

The Soil Water Balance (SWB) model has also been used extensively in South Africa. The model was developed as an irrigation scheduling tool to compute water interception, runoff, percolation and potential evapotranspiration in a given area. Also has a crop component that accounts for crop water use (Annandale *et al*., 2000). The model has been used to model crop yield and soil water balance, facilitate irrigation scheduling and develop computerised management systems for irrigation schemes (Benade *et al*., 1997; Annandale *et al*., 1999; Jovanovic and Annandale, 2000).

Maize production is expected to be affected negatively as the climate changes. This will not only exacerbate food insecurity woes in the country (South Africa) but will affect animals as well. Therefore, the need for more robust investigations on the responses of the maize crop to climate change and variability is of utmost importance of a sustainable livelihood in the future. The Highveld Eco-region is the centre of commercially grown maize producing yields that supply the country with maize and export to other Sub-Saharan countries. As a result, studies aimed at improving production of yields in the Highveld Eco-region are the key in the fight for food security in the increasing population of South Africa. Ideally, climate change impacts should be investigated at all locations in the region in order to ensure precision in results which will aid in correctly diagnosing the problems causing yields to decline or increase at slow rates. This will encourage more precise management response measures that will improve yields.

3. METHODOLOGY

3.1 Overview

This section outlines the methodology implemented in the study. The methods are stipulated in a chronological sequence:

- A description of how the climate data files were obtained and the contents thereof.
- A general description of the location (Highveld Eco-region). The climate, soils information and some physical characteristics of the area are mentioned. Also within this section is a more detailed account of the specific representative locations selected in the study.
- Then follows a discussion on some methods and models used to improve the quality of the climate data which formed part of the input for the modelling. The methods used to patch rainfall; solar irradiance and relative humidity are also stipulated in this section.
- A section on air temperature trends analysis on all locations in the study then follows.
- Finally, is a description of the CLIMGEN and CropSyst models as well as the Scenarios used in the study.

3.2 Sourcing climate data

This study relied heavily on modelling using the CropSyst model. Acquiring input data was a challenge. It required following certain protocols that defined terms and conditions involved for use. Input climate data were obtained from the Agricultural Research Centre (ARC). Two forms of data were received: one was from manually operated weather stations (MWS) and the other from automatic weather stations (AWS) across the country.

The climate files obtained from ARC were representative of stations at various locations in the country. Climate files representing areas located in the Highveld region were then selected. Further selection of stations that fall within the Highveld Eco-region was done and choice was based on the data quality (data with no missing data) and record length. Selection was also influenced by the location in the Highveld region since the intention of the study was to have representative areas from the western and eastern parts of the Highveld.

The MWS datasets had longer record of data with more data errors than AWS data sets. This was expected since meteorological systems operated manually involve high uncertainties mainly from human error and un-maintained equipment. Lack of solar radiation data was remedied by a patching method described in Section3.4 using the daily air temperature range. Relative humidity and wind speed had the most discrepancies and were duly patched as well. Methods of patching are described in Section 3.4. The introduction of the AWS system is relatively recent. As a result, data-sets were characterised by shorter up-to-date data sets, mostly less than 10 years. Therefore, AWS data were only used to extend MWS data sets provided the stations are at the same location or close enough that climatic and geophysical characteristics are the same.

For each station, the weather data contained rainfall, air temperature, relative humidity, wind speed and estimated solar irradiation. Data from the AWS came with daily solar irradiance measurements. These data were not replaced but rather used to validate the model used to estimate solar irradiance (results for this are in Section 3.4).

3.3 Site description

The variation in climatic conditions has resulted in dividing the country into 36 grain-production regions. Regions 1 to 20 cover areas that are not conducive for maize or any crop production. Regions 21 to 36 include all the areas suitable for production of rain-fed maize crops produced on large scales. This region is called the Highveld Eco-region (shown in **Figure 3.1**), extends over parts of five major provinces: North West, Free State, Mpumalanga, Gauteng and KwaZulu-Natal. It covers about 12% of the total area of the country (Mendelsohn *et al.*, 2000). The study focused on the Highveld Eco-region which is a major maize growing area in South Africa. The North West and Free State are the highest producers, whilst Gauteng and KwaZulu–Natal are the least. Production is not only limited to these areas. Small scale farmers across the country produce maize under arid to semi-arid conditions through well executed adaptation strategies, which ensure production that plays a critical role in combating food security within designated local communities (Benhin, 2008).

The Highveld Eco-region (**Figure 3.1**) is generally characterised by plains with low to moderate relief, with low drainage and stream. The region is separated into two distinct agroecological regions; one sub-humid and the other semi-arid (Bennie and Hensley, 2001). The western semi-arid part receives a mean annual precipitation (MAP) of less than 600 mm, whereas the eastern sub-humid region receives 600 to 1400 mm (Walker and Schulze, 2006). This distinction of MAP between the west and east of the Highveld region is shown in **Figure 3.2**. The eastern Highveld is designated an early summer rainfall area (December maximum), the central Highveld a mid-summer rainfall area (January maximum) and the western Highveld a late summer rainfall area (February maximum) (Walker and Schulze, 2006). Altitudes range between 900 and 1800 m above sea level. Generally, poor nutrient soils originating from sandstone parent materials dominate for this region. The soils mostly belong to the sandy clay loam texture class with depths ranging from 0.4 to 1.2 mm (Walker and Schulze, 2008).

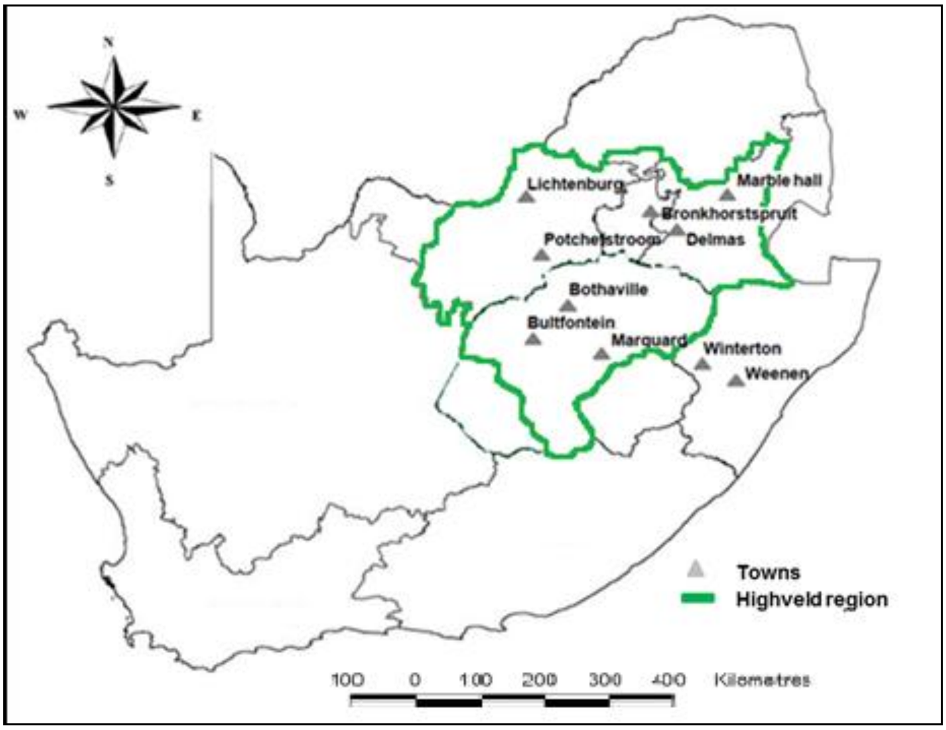

Figure 3.1 The Highveld eco-region with selected representative maize growing areas in South Africa (Benhin, 2008).

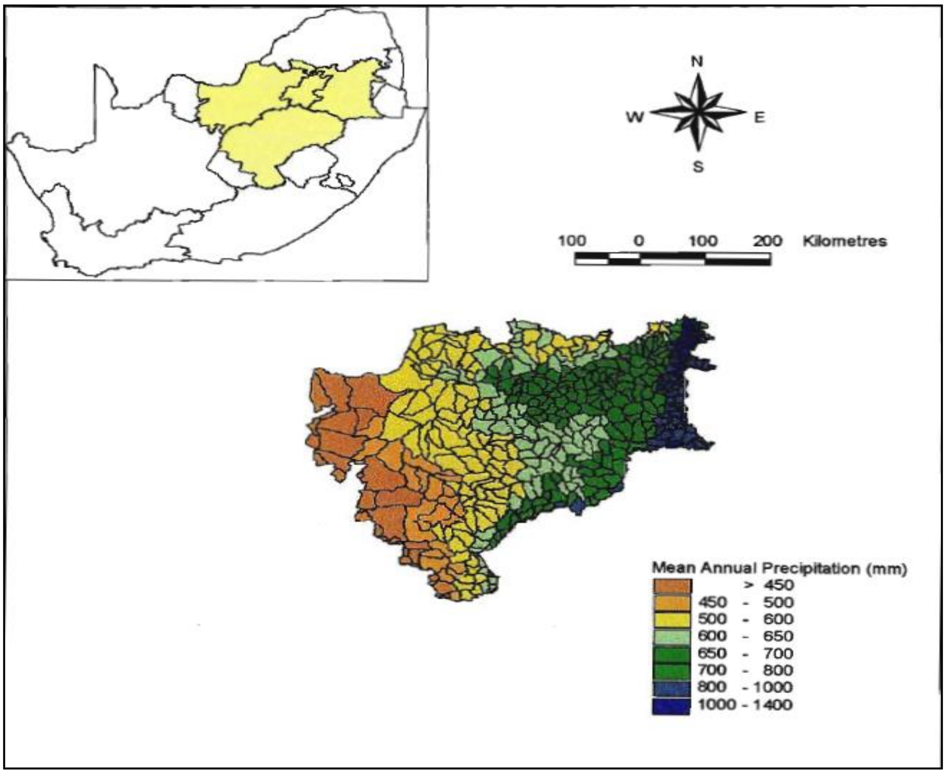

Figure 3.2 Highveld eco-region's Mean Annual Precipitation variation (Walker and Schulze, 2006).

Due to increased sunshine duration, solar radiation is greater in the western than the eastern parts of the Highveld. In the mid-summer months, daily solar irradiance ranges from 32 - 34 MJm^{-2} in the west and 28 - 30 MJm^{-2} in the eastern parts of the Highveld. In mid-winter, i.e. July, daily solar radiation is considerably lower, ranging from 16 - 19 MJm^{-2} (Walker and Schulze, 2008). Monthly means of daily maximum air temperature in the summer months, i.e. December to March, range from 28 to 30 ^{o}C in the west and 26 to 30 ^{o}C in the east, while the means of minimum air temperatures in these months are between 12 and 16 ^{o}C across the region. Frost occurs mainly in May with occasional persistence of up to September at times (Walker and Schulze, 2008).

Depending on data quality and availability, representative stations (locations) were selected to represent the western and eastern parts of the Highveld Eco-region. This is shown in**Table 3.1** with a summary description of important characteristics of the station.

Table 3.1 Characteristic data for the selected stations for the study. Stations represent the eastern and western part of the Highveld Eco-region

Station Location	Longitude (E)	Latitude (S)	Altitude (m)	MAP (mm)	Air temperature range (°C)
Bothaville	26° 14'	26° 39'	1300	552	18 – 30
Lichtenburg	26° 10'	26° 10'	1477	500 - 600	18 – 30
Bronkhorstspruit	25° 47'	28° 46'	1500	600 - 650	18 – 27
Marble Hall	26° 44'	27° 05'	1345	658	18 – 28
Cedara	29° 32'	30° 17'	1076	876	20 – 28

3.4 Patching missing climate data

Patching weather data is a common practice in modeling due to the unreliability of climate data sets. Various models are in place to counteract the lack of good reliable data with the aim of facilitating sound research outcomes. Each climatic attribute has various models for data patching and use depends on user discretion.

3.4.1 Rainfall and Air temperature

Missing precipitation values of driver stations were patched on account of surrounding filler stations. A driver station is the station selected as a host station to represent an area whilst a filler station is one used to patch the driver station. The choice of relevant filler stations depended on proximity as well as altitude. **Table 3.2** and **2.7** depict the characteristics of the driver stations and the filler stations used.

This method of infilling data was mostly used to patch rainfall data and follows a method known as the distance-weighted technique (Teegavarapu *et al*., 2004). This method involves weighting of recorded rainfall from stations surrounding a driver station. Depending on the distance, the closest station is weighted highest and the furtherest, lowest (Gemmer *et al*., 2004). This method was also applied to infill missing air temperature data depending on distance and similarities between the air temperature measurements of the filler station to the driver station. However, good air temperature data sets minimized application of this method.

Table 3.2 Driver stations characteristics for selected representative areas for the Highveld region and Cedara (from KwaZulu-Natal – KZN). The areas extend across four provinces i.e. North West (NW), Free State (FS), Gauteng (GP), and Mpumalanga (MP).

Province	**Driver Station**				
	NW	**FS**	**GP**	**MP**	**KZN**
Station name	Lichtenburg	Bothaville	Bronkhorstspruit	Marble Hall	Cedara
ARC Station number	19828	19884	19998	19995	19850
Latitude (S)	26.167	27.239	25.781	25.017	29.533
Longitude (E)	26.167	26.664	28.769	29.417	30.283
Elevation (m)	1477	1300	1500	964	1076
Record length (years)	22	24	24	30	37

Table 3.3 Filler stations characteristics

Province	**Filler Station**				
	NW	**FS**	**FS**	**MP**	**MP**
Station name	Kameel	Bultfontein	Marquard	Delmas Sensako	Delmas Panner
ARC Station number	22472	19854	19896	19977	19997
Latitude (S)	26.559	28.151	28.504	26.101	26.149
Longitude (E)	25.088	26.067	27.356	28.666	28.701
Elevation (m)	1365	1306	1447	1623	1532
Record length (years)	22	26	22	25	23

With the exception of Bronkhorstspruit and Cedara, sections of data-sets from Bothaville, Lichtenburg and Marble Hall were patched. Lichtenburg data were patched with data from Kameel, Bothaville with data from Bultfontein and Marquard and lastly, Marble Hall data were patched with data from Delmas Sensako and Delmas Panner. The use of filler stations was used on missing rainfall and air temperature values. Other missing climate parameters were patched using models as discussed in Sections 3.4.2 and 3.4.3. Results of model performances on the estimations are discussed in the next sections.

3.4.2 Solar irradiance

Solar radiation was estimated for all datasets. The literature accounts for a number of estimation methods based on daily air temperature range. A simple method suggested by

Hargreaves and Samani (1982) states that daily solar irradiance (R_s) can be estimated from the difference between daily maximum and minimum air temperature using:

$$R_s = K_r\,(T_x - T_n)^{0.5} R_a \tag{3.1}$$

where R_s is the daily solar radiation (MJ m^{-2}), T_x the maximum air temperature (°C), T_n the minimum air temperature (°C), R_a the daily extraterrestrial solar radiation (MJ m^{-2}), and K_r a unit-less empirical coefficient (Hargreaves and Samani, 1982).

This model was chosen because it is simple and has been improving with time Hargreaves, 1982, 1985 and 1994. At some point i.e. Hargreaves and Samani, 1982 and 1985, the equation was simplified such that it required only temperature and latitude. Also, error associated with estimations is minimized to less than 15 % (Samani, 2000). Furthermore, only latitude and day of year are used to calculate R_a. A value of 0.16 for K_r was used since it is representative of interior regions with 0.19 for coastal regions (Hargreaves, 1994; Bandyopadhyay *et al*., 2008). Corrections to K_r were applied to account for elevation influences on the volumetric heat capacity of the atmosphere using (Allen, 1995):

$$K_r = K_{ra}\,(P/P_o)^{0.5} \tag{3.2}$$

where K_{ra} is an empirical coefficient (0.17 for interior regions and 0.20 for coastal regions) and P (kPa) the mean atmospheric pressure at site, the latter estimated from altitude of the site using:

$$P = P_o\,(293 - 0.0065Z/293)^{5.26} \tag{3.3}$$

where P_o (kPa) is the mean atmospheric pressure at sea level, i.e. 101.3 kPa, and Z the site elevation in (m).

Other methods of estimating solar irradiance from air temperature and relative humidity required input data that were not available. For instance, the Self-Calibrating method of estimating solar irradiance by Allen, (1997) required clear-sky solar radiation envelops, regression equation developed by Hook and McClendon, (1992) requires A-pan evaporation measurements which were not available. Bistow and Campbell (1984), Donatelli and Cambell (1998), Donatelli and Bellochi (2001), Hunt et al., (1998) and Mahmood and Habbard (2002) are other models that could have been used but were not chosen due to unavailable input data the required by the models.

Model performance was then graphed and an example shown in **Figure 3.3** which representative of Marble Hall for the year 2006. This is to show the validity of the model in estimating solar irradiance. Generally, the modeled irradiance scatter plot mimicked the measured irradiance plot. Differences were noted to be more from day of year 0 – 100 as well as 250 – 365, months falling within the summer season.

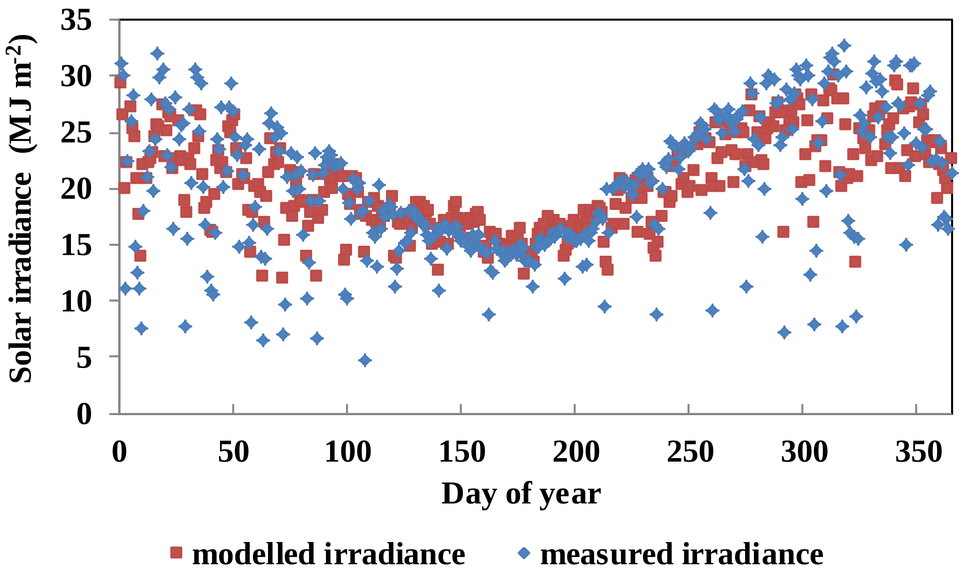

Figure 3.3 Temporal variation of modelled and measured daily solar irradiance for Marble Hall for 2006.

The difference in measured and modelled solar radiance in **Figure 3.3** is easily noted in **Figure 3.4**. A larger range of residuals was noted between day of year 0 – 100 and from 225 – 350, with a narrower residual range from day of year 100 – 225. Despite the difference in the solar irradiance, the Hargreaves and Samani (1982) model performed relatively well (**Figure 3.5**) and is confirmed by an r^2 value of 0.72 implying a relatively good correlation.

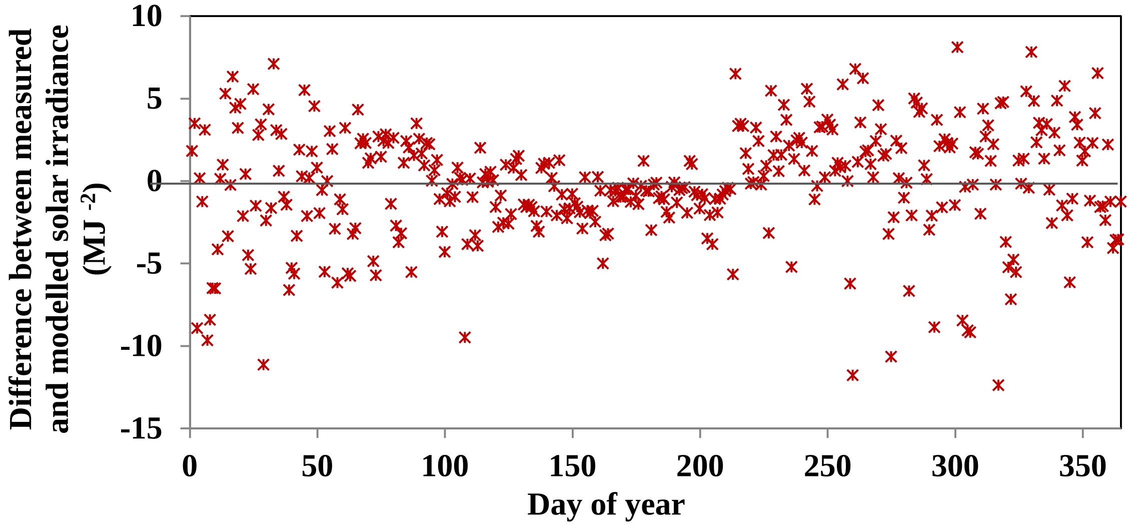

Figure 3.4 Difference between measured and modelled radiation for Marble Hall automatic weather station for the year 2006.

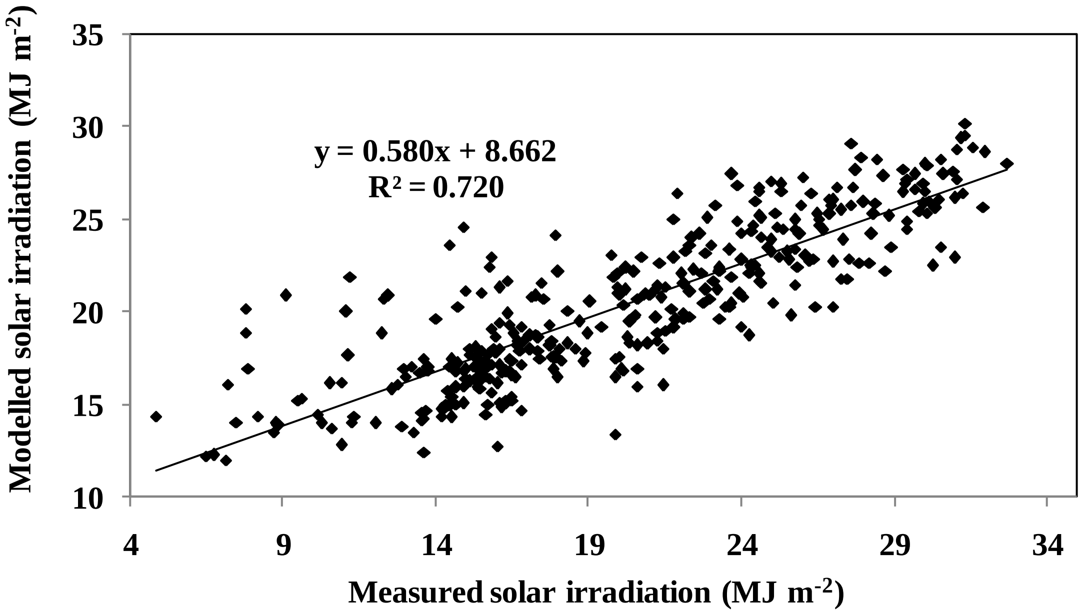

Figure 3.5 A regression between Measured and Modelled solar irradiance.

3.4.3 Relative humidity

Missing relative humidity values were filled using a method that required the determination of water vapour pressures at the maximum (T_x) and minimum (T_n) air temperatures (Eccel, 2011). Success of this method required estimation of dew point temperature by means of two general assumptions:

(a) The minimum air temperature was assumed to be equal to dew point temperature from which the water vapour pressure was calculated;

(b) Correction of the first assumption was carried out depending on either the presence/absence of precipitation or the water balance of the previous day (Eccel, 2011).

From the two assumptions, relative humidity was estimated using air temperature by means of the following ratio:

$$\text{relative humidity} = e/e_s \times 100 \tag{3.4}$$

where e is the water vapour pressure (kPa), and e_s the saturation water vapour pressure (kPa).

The water vapour pressure was calculated using a common exponential function:

$$e_s(T_n) = 0.6108 \exp(17.269T_n/(T_n+237.3)) \tag{3.5}$$

where e_s is the water vapour pressure (kPa) at the daily minimum air temperature (T_n) (°C) (Allen *et al*., 1998)

The model performance was scrutinized and the results are depicted in **Figure 3.6** and **3.7**

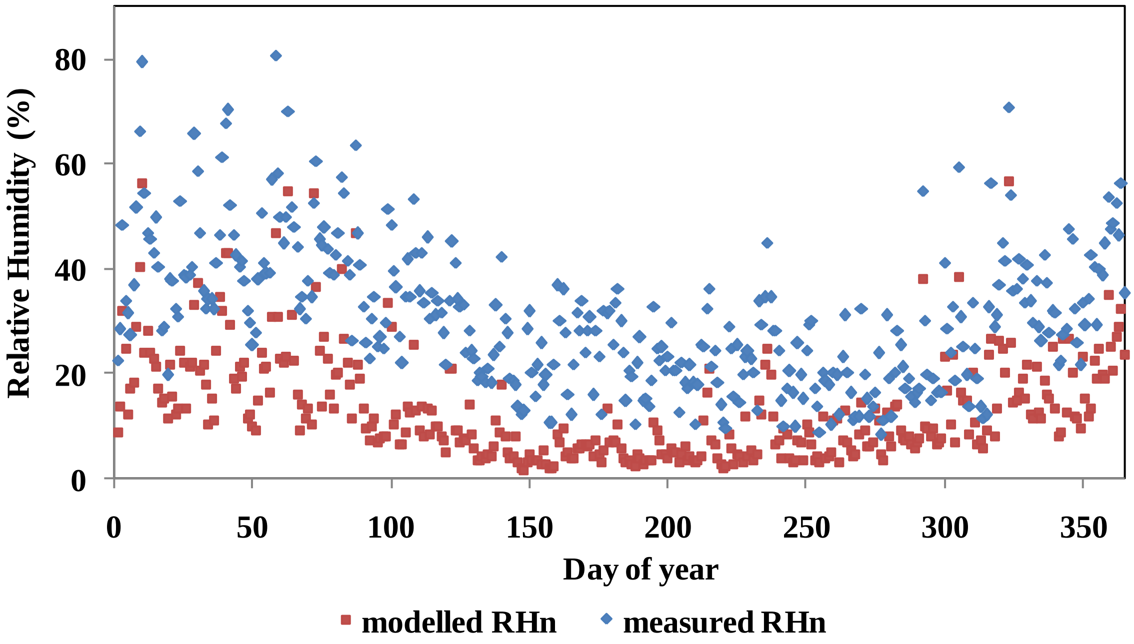

Figure 3.6 Temporal variation in the measured and modelled minimum relative humidity (RH_n) for Marble Hall in the year 2006.

Throughout the year of 2006, there was an underestimation of RH_n values. Differences between measured and modelled RH_n reached a maximum of 35 %. Most differences ranged between 10 and 25 %, with a few falling on either side of this range. This positive difference can be clearly noted in **Figure 3.7**. Greater differences were experienced under warmer conditions due to the greater deviations from the 0 % line particularly between day of year 0 – 175 as well as 300 – 365.

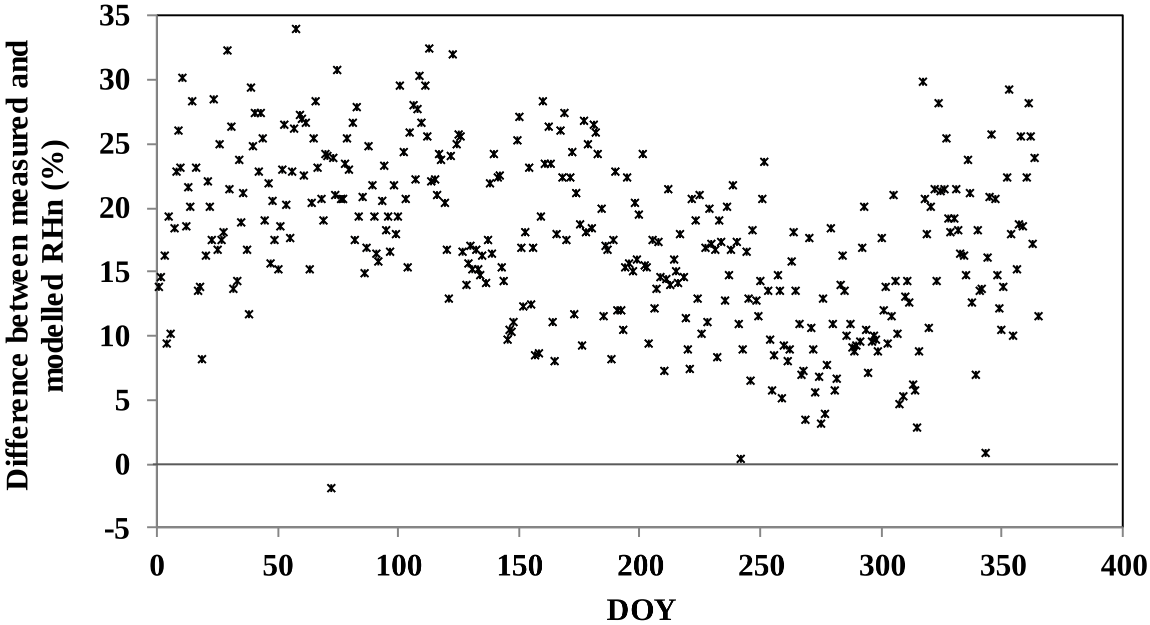

Figure 3.7 Differences between measured and modelled Relative Humidity (*RH_n*) for Marble Hall for 2006.

Though simple to use, the model proved to almost always underestimate *RH_n*. Fortunately, the effect on the simulations is likely to be minimal since most data sets had a complete set of relative humidity data. The extent of patching that was done is shown in **Table 7.15** in APPENDIX E.

Wind speed gaps were patched with a 2.0 m s^{-1} value since it is a standard acceptable average wind speed infilling value for most locations (Trajkovic, 2005).

The study also required maize crop biophysical parameters and soils information to be used as input in the model. A detailed account of the relevant crop and soils information are described in APPENDIX C.

3.5 Temperature trends analyses

In this section, only the air temperature climate data were used for analysis. The data were then analysed in Microsoft Excel were a statistical analysis was conducted. The data were initially analysed on a seasonal and annual basis. However, statistical analysis showed no difference between seasonal trends and therefore was excluded from this study. Annual trends were analysed and the change in air temperature over time (year) was determined. This was achieved by determining the slope of the relationship between the years and the corresponding minimum and maximum air temperatures for all the years for the entire record lengths at all locations considered in this study. The slope was then converted to degree Celsius per decade (commonly used in literature). The results were then compared amongst the study areas and with previous studies done in South Africa and Africa.

3.6 Modelling

In order to determine the impact of air temperature change on maize yields in selected areas of the Highveld region, various climatic scenarios were applied on the climate data and inputted through the CropSyst model. The model has only been used once in South Africa when Abraha (2006) studied the potential effects of climate change on maize yield in Cedara, KwaZulu-Natal. Using this model offered a comparative option to the performance of the CERES model on various studies conducted by du Toit *et al.*, (2000) on maize in the Highveld region.

Prior to modelling yield responses to climate change, climate data inputted into the CLIMGEN weather generator. This was done in order to generate longer synthetic data that could be manipulated according to the different Scenarios to be used in this study.

3.6.1 The CLIMGEN weather generator: a brief description

The CLIMGEN weather generator is a daily time step stochastic model that generates synthetic daily rainfall, minimum and maximum air temperature, solar irradiance, atmospheric humidity and wind speed data series (Stöckle *et al.*, 2001). Operations within the generator use principles similar to those in the WGEN weather generator, but with significant modifications and additions. The additions include (Tingem *et al.*, 2007):

- use of a Weibull distribution over the Gamma distribution used by the WGEN to generate rainfall. The Weibull distribution has been found to be superior over other probability distribution of daily rainfall amount (Selker and Haith, 1990),
- use of the quadratic spline functions to ensure a continuous average of daily values across months,

- estimates of daily solar irradiance are possible from existing air temperature records (Bristow and Campbell, 1984)
- inclusion of generation of water vapour pressure is an added incentive (Tingem *et al.*, 2007)

Generated maximum and minimum air temperatures result from a multi-variate stochastic process with the daily means and standard deviations conditioned by the dry or wet state of the data (Stöckle *et al.*, 2001). Wet and dry days are generated using a first order Markov chain. Rainfall amounts and wind speed are generated using the Weibull distribution with the latter generated independently of other variables (Stöckle *et al.*, 2001).

The CLIMGEN weather generator can be applied at any location in the world so long as measured rainfall and air temperature (daily maximum and minimum) are available. Absence of daily solar irradiance and relative humidity can be overcome since various models can estimate the parameters very well.

The CLIMGEN weather generator validation was accomplished by using climate data that was intended to be used to model yield responses from the CropSyst. In order to determine whether rainfall data generation was successful, comparisons of wet and dry-day counts of the observed and generated climate data were done. Ideally, the original and generated rainfall data should have the same wet-day counts. A comparison of the air temperature, solar irradiance was also done. The results are shown in section 4.2. Furthermore, validation was also done using the CropSyst model by modelling maize yields using measured and the corresponding generated data.

3.7 The Model: CropSyst

The synthetic climate data (generated from the CLIMGEN weather generator) was then inputted into the CropSyst model. With all other input data complete (soils and all needed maize parameters), the CropSyst model was run with the measured data as well as the synthetic data to determine yields. This was represented graphically and the differences were noted. The synthetic climate data was then subjected to changes according to the stipulated Scenarios from section 3.9 and then was inputted into the CropSyst.

3.7.1 Model description

The CropSyst (Cropping Systems Simulation Model) is a multi-year, multi-crop, daily time-step crop growth simulation model designed to serve as an analytical tool to study the effect of cropping systems management on productivity and the environment (Stöckle *et al.*, 2003). CropSyst attempts to reproduce soil plant biophysical processes based on known physical and biological laws or empirical relationships based on climatic and crop management practices (Stockle and Nelson, 2000; Stöckle *et al.*, 2003; Yadav, 2005). The model simulates the soil water budget, soil-plant nitrogen budget, crop canopy and root growth, crop phenology, dry matter production, crop yield, residue production and decomposition and erosion. This is affected by the input files: daily weather data (rainfall, maximum and minimum air temperature, solar irradiance, relative humidity and wind speed), location, soil chemical and physical characteristics and management practices (Stöckle *et al.*, 2003).

The water budget sub-model of CropSyst includes rainfall, irrigation, runoff, interception, infiltration, redistributions within soil profiles as well as evapotranspiration. The model uses a simple cascading approach or the Richard's soil flow equation (Garofalo *et al.*, 2009). Grass reference evapotranspiration (ETo) is estimated by the Penman-Monteith or Priestley-Taylor methods within the model. An option of a simpler Priestley-Taylor method that only requires air temperature is also available. Crop evapotranspiration (ET) is determined from a crop coefficient at full canopy and ground coverage determined by canopy leaf area index (Stöckle *et al.*, 2003). The soil nitrogen (N) budget includes transformations (mineralization, nitrification, denitrification, and volatilization), ammonium sorption, symbiotic N fixation, and crop N demand and uptake. Interaction between the water and N budget produce the simulation of N transport within soil profiles (Bellocchi *et al.*, 2002).

In the model, crop development is simulated based on thermal time accumulated to reach specific plant growth stages. Thermal time is the required daily accumulation of average air temperature above a base temperature and below the optimum temperature to reach specific growth stages (considering photoperiod and vernalization requirements) (Yadav, 2005). Daily crop growth is a function of biomass increase per unit ground area factoring in four limiting factors to crop growth: water, nitrogen, light and temperature (Stöckle *et al.*, 2003). **Figure 3.8** shows the flow chart describing the approach used in the model to calculate biomass accumulation. The core of the calculations is based on potential biomass growth based on crop potential transpiration and crop intercepted photosynthetic active radiation (PAR) (Stöckle *et al.*, 2003).

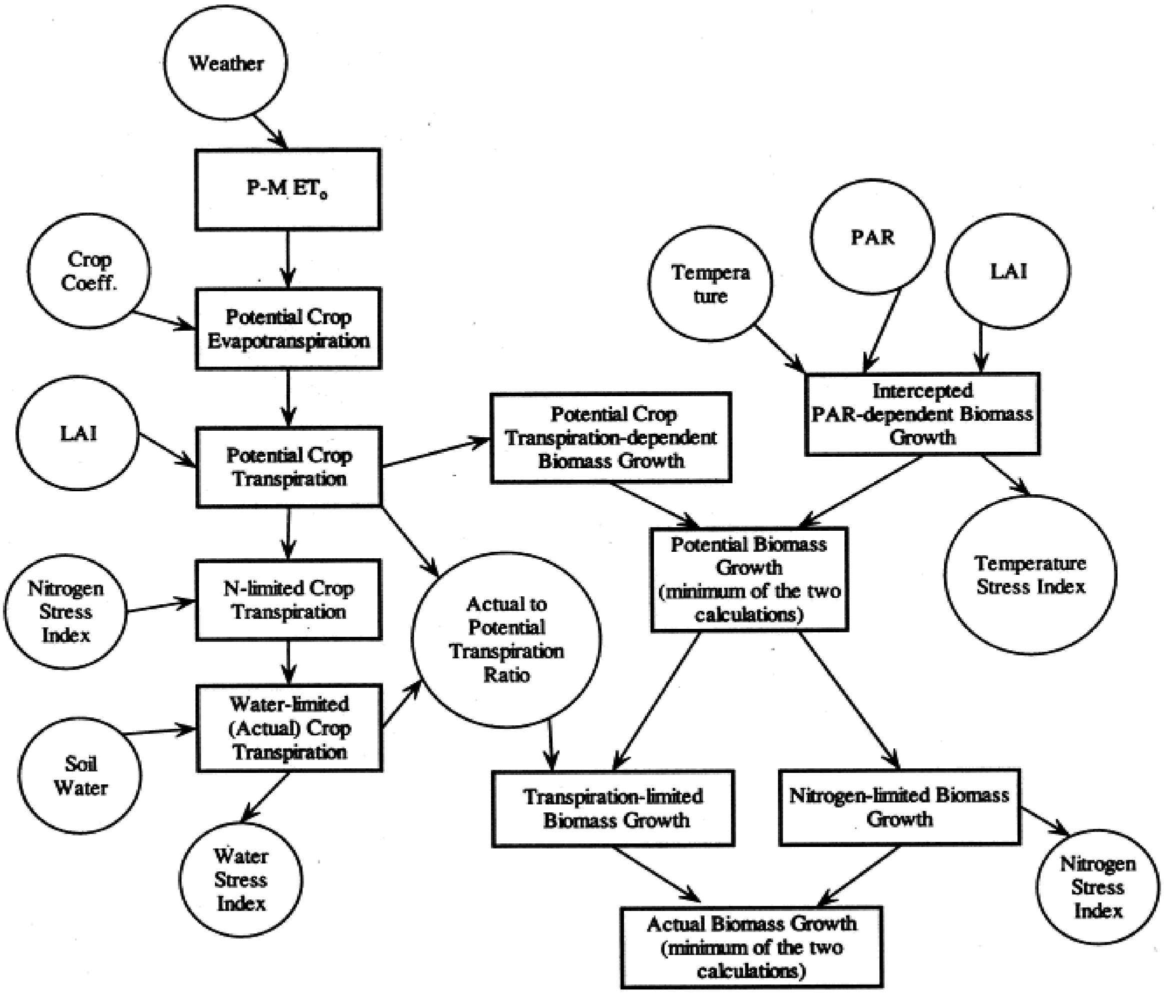

Figure 3.8 Flow chart of biomass growth calculations in CropSyst (Stöckle *et al.*, 2003).

The daily above ground biomass accumulation is then calculated using a relationship between crop transpiration and biomass production. The relationship is shown in Equation 2.6 (Stöckle *et al.*, 2003; Yadav, 2005).

$$B_T = K_{BT}T / \text{VPD} \qquad (2.6)$$

where B_T is the transpiration-dependent biomass production (kg m^{-2} day^{-1}), T is actual transpiration (kg m^{-2} day^{-1}), and VPD is the mean daily vapour pressure deficit of the air (kPa).

However, at low VPD, this relationship becomes unstable and can estimate infinite growth at near zero VPD. Therefore, the model provides another method of calculating biomass production:

$$B_L = e\ I_{PAR} \tag{2.7}$$

where B_L is the light-dependent biomass production (kg m^{-2} day^{-1}), e is the light-use efficiency (kg MJ^{-1}) and I_{PAR} is the daily amount of crop-intercepted photosynthetically active radiation (MJ^{-1} m^{-2} day^{-1}) (Stöckle *et al.*, 2003; Yadav, 2005).

Each simulation day, the minimum of B_T and B_L is taken as the biomass production for the day. The e variable in Equation 2.7 accounts for temperature limitations in biomass accumulation. To account for nitrogen limitations, the minimum of B_T and B_L is used as a base to determine the nitrogen-dependent biomass production (B_N):

$$B_N = \mathrm{Min}\ (B_T\ , B_L)\ [1 - (N_{pcrit} - N_p) / (N_{pcrit} - N_{pmin})] \tag{2.8}$$

where B_N is in kg m^{-2} day^{-1}, N_p is plant nitrogen concentration in (kg kg^{-1}), N_{pcrit} is the critical plant nitrogen concentration (kg kg^{-1}) below which growth is limited, and N_{pmin} is the minimum plant nitrogen concentration (kg kg^{-1}) at which growth stops (Stöckle *et al.*, 2003; Yadav, 2005).

Increase in leaf area index (LAI) during the vegetative period of plant growth is expressed as leaf area per unit soil area. It is calculated as a function of biomass accumulation, specific leaf area and a partitioning coefficient and is expressed as follows:

$$\mathrm{LAI} = \mathrm{SLAB}/1 + p\mathrm{B} \tag{2.9}$$

where LAI is in m^2 m^{-2}, is the above-ground biomass (kg m^{-2}), SLA is the specific leaf area (m^2 kg^{-1}), and p is a partitioning coefficient (m^2 kg^{-1}) controlling the fraction of biomass apportioned to leaves (Stöckle *et al.*, 2003; Yadav, 2005).

Based on Equation 2.9, biomass change can be estimated which allows for the determination of the new LAI amount produced in each simulation day as a function of biomass production on that day (Yadav, 2005). LAI in the model is vital since it affects canopy senescence. Root growth is synchronized with canopy growth, and root density by soil layer is a function of root depth penetration (Stöckle *et al.*, 2003).

Yield is determined according to the harvest index and a total biomass accumulated at physiological maturity (Stöckle *et al.*, 2003; Garofalo *et al.*, 2009). The relationship is expressed as:

$$Y = B_{\mathrm{PM}}\ \mathrm{HI} \tag{2.10}$$

where Y is yield in kg m^{-2}, B_{PM} is the total biomass accumulated at physiological maturity (kg m^{-2}) and HI is the harvest index (grain yield/above ground biomass) (Stöckle *et al.*, 2003; Yadav, 2005).

The CropSyst model requires four input data files: Location, Soil, Crop, and Management files. These are described in more detail in Section 3.8.

3.7.2 Calibration and validation

Model calibration is a requirement for every model prior to use. With the CropSyst model, calibration of the model must be done sequentially (Donatelli *et al.*, 1997):

- Crop phenology (thermal time at emergence, flowering and physiological maturity),
- Crop morphology (maximum root depth and PAR extinction coefficient),
- Crop physiological parameters (specific leaf area, stem/leaf partitioning coefficient, leaf duration, optimum temperature for growth and the duration of the effect).

Comparing the model outputs and the experimental observations validates the model. This is important in ensuring that the model simulates outcomes that represent adequately the natural system being modeled well. Use of the model for areas in the Highveld region posed a major challenge in the study. Lack of maize phenological and adequate soils information at study sites limited chances to calibrate and validate the model at specific sites. However, since the model has been calibrated and validated for South African conditions, the model was applied at all sites.

Abraha and Savage (2008) calibrated and validated the CropSyst prior to investigating impacts of climate change on the maize crop in Cedara, KwaZulu-Natal. They calibrated and validated various parameters in the model but in this study, concern was given to aspects within the model involved in simulating maize crop yield, i.e. crop phenology (thermal time, photoperiod) and crop growth (water and radiation dependent growth). Their findings showed that the model performed well in simulating fallow and cropped plots (maize). They found that the soil water was slightly under-estimated in maize-planted plots and advised that soil water parameters should be updated using field observations especially following high rainfall events. They also found that the models ability to model maize phenological stages was good(Abraha and Savage, 2008). In this study, version 4.14.04 (19 January 2013) of the CropSyst model was used.

3.8 Model input data requirements

3.8.1 Location file

The location file includes input information such as latitude, weather file name or station name, climate data (rainfall, air temperature, solar irradiance, relative humidity, wind speed, dew point temperatures) (Stöckle *et al.*, 2003). In this study, information used to complete the location files is documented in Section 2.1 and 2.2.

3.8.2 Soil file

The soil file includes soil cation exchange capacity, pH, texture, soil layer and thickness, soil's field capacity, permanent wilting point, bulk density and bypass coefficient. Detailed documentation on soil physical and chemical information was obtained from the land type maps compiled by the Institute of Soil, Climate and Water (Land Type Staff, 1972 – 2006). The physical, chemical and hydraulic properties were determined through field work by conducting particle size analysis, modulus of rupture, water retention, cation exchange capacity, pH, organic carbon, phosphorus status and sorption (Land Type Staff, 1972 – 2006).

Soil attributes such as soil horizon thickness, texture, bulk density, cation exchange, pH and volumetric soil water content were obtained for each area of study from the land type maps. The volumetric water content was also assumed to be the initial soil water content at the beginning of each season. All soil parameters used as input in the model are shown in APPENDIX C.

3.8.3 Crop file

Typical crop input parameters for maize are available in the model but if field measured data is available, relevant adjustments should be made.This file is structured in four general sections: phenology (thermal time requirements to reach specific growth stages, modulated by photoperiod and vernalization requirements if needed), morphology (Maximum LAI, root depth, specific leaf area and other parameters defining canopy and root characteristics), Growth (transpiration-use efficiency normalized by VPD, light-use efficiency, stress response parameters, etc.) and harvest component. Due to lack of phenological and morphological data, default maize crop parameters required in the crop file were used (shown in APPENDIX D).

3.8.4 Management file

The CropSyst management file includes automatic and scheduled management events. Automatic events (irrigation and nitrogen fertilization) are generally specified to provide optimum management for maximum growth (Stockle and Nelson, 2000). Management events can be scheduled using actual date or relative date. Scheduled events include irrigation (application date, amount, chemical or salinity content), nitrogen fertilization (application date, amount, source- organic and inorganic, and application mode- broadcast, incorporated, injected), tillage operations (primary and secondary tillage operations), and residue management (such as grazing, burning and chopping) (Stockle and Nelson, 2000).

In this study, management input parameters that were used included only fertilization and harvesting. Tillage, irrigation and residue application were not utilized since most commercial farmers practice conservation farming (minimal or no till) with crops entirely dependent on rainfall. Also, since one of aims of the study is to determine the effect of increased rainfall amounts on maize yields, thus water supply by irrigation should not be considered in order to obtain precise results. Nitrogen (N) application was considered to occur five days before and at planting. In South Africa, N application ranges from 20 – 30 kg ha^{-1} depending on the soil conditions (Maine *et al*., 2009). In this study, 30 kg ha^{-1} of inorganic N fertilizer was used for each location. Ideally, N supplements should be applied during the growing season in order to replenish lost N. A plant density of 3 plants per meter was assumed for each location (adopted from Walker, (2005)). Fixed planting dates are generally not used in South Africa. It depends on spring/early summer rainfall having been received at a specified window. However, in this study, planting dates for the eastern parts of the Highveld were assumed to be on the 1st of November and on the 15st of November for the western parts. The reason for this was that the eastern parts are wetter and also receive rainfall earlier than the western parts (under normal circumstances) (Walker, 2005). The model executes harvesting 5 days after at maturity.

3.8.5 Simulation control file

The CropSyst simulation control file allows the user to build simulation conditions from an existing database i.e. location, soil, crop and management files. The file determines the start and ending day of simulations, defines the crop rotation to be simulated and set the values of all parameters requiring initialization. Within the simulation control file wizard are options to input initial values and parameters that influence different sub-models (Stockle and Nelson, 2000). **Figure 7.1** in APPENDIX E shows the simulation control file.

Once the simulation control file has been defined, the user can then choose the desired output variables. The variables can either be daily, annual (annual summery of variables accumulated throughout the calendar year) or harvest variables (provide harvest yield and relevant crop conditions at harvest time accumulated throughout the growing season) (Stockle and Nelson, 2000). The output files or reports are formatted as excel spreadsheets or notepad.

In this study, a few output variables were chosen with the harvest variables being the most important. **Figure 7.2** in APPENDIX E shows the model's output report format editor and **Figure 7.3** shows an example of the harvest output report.

3.9 Scenarios

Present and plausible future climate conditions were performed in this study. The plausible future climatic scenarios were selected as previously determined by Walker and Schulze, (2008). After analyses of outputs from General Circulation Models (GCM) and the Conformal-Cubic Atmospheric Model (C-CAM), they found that plausible rainfall changes from 2008 in the Highveld would range from -10 to 10 % by linear change of present daily values in 2008. Plausible future air temperature perturbations for the Highveld region were found to be +1, +2, +3 °C by means of various GCMs. The following scenarios were therefore formulated for this study, where [CO_2] refers to the CO_2 concentration of the atmosphere in the CropSyst model. Air temperature increments were weighted differently between T_x and T_n (with T_n weighted twice that of T_x i.e. T_x + 2/3 and T_n + 4/3 for 2 °C increments whilst for 4 °C increments, T_x + 4/3 and T_n + 8/3). Minimum temperatures have been found to increase twise as much as the maximum temperatures (Karl *et al*., 1993; Abraha and Savage, 2006). Therefore, weighting the minimum and maximum temperatures differently is a more accurate representation of the climate change.

- [CO_2] = 700 μL L^{-1} (Scenario A);
- [CO_2] = 700 μL L^{-1} and 10 % increment to daily rainfall (Scenario B);
- [CO_2] = 700 μL L^{-1} and 20 % increment to daily rainfall (Scenario C);
- [CO_2] = 700 μL L^{-1}andan increment of 2 °C to the mean daily air temperature (Scenario D);
- [CO_2] = 700 μL $L^{-1}$and an increment of 4 °C to the mean daily air temperature (Scenario E);
- [CO_2] = 700 μL L^{-1} and an increment of 2 °C to the mean daily air temperature along with 10 % increment to daily rainfall (Scenario F);
- [CO_2] = 700 μL $L^{-1}$and an increment of 2 °C to the mean daily air temperature along with 20 % increment to daily rainfall (Scenario G);
- [CO_2] = 700 μL L^{-1} and an increment of 4 °C to the mean daily air temperature along with 10 % increment to daily rainfall (Scenario H);
- [CO_2] = 700 μL L^{-1} and an increment of 4 °C to the mean daily air temperature along with 20 % increment to daily rainfall (Scenario I).

The yield outputs from the CropSyst model were compared and a statistical analysis using the *t*-test at 5 % level of significance was used in order to determine whether differences existed between yields under the different Scenarios. This was achieved by comparing yields simulated from the different scenarios to yields simulated under Baseline conditions. Scenarios F and G were used to determine the statistical difference when rainfall was adjusted by 10 and 20 %, whilst Scenarios D and E was representative of the effect of air temperature change on yields.

4. RESULTS AND DISCUSSION

4.1 Temperature trend analysis

Analysis was done on all five representative areas chosen for the study. It was noted that each location had a different time period for the study. The longest data-set analysed was from Cedara with record length from 1970 – 2010 with shortest from Bronkhorstspruit and Bothaville with record lengths 1988 – 2010 and 1980 – 2006 respectively. Lichtenburg and Marble Hall had record lengths of 1978– 2004 and 1981 –2011 respectively. Linear trends were determined are shown in **Table 4.1**.

Table 4.1 Air temperature trends in °C/decade for annual mean maximum (T_x), minimum (T_n), and diurnal air temperature range (DTR) based on daily minimum and maximum air temperatures for selected locations in the Highveld region of South Africa and Cedara.

Location	**Slope (°C/decade^{-1})**		
	$\boldsymbol{T_x}$	$\boldsymbol{T_n}$	**DTR**
Bothaville	-0.02^{NS}	0.18^{NS}	-0.19^{NS}
Bronkhorstspruit	0.19^{NS}	-0.18^{NS}	0.37^{NS}
Lichtenburg	-0.08^{NS}	0.24^{NS}	-0.32^{NS}
Marble Hall	0.00^{NS}	-0.35^{+}	0.35^{NS}
Cedara	-0.10^{NS}	-0.05^{NS}	-0.05^{NS}

$^{+}$significant at 5 %

^{NS} insignificant at 5 %

Areas located towards the western part of the Highved, i.e. Lichtenburg and Bothaville generally showed similar trends. They showed negative annual T_x trends of 0.08 and 0.02 ^{o}C/decade and positive T_n trends of 0.24 and 0.18 ^{o}C/decade. This implied a negative DTR for both locations. Lichtenburg showed a greater annual DTR decline of 0.32 ^{o}C/decade compared to that of Bothaville (0.19 ^{o}C/decade). Similar trends were observed for the two locations and were found to behave differently from Bothaville and Lichtenburg. Bronkhorstspruit and Marble Hall showed a general positive trend in annual T_x of 0.19 ^{o}C/decade and 0.00 ^{o}C/decade and a negative trend of 0.18 ^{o}C/decade and 0.35 ^{o}C/decade in T_n respectively. This implied a positive annual DTR trend for both locations i.e. 0.37 ^{o}C/decade and 0.35 ^{o}C/decade respectively. Cedara showed negative annual trends for both T_x and T_n with T_x decreasing at a rate twice that of T_n. The T_x decreased at a rate of -0.099

^{o}C/decade whilst T_n decreased at a rate of-0.047 ^{o}C/decade. As a result, DTR is decreasing and from the data analysed, DTR decreased at a rate of -0.05 ^{o}C/decade.

A *t*-test at 95 % level showed no statistical significance for T_x , T_n and DTR at all locations except T_n from Marble Hall. Bronkhorstspruit and Marble Hall are located more to the eastern part of the Highveld.

Kruger and Shongwe (2004) conducted a similar study with data from 1960 – 2003. This study included data beyond 2003 at all locations except Lichtenburg. In order to determine whether trends followed those found by Kruger and Shongwe (2004), an analysis on the data up to the year 2003. The results are shown in **Table 4.2**.

Table 4.2 Air temperature trends in°C/decade for annual mean maximum (T_x), minimum (T_n), and diurnal air temperature range (DTR) based on daily minimum and maximum air temperatures for selected locations in the Highveld region of South Africa and Cedara. Analysis exlude data beyond 2003

Location	**Slope (°C/decade^{-1})**		
	$\boldsymbol{T_x}$	$\boldsymbol{T_n}$	**DTR**
Bothaville	-0.30	0.34	-0.64
Bronkhorstspruit	-0.45	-0.38	-0.07
Lichtenburg	-	-	-
Marble Hall	0.00	-0.40	0.10
Cedara	0.21	0.19	0.01

Generally, exclusion of 2003 increased the rate of T_x trend reduction for Bothaville, Bronkhorstspruit and Marble Hall when compared to the results in **Table 4.1**. Cedara showed an increased positive trend. On the other hand, T_n trends became more positive for Bothaville Marble Hall and Cedara. Litchtenburg is excluded in Table 4.2 because its record length ends in 2004.

4.1.1 Discussion

An analysis of global climate data from 1950 - 2004 has shown an increasing annual maximum air temperature by 0.20 ^{o}C/decade, minimum air temperature by 0.14 ^{o}C/decade and a DTR of -0.07 ^{o}C/decade (Vose *et al.*, 2005). The magnitude of rate of increase or decrease was compared to the global rates in order to quantify the of significance in trends obtained in this study.

Kruger and Shongwe (2004) found an increase in both mean annual T_x and T_n after investigating data from 26 climate stations across South Africa for 1960 to 2003. An earlier similar study done by Hughes and Ballings (1996) for the period 1960 – 1990 demonstrated similar results. None of the areas studied in either the western (Bothaville and Lichtenburg) or the eastern (Bronkhorstspruit and Marble Hall) part of the Highveld showed simultaneous increase in both T_x and T_n. The western part showed negative T_x, positive T_n and negative DTR trends. The negative T_x trends contradict the global trends as well as various findings from similar previous studies conducted in South Africa. Positive T_n and DTR trends agree to the global trends revealed by Easterling *et al*., (1997); Vose *et al*., (2006), who studied global historical climate data (1950 – 1999) and found a substantial decreasing trend in global averaged DTR. Many other models have predicted further significant changes (Stone and Weaver, 2004).

The eastern part showed trends opposite to that of the western part (postive T_x, negative T_n and positive DTR trends). Notably, both the eastern and western annual T_x trends are less than the global annual T_x trend of 0.20 ^{o}C/decade whilst the annual T_n trends from the western part are above the global T_n trends of 0.14 ^{o}C/decade (see **Table 4.1**) (Vose *et al*., 2005). This implies that temperatures are increasing at a faster rate in the western half than the eastern part of the Highveld Eco-region.

Results obtained in the study are dependent on the time frame of the available data. The record lengths analysed for all the areas of the study are a subset to that analysed by Kruger and Shongwe (2004) which included data from 1960 – 2003. Data from all the locations exclude the possible influence of the period 1960 – 1970, during which South Africa experienced a cooling trend (Hughes and Balling, 1996). This was followed by a relatively large increase in mean air temperature during the early 80s. Exclusion of either of these periods could have influenced results obtained by (Kruger and Shongwe, 2004). Data from locations such as Bronkhostspruit and Marble Hall included data beyond 2003, the last year Kruger and Shongwe (2004) included in their study. With reference from **Table 4.2**, exclusion of the years beyond 2003 reduced trends made them more negative except Cedara while for T_n, Bothaville and Cedara showed more positive trends. Bronkhorstspruit and Marble Hall showed more negative trends. Therefore, inclusion of the years beyond 2003 in this study cannot be considered to be a factor that influenced trends to deviate from other trends from previous studies. However, when compared to Northen and Southern Hemisphere trends (**Table 2.1**), only DTR from Bothaville exceeded that of the Southern Hemisphere. Both minimum and maximum air temperature trends fell short of those from both Northern and Southern Hemispheres.

Furthermore, another possible factor to have influenced the results could have been the quality of the data. Past methods of data collections were done manually and thus relied heavily on human effort of which greater uncertainty exists. Presently, AWS systemshave replaced their manual equivalent. Well maintained AWS systems are now well equiped to capture and collect accurately various kinds of climate, soil and plant data. The uncertainty involved in data treatments could have also affected the observed outcomes.

There is a general increase in DTR in the eastern part (Bronkhorstspruit and Marble Hall) of the Highveld and a decrease in the western part (Bothaville and Lichtenburg). The decrease in DTR in the western half resulted in increased T_n temperature trends as opposed to decreased T_x temperatures. Karl *et al*., (1993) also found that DTR generally decreased in South African conditions. Therefore, a decrease in DTR (T_x - T_n) reduces solar irradiance which implies more cloud and possibly more rain. Even though more rainfall could benefit yields, the influence of decreased solar irradiance could mask the benefits of increased rainfall thus posing a major risk to the development of the maize crops by decreasing photosynthetic function, sugar and starch content (particularly as T_n increases faster than T_x) (Loka and Oosterhuis, 2010). Other effects include: supressed floral bud development, male sterility and low pollen viability hastening maturity (Ahmed and Hall, 1993). As a result, crop yields decrease.

Air temperature controls the rate of growth as well as mediates various biochemical reactions in plants. Increased T_x temperatures can impede crop development in various ways. One area of concern is the sensitivity of cereal crops during the grain filling processes. Studies on wheat have shown that air temperatures beyond 31 ^oC decrease the rate of grain filling (Al-

Khatib and Paulsen, 1990). Also, temperatures well above the plant cells optimum functional temperatures affects cell activity and if plant development is around the anthesis period, pollination may be inhibited. In fact, the transfer of pollen to stigma, germination of pollen grains and growth of pollen tubes down the style, fertilization and development of the zygote are all temperature sensitive. If affected, yields can be reduced significantly.

Ideally, DTR should neither increase nor decrease significantly enough to affect agricultural production. Global night time (T_n) have been found to increase twice as much as T_x. This is due to the enhanced greenhouse effect which retains more infra-red radiation due to increase water vapour, carbon dioxide, methane, nitrous oxide, ozone, aerosols halocarbons (a group of gases containing fluorine, chlorine and bromine) and sulphur hexafluoride (Boadi et al., 2002). The accumulation of these gases due to anthropogenic activities increase the heat retaining capacity of the atmosphere causing warming. Also, re-radiation of the infra-red that was absorbed during the day as shortwave radiaiton, occurs in mostly in the night time. Therefore, with higher degrees of warmth experienced with time, more warmer night time temperatures will be experienced (Rasul *et al*., 2011) .

For Cedara, decreasing nature of trends for T_x agreed with that of the western part whilst of T_n trends agreed to that found from the eastern part. The difference in rates of decrease, i.e. T_x decreasing twice as much as the T_n rates is verified by the negative annual DTR. This shows that warming is taking place gradually. Kruger and Shongwe (2004) showed annual T_x and T_n trends to be positive for Cedara. They showed T_x annual rates to increase by about 0.14 ^{o}C/decade and T_n annual rates to increase by 0.18 ^{o}C/decade. Findings of this study contradicts this finding as negative trends were obtained (see **Table 4.2**). However, inclusion of the years 2003 – 2011 altered T_x and T_n trends such that they became similar to those found by Kruger and Shongwe (2004).

Even though the were variations in the annual trends for both T_x and T_n it was noted that trends at all locations except T_n for Cedara were considered statistically insignificant. Therefore, the general DTR decrease and increase in the western and eastern parts respectively, have not reached levels that can potential cause major reductions in yields. However, it is evident that temperatures are on the rise especially in the western part of the

Highveld. Therefore, modeling possible future air temperature changes in order to predict future crop losses is necessary.

4.1.2 Conclusion

Although both the minimum and maximum mean annual air temperatures were expected to increase, the decline noted in some locations were considered inconclusive based on a comparison with global trends. Only T_n trends from Marble Hall was considered to be significant after *t*-test at 5 % level of significance. In essence, the annual variations showed that the results are inconclusive if observed on a regional scale which is in agreement with the findings of Kruger and Shongwe (2004). However, T_n trends from the western part of the Highveld Eco-region should raise concerns since they are greater than global ternds. Air temperature increase in a reality and thus adaptation and mitigation strategies are a necessary in order to ensure life suistanability. Success can only be achieved when the climate data analysed is of good quality and if not, proper methods are applied to improve the data. Unfortunately, challenges are still experienced in assessing warming particularly on smaller scales. However, new improved technology and improvements in data quality may allow for more accurate analyses both regionally and seasonally.

4.2 Maize yields changes

This section includes the results of data generation by the CLIMGEN model as well as maize yield analyses after simulation using the CropSyst model. Climate data were generated for the purpose of increasing record lengths in order to assess the risks associated with climate change. Generated data were used for all locations and a comparison of the measured and generated daily rainfall: air temperature and daily solar irradiance data are discussed in Section 4.2.1.

4.2.1 Comparison of measured and generated data

Validation of the CLIMGEN model showed an acceptable percentage difference of 9 % at most from the measured wet days throughout the growing season. An exception to this limit was noted for Marble Hall in January, where the percentage difference in wet-day count was 38 %. The percentage differences of the months in the growing season are shown in **Table 4.3** for five locations.

Table 4.3 Percentage difference between measured and generated seasonal wet day counts for Lichtenburg (1978 – 2004), Bothaville (1980 – 2006), Bronkhorstspruit (1988 – 2010), Marble Hall (1981 – 2011) and Cedara (1970 – 2010).

Location	**Wet day count difference (%)**					
	Jan	**Feb**	**Mar**	**Oct**	**Nov**	**Dec**
Lichtenburg	-2.72	-4.04	0.70	-2.62	-2.91	1.42
Bothaville	2.59	-4.20	1.45	0.13	1.11	0.74
Bronkhorstspruit	-1.08	-1.92	-0.54	1.48	3.06	0.98
Marble Hall	-37.53	-0.12	2.04	-0.32	-0.33	0.11
Cedara	2.75	8.96	5.41	5.59	8.37	8.50

Solar irradiance estimates generated using the Hargreaves and Samani (1982) method produced percentage differences of less than 10 % for most locations across the growing season, with the exception of Cedara and Lichtenburg in January, with differences of 20 and 14 % respectively. The percentage differences shown in **Table 4.4** display a trend of greater generated solar irradiance throughout the growing season for Lichtenburg.

Table 4.4 Percentage difference between the means of seasonal measured and generated solar irradiance (I_s) corresponding to similar months of the entire period of study.

Location	Seasonal I_s percentage difference (%)					
	Jan	Feb	Mar	Oct	Nov	Dec
Bothaville	-0.75	1.74	0.00	-0.94	0.74	1.35
Bronkhorstspruit	0.48	-0.31	1.38	-0.44	-0.93	-1.01
Lichtenburg	13.5	4.90	8.61	7.52	8.10	9.59
Marble Hall	1.54	0.95	-0.13	-0.29	-0.62	4.44
Cedara	-19.9	-0.50	3.44	4.02	3.47	4.09

Differences in air temperature were computed and are tabled in a series of tables in APPENDIX B (**Tables 7.6 – 7.11**). A summary of these results is presented in **Table 4.5**, where the average seasonal mean of the T_x and T_n for the entire record length are shown. As with the wet-day and solar irradiance estimates, the differences in measured and generated temperatures were marginal.

Table 4.5 Measured and generated mean air temperatures for the respective locations. The means are for the entire length of record for either maximum or minimum air temperature.

Location	Mean Air temperature (°C)					
	measured		generated		difference	
	T_n	T_x	T_n	T_x	T_n	T_x
Bothaville	14.2	28.9	14.1	28.8	-0.06	-0.12
Bronkhorstspruit	13.6	26.7	13.5	26.8	-0.07	0.04
Lichtenburg	14.0	28.0	14.0	27.8	0.07	-0.19
Marble Hall	17.4	30.6	17.3	30.6	-0.02	0.00
Cedara	13.7	24.4	13.9	24.9	0.13	0.47

The differences between measured and generated rainfall, air temperature and solar irradiance data were found to be acceptable. However, the yield estimates generated using the CropSyst model were influenced. This is shown by the slight differences in graphs from **Figure 4.1 - 4.5** which show CropSyst output of yields under measured and generated weather data.

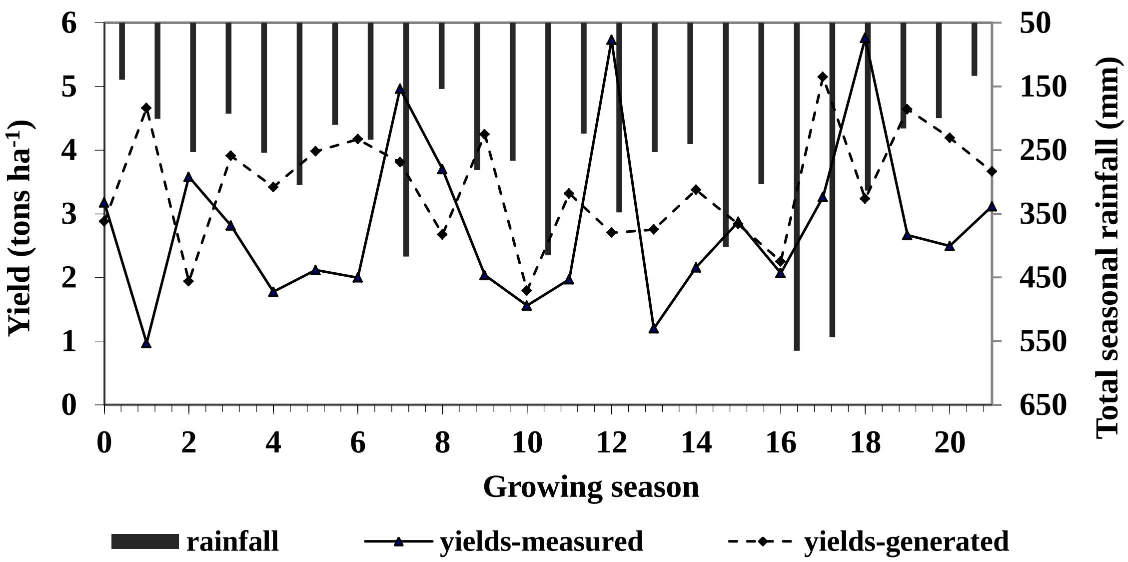

Figure 4.1 Yields generated using the CropSyst model from measured and synthetic (generated) climate data at [CO_2] of 390 μL L^{-1} in relation to measured rainfall comparison at Bothaville.

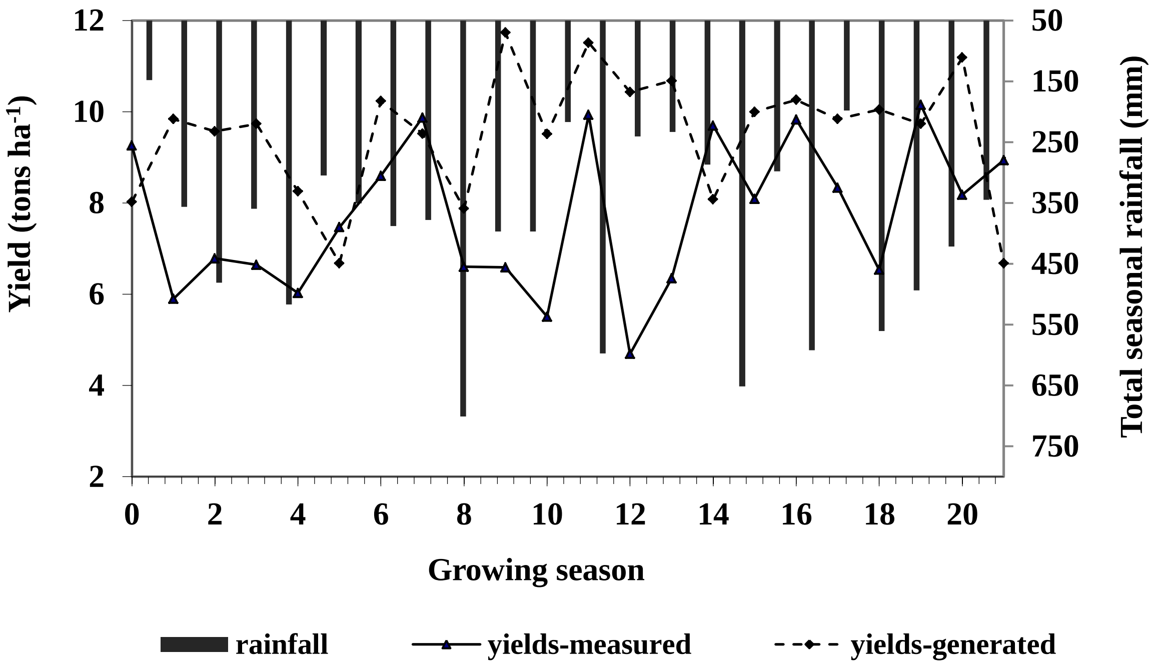

Figure 4.2 Yields generated using the CropSyst model from measured and synthetic (generated) climate data at [CO_2] of 390 μL L^{-1} in relation to measured rainfall comparison at Bronkhorstspruit.

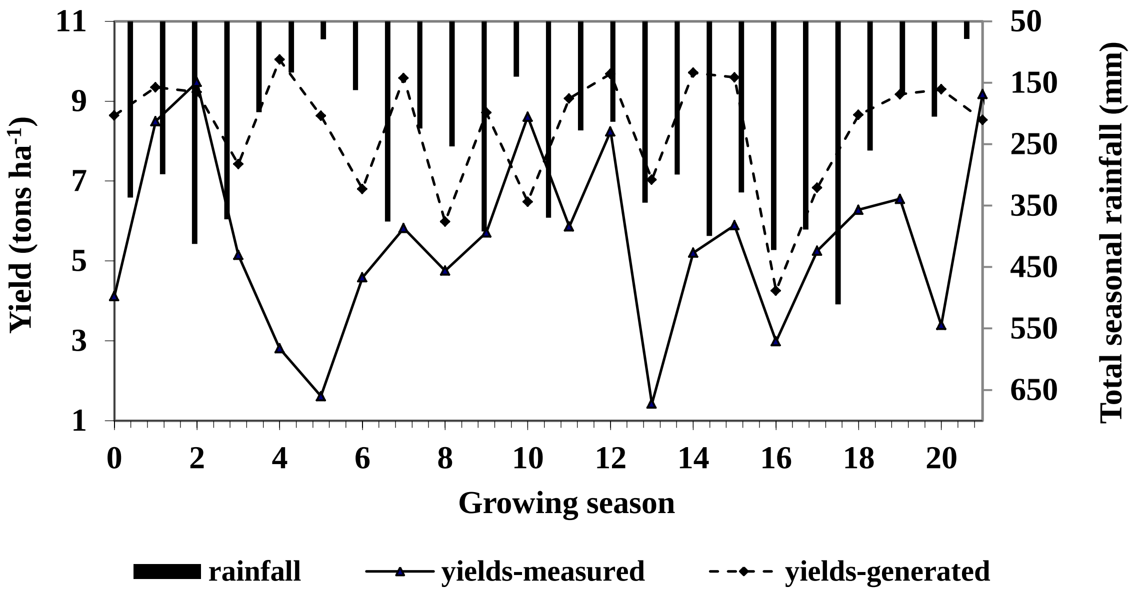

Figure 4.3 Yields generated using the CropSyst model from measured and synthetic (generated) climate data at [CO_2] of 390 μL L^{-1} in relation to measured rainfall comparison at Lichtenburg.

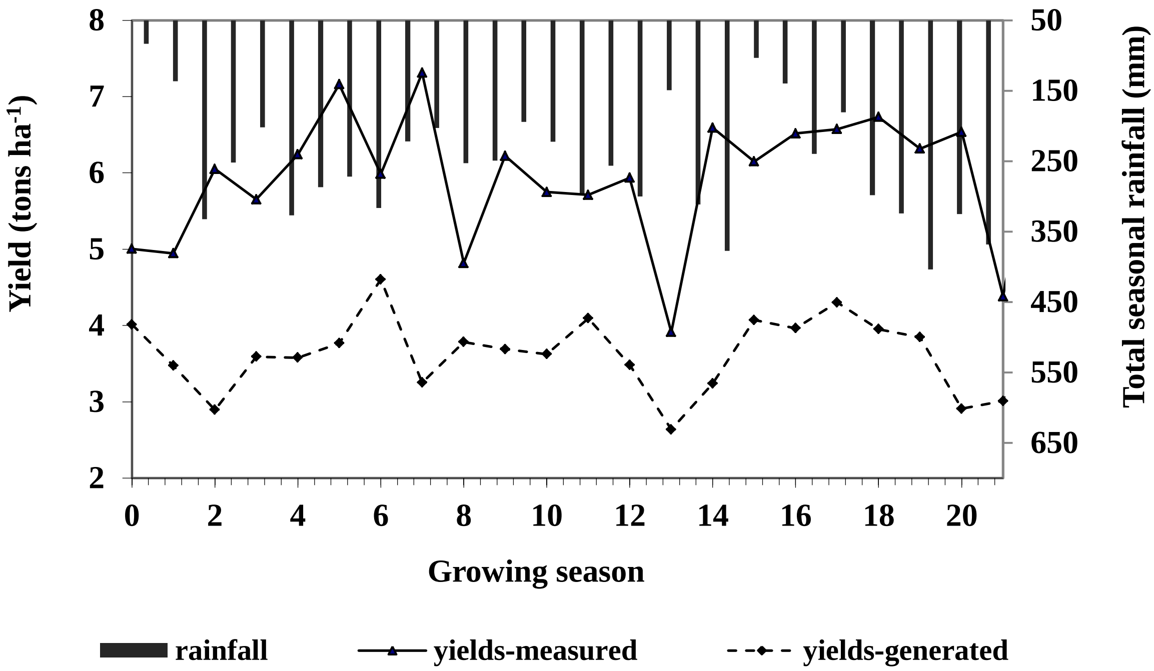

Figure 4.4 Yields generated using the CropSyst model from measured and synthetic (generated) climate data at [CO_2] of 390 μL L^{-1} in relation to observed measured comparison at Marble Hall.

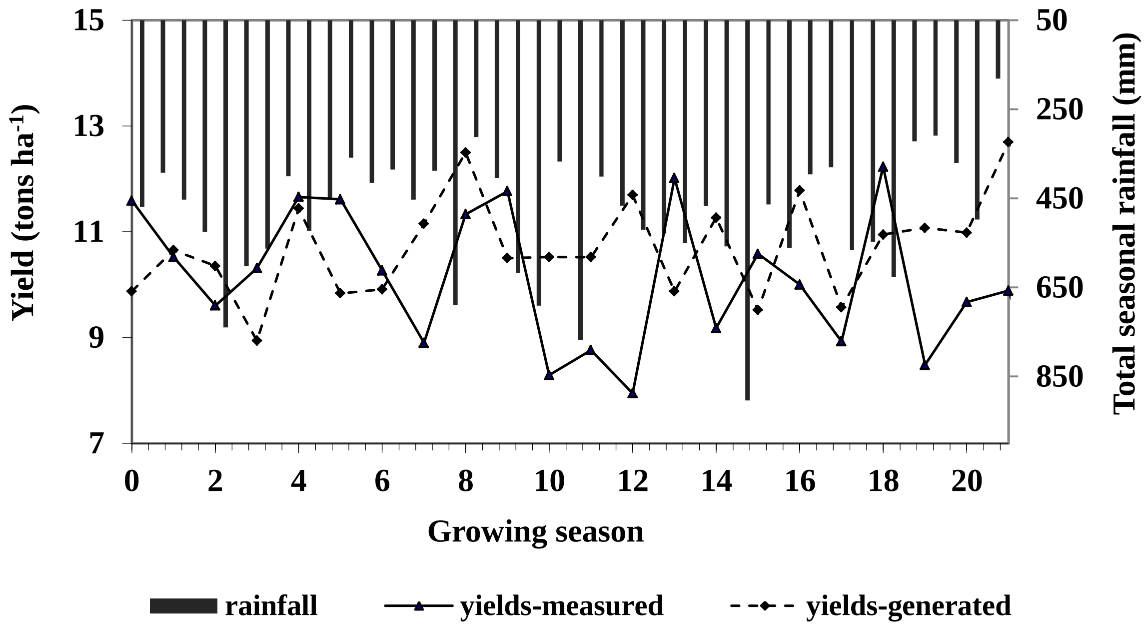

Figure 4.5 Yields generated using the CropSyst model from measured and synthetic (generated) climate data at [CO_2] of 390 μL L^{-1} in relation to measured rainfall comparison at Cedara.

In **Figure 4.1**, **4.2** and **4.4** (Bothaville, Bronkhorstspruit and Cedara) showed some similarities in the trends of the graphs for both measured and generated across the seasons studied.

This is verified by the slight differences in the average yields simulated from measured and generated data at Bothaville, Bronkhorstspruit and Cedara (**Table 4.6**). The greatest difference in yields from measured and generated data was from Bothaville where yield increase of up to 3.0 ton ha^{-1} was noted (simulated from generated data). Generally, yields simulated from generated data showed greater yields as opposed to yields under measured data.

Also, the coefficient of variance (CV) was computed and was used to indicate yield variation of risk. Simulation using generated data decreased CV when compared to yields from measured data across all locations (**Table 4.6**). Lichtenburg and Bothaville showed the greatest CV of more the 45 % with Cedara and Bronkhorstspruit showing CVs of 24 and 22

% respectively (under measured data). Marble Hall was the lowest with a CV of 18 %. For yields under generated data, the CV range was 9.6 (Cedara) – 29.6 % (Bothaville).

Table 4.6 Maize mean yields representative of the entire record length simulated from observed and generated data sets with length of up to 25 years at different locations in the Highveld region.

Location	Weather data	Mean Yield (ton ha^{-1})	Coefficient of variation (%)
Lichtenburg	measured	5.18	45.15
	generated	8.14	24.59
Bothaville	measured	2.73	47.44
	generated	3.40	29.62
Bronkhorstspruit	measured	8.06	22.17
	generated	8.12	18.83
Marble Hall	measured	5.91	18.58
	generated	4.21	10.52
Cedara	measured	9.49	24.73
	generated	9.61	9.09

In order to determine whether the mean yields were statistically the same (null hypothesis) or that yields were different (alternative hypothesis), the student test *t* at 5% level of significance were conducted across allocations with the results shown in **Table 4.7**.

Table 4.7 The 95 % student *t*-test for maize means yields between measured and generated climate data. Calculations are based on **Table 4.6**.

	Bothaville	Bronkhorstspruit	Lichtenburg	Marble Hall	Cedara
Computed *t*	2.01^{NS}	1.12^{NS}	4.91^{+}	7.75^{+}	1.08^{NS}

$^{+}$significant at 5 %
^{NS} insignificant at 5 %

The computed *t* for Lichtenburg and Marble Hall were statistically significant as depicted by **Table 4.7** and thus the alternate hypothesis is accepted. This implies a difference in mean yields between the observed and generated data for the two locations. Bothaville, Bronkhorstspruit and Cedara had statistically insignificant *t*-test results.

4.2.2 *Yields undertaken for the different Scenarios*

Increasing CO_2 concentration increased yields by 30 % across all locations. This was deduced from **Table 4.88**, were Scenario A was compared with baseline conditions. Altering rainfall from the input generated weather data by 10 and 20 % to test the sensitivity of the estimates increased yields. However, Scenarios B and C (involved altering changing rainfall without air temperature change) were excluded from further investigations but the impacts of rainfall increments were deduced from comparing Scenarios D, F and G which depicted sequential rainfall increments of 0, 10 and 20 %.

Table 4.8 Summary table of simulated average maize yield (ton ha^{-1}) and coefficient of variance – Coefficient of Variation (CV in %) for different locations based on the scenarios undertaken.

		SCENARIOS							
	WEATHER PARAMETER	**baseline**	**A**	**D**	**E**	**F**	**G**	**H**	**I**
		350	700	700	700	700	700	700	700
	Air temperature increase (°C)	-	-	2	4	2	2	4	4
	Rainfall increase (%)	-	-	-	-	10	20	10	20
LOCATION									
Bothaville	Mean yield	3.40	4.38	3.85	3.44	4.03	4.16	3.57	3.68
	CV	29.62	30.26	31.58	30.52	30.43	29.80	29.86	28.95
Bronkhorstspruit	Mean yield	8.12	10.84	9.72	8.54	10.07	10.36	8.78	9.01
	CV	18.83	15.94	18.00	17.91	13.26	12.05	14.38	13.13
Lichtenburg	Mean yield	8.14	10.76	9.30	7.99	9.57	9.78	8.22	8.37
	CV	24.59	22.42	20.74	18.52	19.81	18.86	17.45	16.59
Marble Hall	Mean yield	4.21	5.19	4.38	3.67	4.38	4.38	3.67	3.67
	CV	10.52	10.54	12.73	12.93	12.73	12.73	12.92	12.91
Cedara	Mean yield	9.61	11.99	10.74	9.18	10.58	10.60	8.93	8.94
	CV	9.09	8.26	8.21	9.87	8.28	8.28	8.95	8.96

Considering Scenarios D, F and G (no change in air temperatures), an increase in rainfall was noted across all locations except Cedara were yields decreased yet all other climatic variables remained constant. Under 10 % increments, yields increased by 4 % from Lichtenburg, Bronkhorstspruit and Bothaville. Insignificant increases in yields were noted for Marble Hall. With 20 % increments, yields generally increased by 7 % for Lichtenburg, Bronkhorstspruit and Bothaville with slight insignificant changes for Marble Hall. The percentages increase and decrease were deduced from **Table 4.8** and **4.9**.

Table 4.9 Percentage increase or decrease in mean simulated maize yield as compared to baseline ($[CO_2]$ = 390 µLL^{-1} without altering neither air temperature, nor rainfall) conditions and scenario A conditions ($[CO_2]$ = 700 µLL^{-1} with no changes in air temperature and rainfall).

PARAMETER	SCENARIOS					
	D	E	F	G	H	I
$[CO_2]$ (µl l^{-1})	700	700	700	700	700	700
Air temperature increase (°C)	2	4	2	2	4	4
Rainfall increase (%)	-	-	10	20	10	20

LOCATION	Reference	PERCENTAGE YIELD INCREASE OR DECREASE (%)					
Bothaville	baseline	13.22	1.18	18.62	22.28	4.89	8.23
	A	-12.19	-21.53	-8.00	-5.16	-18.65	-16.06
Bronkhorstspruit	baseline	19.70	5.19	23.93	27.61	8.07	10.89
	A	-10.35	-21.22	-7.18	-4.43	-19.07	-16.95
Lichtenburg	baseline	14.25	-1.85	17.53	20.14	0.94	2.79
	A	-13.57	-25.75	-11.09	-9.11	-23.64	-22.24
Marble Hall	baseline	4.07	-12.77	4.09	4.11	-12.75	-12.74
	A	-15.62	-29.27	-15.60	-15.59	-29.26	-29.25
Cedara	baseline	11.74	-4.53	10.05	10.26	-7.07	-7.00
	A	-10.45	-23.48	-11.80	-11.64	-25.52	-25.47

From **Table 4.9** (with reference from baseline conditions), it can be seen that there was a general increase in yields even after air temperature increments across locations when compared to baseline conditions. Only Lichtenburg, Marble Hall and Cedara experienced losses at some stage. When considering Scenarios D and E, only Lichtenburg, Marble Hall and Cedara (1.8, 12.8 and 4.5 % yield losses, respectively) experienced yield losses when air temperature was increased by 4 °C. Slight increases in yields were noted for Bothaville and Bronkhorstspruit from Scenario E. Yield increases ranging between 10 – 20 % occurred under Scenario D except Marble Hall. Losses were also experienced under Scenarios H and I from Marble Hall and Cedara and slight increments from Lichtenburg. Generally, 2 °C increments increased yields across all locations.

Comparisons with Scenario A eliminate the influence of increased CO_2. As a result, reductions in yields are noted across all locations with greater reductions experienced from Scenarios that included 4 °C increments.

With reference to **Table 4.8**, increasing CO_2 concentration generally decreased CV (see Scenarios A and Baseline) but increase in air temperature increased CVs (see Scenarios A, D and E). Even higher CVs were noted after increasing temperatures by 4 °C. Rainfall increments reduced CVs and this can be seen from Scenarios D, F and G.

In order to determine whether the difference in yields are significant to raise concerns, a *t*-test at 5 % level of significance was conducted and is shown in **Table 4.1010**. Yields obtained under Scenarios F and G were compared to Baseline yields and showed significant increments from both 10 and 20 % from Lichtenburg, Bothaville, Bronkhorstspruit and Cedara. Yields under 2 °C increments showed significant increase in yields from Lichtenburg and Cedara whilst Marble Hall and Cedara showed significant decrease under 4 °C increments.

Table 4.10 Student *t*-test for maize mean yields computed from data sets used to generate results in **Table 4.6**. The statistics were determined from Scenarios F (10 %) and G (20 %) and D (2 °C) and E (4 °C) with reference to yields simulated under Baseline Scenario.

	Computed t			
Location	**Rainfall**		**Air temperature**	
	10 %	20 %	2 °C	4 °C
Lichtenburg	2.59^{+}	3.01^{+}	2.09^{+}	0.30^{NS}
Bothaville	2.18^{+}	2.59^{+}	1.56^{NS}	1.04^{NS}
Bronkhorstspruit	5.42^{+}	6.43^{+}	3.89^{NS}	1.10^{NS}
Marble Hall	1.30^{NS}	1.31^{NS}	1.29^{NS}	4.46^{+}
Cedara	4.94^{+}	5.03^{+}	5.75^{+}	2.19^{+}

4.2.3 Discussion

Generating reliable data using the CLIMGEN weather generator was successful except in generating climate data for Lichtenburg and Marble Hall. Slight differences between measured and generated climate data were expected due to CLIMGEN's inability to generate an equal number of wet days from the measured data. The weather generator tends to eliminate longer dry spells and assigns more wet days, thus increasing the wet-day count.

However, the difference between the climate data-sets is negligible due to percentage differences below 10 %. The high seasonal wet-day count percentage difference from Marble Hall could have resulted from a series of outlier data that went undetected during data treating. Also, it was found that the CLIMGEN weather generator can also underestimate the number of the wet-day counts (as shown by the negative percentage difference values in **Table 4.3**).

Statistical differences between measured and generated (using the CLIMGEN) climate data can be attributed to various factors from either the original data or within the model. the differences are a result of discrepancies within the original data, or as reports have revealed, at times errors occur during generation within the CLIMGEN model (McKague *et al.*, 2003). A careful approach in handling such data during impact assessment studies should be a priority, clearly outlining the levels of uncertainty involved. The need to assess the data quality adequately is a vital process in these kinds of studies but even more so, comparisons between measured and generated data aid in the overall model validation process (Tingem *et al.*, 2007).

Tingem *et al*., (2007) performed an assessment of the performance of the CLIMGEN weather generator in selected areas in Cameroon. Their findings showed that the model reproduced annual means well for rainfall and air temperature. However, in one particular area (Kribi) the generated means were lower and at times greater than mean rainfall. The student *t* and *F*-tests showed significant differences in rainfall between measured and generated data in Kribi. Air temperature and solar radiation were generated well (Tingem *et al.*, 2007). Furthermore, Abraha and Savage (2006) used the CLIMGEN weather generator to generate data from observed climate data from Cedara, South Africa. They found that the CLIMGEN weather generator generated a larger wet-day count in some months, whilst underestimating wet-day count in other months. From **Table 4.3**, **4.4** and **4.5** it was concluded that the CLIMGEN validation was a success due to minimal statistical differences between the measured and generated data and was therefore used for sensitivity analysis of climate change involving plausible future climatic scenarios.

The discrepancies experienced at generating climate data tend to affect the quality of the yield simulation. The overestimation of the wet-day count and solar irradiance from Lichtenburg effected simulated yields since a difference in yield trends as well as average yields were noted. This was proved by a 5 % level of significance *t*-test analysis which showed a significant difference between yields simulated from measured and generated data. Marble Hall was also found to have statistically significant difference in yields from the two data-sets. Therefore, any analysis done on these two locations was subject to scrutiny based on the poor quality of the data used. However, the *t*-test at 5 % level of significance showed insignificant differences in yields simulated for Bothaville, Bronkhorstspruit and Cedara.

Once the data were generated adequately, a sensitivity analyses was employed across all locations. Increasing CO_2 concentration without air temperature and water regime changes increased yields by 30 % across all locations (Scenario A). The maize crops benefits from CO_2 fertilization indirectly. Being a C4 plant, the maize photosynthetic pathway should not be affected by elevated CO_2 concentration because the CO_2 concentration within cells is more than 3 - 6 times greater than in the atmosphere (Leakey *et al.*, 2006). At current atmospheric CO_2 concentration, maize or any other C4 crops are already saturated and should not theoretically assimilate CO_2 at greater rates in elevated atmospheric CO_2 concentration. In fact, stomata experience reduced conductance and partial stomatal closure, decreasing transpiration (Ghannoum *et al.*, 2000). This conserves water and improves water use efficiency at the same time increasing photosynthesis, resulting in the positive growth responses in maize (Drake *et al.*, 1996). The increased yield response to elevated [CO_2] has been found to be greater under water limiting conditions. However, this is more in the short-term rather than long-term, since actual yields may still be greater under non-stress condition (Chaudhuri *et al.*, 1990). This is consistent with the findings in this study were average yields from measured data for Bronkhorstspruit and Cedara (**Table 4.6**) were greater. Also, greater MAPs i.e. 845 and 708 mm (Bronkhorstspruit and Cedara respectively) contributed to the increased yields for when compared to the other locations.

Maize growing season covers only October to March the following year (can be shorter depending on planting date). Average seasonal totals are more likely to be a more accurate representative of the water used for crop development. The generated seasonal average rainfall totals were less than 500 mm for all locations. Bothaville and Lichtenburg had average seasonal totals of about 280 mm with Marble Hall having the least (252 mm). Cedara and Bronkhorstspruit had 490 and 396 mm respectively. In light of this, the effect of the amount of seasonal totals had an effect of yields. Lower seasonal rainfall totals resulted in lower average yields as depicted by results from Bothaville and Marble Hall whilst the rest of the locations produced yields above 5.0 t ha^{-1}.

The influence of rainfall increments by either 10 or 20 % increased yields as seen from **Table 4.88.** In Table 4.10, a *t*-test at 5 % level of significance showed a statistical difference in yields as influenced by rainfall increments across all locations except Marble Hall. This strengthens the validity of the important role rainfall plays in maize production. Perhaps the lower Mean Annual Precipitation experienced on the western parts of the Highveld should be supplemented with irrigation to improve yields. However, since South Africa is a semi-arid region and has already been declared as a water scares country, irrigation may come at a cost and thus the need to pursue other cost-effective measures such as rainfall harvesting ensure that yields increase and reduce variability. Marble Hall had the lowest average yields. Therefore, differences in yields were not as pronounced and thus any increase in yields (as a result of rainfall increments) may not have had significant changes in yields.

Even though others have found that rainfall increments by 10 and 20 % had little or no influence on maize (Abraha and Savage, 2008), this study has found that rainfall increments by the same margin benefits maize yields positively. This agrees with a study that revealed that a 10 – 20 % rainfall increment resulted in 30 % and more yield reduction in parts of South Africa (Waha *et al*, 2013). Furthermore, yields variability (CV) decreased with increase in rainfall. Less yield variability is ideal for either consistency or growth in production seasonally in yields.

With reference to Scenarios A, D and E in **Table 4.88**, the magnitude of increase in CV is generally directly proportional to increments in air temperature. At all locations, increasing air temperatures increased variation in yields. Therefore, since predictions suggest a future with higher air temperatures, strategies aimed at stabilizing yields should also be given much consideration. The goal is to ensure that maize yields increase with minimal variation in order to eliminate periods where supply falls short of the demand thus risking lives, economies and sustenance of certain agricultural practices (livestock feed). The hotter western part requires more urgent attention if yields are to be maintained or increased.

A 2 ^{o}C air temperature increment reduced the growing season by 30 days after simulation through the CropSyst model. A reduction of the growing season reduces yields but still maintains high photosynthetic activity. This justifies the yield increments experienced across all locations after temperatures were increased by 2^{o}C. The influence of air temperature increment was masked by the increased CO_2 concentration. Reductions in yields were noted only after 4 ^{o}C increment at from Lichtenburg, Marble Hall and Cedara. Though the reduction seemed random, it was noted that both Lichtenburg and Marble Hall are located on the northern parts of the Highveld, almost falling into the Limpopo province. These areas are characterised by lower rainfall and higher maximum and minimum temperatures. Also, securing arable land that can sustain adequate maize production in these areas can be challenging since marginal production areas dominate (Benhin, 2008).

Air temperature increments by 4 °C further shortens the growing season to 50 days with an even narrower daily air temperature range which resulted in reduced solar radiant density implying increased cloud duration. This could result in a possible increase in rainfall which can benefit yields. Yields were expected to decline across all Scenarios but this was only noted to be the case for Marble Hall and Cedara. The declines from these locations were considered to be statistically significant after a *t*-test at 5 % level of significance. Bothavile, Bronkhorstspruit and Lichtenburg all showed increase in yields under Scenarios E, H and I but were considered statistically insignificant (with reference to Baseline yields). Therefore, future maize yields will be more or less maintained at current yields. However, with a population increase of 2 % every year and a projected population growth of up to 82 million by 2035, maize yields have to increase in order to meet the demands. Already, changes in air temperature regimes and water shortages as well as loss of arable land, have reduced yields in the Highveld (Benhin, 2006; Abraha and Savage, 2006; Walker and Schulze, 2008).

However, the impact of changing air temperature was noted when comparisons were done with Scenario A. this eliminated the influence of increased CO_2 on yields. High reductions due to 4 °C increments were evident with much less reductions were experienced from the 2 °C increase in temperature. This showed that air temperatures reduces yields and therefore, expected future air temperature increments will reduce maize yields unless adaptation measures that focus on improving management strategies (such as planting early, reducing plant densities and using genetically modified maize breeds that can withstand harsher conditions) are practiced.

Higher in air temperature increased the CV. Higher variations were noted from the western than the eastern part. This confirms the urgency of focusing most of the energy onto the western than the eastern part. A study by Walker and Schulze (2008) showed that increasing air temperature in three selected quaternary locations from driest, intermediate and wettest part of the Highveld increased the variability of maize yields. They concluded that the CV increases from east to west following the MAP pattern (**Figure 3.2**).

The increase in yields as a result of higher air temperatures can be attributed to the maize cell's ability to increase the CO_2 saturation point at higher air temperatures which then encourages CO_2 assimilation causing photosynthesis to increase (Allen *et al.*, 2011). In fact, some modelling studies conducted in the mountainous regions of South Africa have shown that air temperature increases are beneficial for maize growth and lead to increasing crop yields of at least 6 % (Waha *et al.*, 2013). However, air temperature increments that exceed maize's specific optimal temperature for photosynthesis (21 – 26 ^{o}C) result in a steady decline in the rate of photosynthesis (Haxeltine and Prentice, 1996). All locations studied had mean air temperatures that exceeded the photosynthesis optimal temperature range but below fatal temperatures (40 ^{o}C) which reduces crop growth by inflicting oxidative damage to cells, modifies membrane functions, denature proteins, reduces pollen germination ability and reduces kernel growth rate (Barnabás *et al.*, 2008).

A similar study conducted using the CropSyst model at Cedara KwaZulu-Natal South Africa by Abraha and Savage (2006) revealed that minimum air temperature increased twice as much as the maximum air temperature increase (as was done in this study), reduced the daily range and in turn the solar radiant density. Reduced radiant density received by the crop can reduce yields and therefore could have contributed to reduction from scenarios D, F and G as well as scenarios E, H and I (when compared to scenario A).

Rainfall and air temperature are vital climatic variables that affect crop production and a change in either of them may increase or decrease yields. Therefore, attempts to aid either, farmers' adaptation to changes in climate or measures to reduce rate of climate change should be in response to changes in air temperature. The significance of rainfall variability on yield is important and should be taken seriously without negating impacts by air temperature increments. For instance, in the 2011/2012 season, maize yields were greatly reduced after farmers opted to plant early after being misled by early spring rains. This was followed by drought conditions that hampered crop growth reducing subsequent yields which led to fewer exports and a need to import maize from Zambia. According to the Crop Estimates Committee (CEC), production has since decreased and is less variable. With prices at R2 700 per ton, poor growing conditions and increase in consumption, the pressure is on the farmers to produce enough yields. A study by Durand and du Toit (1999) revealed the breakeven maize yield for a commercial farmer in the western Highveld was 2.20 ton ha^{-1} and 3.60 ton ha^{-1} for the eastern Highveld (Walker and Schulze, 2008). Yields obtained in this study exceeded these two breakeven values. However, having more locations represent the western and eastern Highveld could lower average yields. Also, since the breakeven values were determined based on the 1997/1998 season, application is irrelevant as yields have changed.

The soils physical and chemical properties could also have affected yields. Soils from the western half showed to have less silt and clay percentages than sand. More sand reduces the Cation Exchange Capacity (CEC - soils ability to absorb nutrients available in the soil). Soil particles responsible for the absorption are found in the smaller fragments of clays and silt particles (Pansu and Gautheyrou, 2006). Both Bothaville and Lichtenburg have less silt and clay particles in the upper horizons than the lower (APPENDIX C, **Table 9.1.**). Low CEC also affects the water holding capacity of the soil (Glaser *et al*., 2002). Therefore, a dry western half of the Highveld with soils having reduced water holding capacity will affect maize yields negatively. Also, highly weathered soils are associated with low CEC and thus have low plant available nutrient content (Cahn *et al*., 1993). Applied nutrients are rapidly leached below the root zone and accumulate in lower horizons (Cahn *et al*., 1992). To remedy this problem, slow-release nutrients such as organic fertilisers and increasing the soils sorption sites can help retain nutrients for longer periods thus allowing yields to increase in the western half.

Bronkhorstspruit had well balanced textural ratios of sand silt and clay (**Table 9.1** in the APPENDIX C section shows this) with a greater CEC value than the locations from the western half. As a result, the soils hold more water and nutrients which could influence yields positively. The high yields from Bronkhorstspruit could have also been a result of good soil physical characteristics. In Marble Hall, yields were not as high. Possibly, the soils physical and chemical characteristics may not have affected yields as significantly as rainfall and air temperatures did. Cedara had soils with fairly high clay and silt contents which reduced leaching due to the improved water holding capacity.

Understanding the changing climate and environment in the Highveld will ensure that current maize growing areas remain arable as long as soil factors needed for optimal growth are provided. More urgently, the western part is likely to expect yield reductions as a result of air temperature increments. Therefore, adaptation strategies such as growing hydrids that either have shorter growing seasons or tolerate dry conditions should be enforced or improved. Research on this should be in paralleled with climate change studies since the climate is ever changing. Seasonal climate forecasts and application to agriculture can assist farmers. This will also provide a good prognosis of the best times to plant since yields can be impacted by planting date. Abraha and Savage (2006) found that varying the planting date in maize farming reduced impacts of climate change.

5. CONCLUSIONS AND RECOMMENDATIONS

The focus in this study was on the simulation of plausible future maize crop yields based on scenarios that incorporate future climate changes using the CropSyst model. Rainfall and air temperature are the two climatic variables that have been noted to change with global warming. An increase in summer rainfall totals in the Highveld region increased maize yields at all locations in this study. This highlights the critical role water plays in maize production and therefore supply should be ensured if yields are to be increased in the future. However, with South Africa already declared a water scarce country, considering irrigation or other mechanisms that supplement water supply is necessary for the future. Rainfall alone may not meet future demands considering the population growth rate and loss of arable land. If water supply is adequate, yields will increase and yield variation will be reduced. This study showed that CV reduced when rainfall was increased. Walker and Schulze (2008) also found that higher MAPs reduced maize yields using the CERES-Maize model.

Also, it was found that increase in air temperature generally increased yields. Mainly, influence of air temperature increase was masked by CO_2 fertilization. However, when kept constant, the influence of increasing air temperature by 2 and 4 ^{o}C decreased yields. This agrees with the findings of Abraha and Savage (2006) and Walker and Schulze (2008) who reported a decrease in yields after increments of 2 ^{o}C and above. Also, increase in air temperatures increased yield variation, agreeing with the findings of Walker and Schulze (2008). Therefore, yields will be affected as the climate changes particularly in areas on the margins of the Highveld Eco-region. Lichtenburg and Marble Hall were found to be located towards the margins of the northern part of the Highveld and both locations experienced the highest yield reductions after 4 °C increments.

Generally, the study found that increase in rainfall impacted yields positively by increasing yields and reducing variation. Slight increase in air temperature increases yields but losses are experienced when increments exceed 2 °C. Also, air temperature increments increase yield variability. The results from the climate sensitivity analysis showed that the western part is more vulnerable to decrease in yields due to lower MAPs and higher air temperatures. The main revelation in this study was the impact changes in rainfall and air temperature on yield variation. Higher rainfall (MAPs) and lower air temperatures on the eastern part reduced variation whilst lower MAPs and higher air temperatures increased yield variation on the western parts. Therefore, adaptation strategies such as conservation agriculture, rainfall harvesting, supplementary irrigation and planting drought or heat resistant varieties, should be implemented in order to ensure high yields. Development of new infrastructure and policies that are aimed at improving the capacity to adapt are also vital (Walker and Schulze, 2008).

On another note, an analysis of the temperature trends of the eastern part showed negative rate of change for T_n and positive T_x and DTR, whilst the western showed the opposite. A *t*-test at 5 % level of significance showed that the trends were insignificant; a conclusion consistent with that of Kruger and Shower (2004). However, the study found that T_n trends from the western part exceeded global trends and thus should raise concerns.

Such a study can be improved by use of better quality longer record climate data. Most of data acquired for this study required data treating and patching prior to use. This increased uncertainty in yields modelled thereafter. Better generation of input climate data across all locations is mandatory to ensure better results. Possibly, use of more than one model to generate data could eliminate poor data generation as well as reveal model discrepancies under different climatic regimes. Soil input data relied solely on the findings from past studies. Field soil analyses may improve results of a study such as this since more accurate soil parameters could be used rather than estimates or ranges proposed in previous studies. In essence, field assessments at all the locations to be studied can benefit the study by validating the model and ensuring sound and more realistic results. Also, since both yellow and white maize are grown in the Highveld, studying impacts separately could draw more accurate results aiding in revealing which of the two is more affected by climate change.

Another area of possible focus to improve studies is for modellers to consider average seasonal totals as opposed to mean annual precipitation in order to maximise model outputs. This study focused more on the impacts of seasonal rainfall amounts rather than within-season variation and thus, there is a need to extend the study to incorporate this aspect with greater emphasis on the western part of the Highveld. Also, ensuring that site specific input data such as initial water content, plant density, soil physical and chemical properties, are determined through field work in order to improve the accuracy of the simulations.

Climate change will have negative impacts on maize yields across the Highveld Eco-region. This justifies the need for further research to ensure that production supply meets the demand now and in the future. With the future uncertain, policies that ensure crop adaptation to changes in climate should be prioritized by Government. The policies should encompass formulation of strategies to deal with climate change, favourable trade policies and improved access to credit and markets Walker and Schulze (2008). This will not only increase the Government support system to the commercial and subsistence farmers, but will also promote farmer continuity ensuring that maize production contributes significantly to the economy of the country.

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7. APPENDIX

7.1 Appendix A

Table 7.1 Mean maize yields for all scenarios at Lichtenburg

	Scenarios									
	baseline	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
[CO_2] ($\mu l\ l^{-1}$)	350	700	700	700	700	700	700	700	700	700
Air Temp increase (°C)	-	-	-	-	2	4	2	2	4	4
Rainfall increase (%)	-	-	10	20	-	-	10	20	10	20
Mean Yield (ton ha^{-1})	11.12	14.23	14.24	14.24	12.03	10.03	12.06	12.06	10.03	10.05
Yield increase (%)	0.00	28.04	28.07	28.09	8.21	-9.78	8.49	8.50	-9.77	-9.59
Stdev	0.70	0.90	0.90	0.90	0.83	0.71	0.84	0.84	0.71	0.73
CV	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.07	0.07	0.07
Slope (ton ha^{-1})	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01

Table 7.2 Mean maize yields for all scenarios excluding B and C at Bothaville

	Scenarios							
	baseline	**A**	**D**	**E**	**F**	**G**	**H**	**I**
[CO_2] ($\mu l\ l^{-1}$)	350	700	700	700	700	700	700	700
air Temp increase (°C)	-	-	2	4	2	2	4	4
Rainfall increase (%)	-	-	-	-	10	20	10	20
Mean Yield (ton ha^{-1})	6.72	8.82	7.48	6.32	7.49	7.51	6.34	6.36
Yield increase (%)	0.00	31.22	11.38	-6.00	11.43	11.80	-5.64	-5.41
Stdev	0.84	1.07	0.87	0.76	0.87	0.87	0.74	0.73
CV	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.11
Slope (ton ha^{-1})	0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01

Table 7.3 Mean maize yields for all scenarios excluding B and C at Bronkhorstspruit

	Scenarios							
	baseline	**A**	**D**	**E**	**F**	**G**	**H**	**I**
[CO_2] ($\mu l\ l^{-1}$)	350	700	700	700	700	700	700	700
air Temp increase (°C)			2	4	2	2	4	4
Rainfall increase (%)					10	20	10	20
Mean Yield (ton ha^{-1})	8.85	11.44	9.84	8.47	10.13	10.15	8.57	8.57
Yield increase (%)	0.00	29.34	11.21	-4.26	14.46	14.69	-3.09	-3.08

Stdev	0.98	1.28	1.23	1.11	0.97	0.97	1.06	1.06
CV	0.11	0.11	0.12	0.13	0.10	0.10	0.12	0.12
Slope (ton ha^{-1})	0.05	0.07	0.05	0.05	0.02	0.02	0.05	0.05

Table 7.4 Mean maize yields for all scenarios excluding B and C at Marble Hall

	Scenarios							
	baseline	**A**	**D**	**E**	**F**	**G**	**H**	**I**
[CO_2] (µl l^{-1})	350	700	700	700	700	700	700	700
air Temp increase (°C)	-	-	2	4	2	2	4	4
Rainfall increase (%)	-	-	-	-	10	20	10	20
Mean Yield (ton ha^{-1})	3.62	4.67	3.81	3.03	3.80	3.80	3.01	3.01
Yield increase (%)	0.00	29.19	5.33	-16.39	5.09	5.09	-16.71	-16.71
Stdev	0.44	0.56	0.50	0.45	0.50	0.50	0.45	0.45
CV	0.12	0.12	0.13	0.15	0.13	0.13	0.15	0.15
Slope (ton ha^{-1})	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00

Table 7.5 Mean maize yields for all scenarios excluding B and C at Cedara

	Scenarios							
	baseline	**A**	**D**	**E**	**F**	**G**	**H**	**I**
[CO_2] (µl l^{-1})	350	700	700	700	700	700	700	700
air Temp increase (°C)	-	-	2	4	2	2	4	4
Rainfall increase (%)	-	-	-	-	10	20	10	20
Mean Yield (ton ha^{-1})	6.83	8.87	7.72	6.46	7.72	7.72	6.50	6.51
Yield increase (%)	0.00	29.86	13.09	-5.32	13.00	13.10	-4.77	-4.71
Stdev	0.71	0.93	0.98	0.90	0.86	0.86	0.74	0.74
CV	0.10	0.10	0.13	0.14	0.11	0.11	0.11	0.11
Slope (ton ha^{-1})	0.01	0.02	0.04	0.04	0.04	0.04	0.03	0.03

7.2 Appendix B

Table 7.6 Seasonal statistical analysis for the entire record length of Bothaville

		Jan	Feb	March	Oct	Nov	Dec
OBSERVED							
Wet day count		196	168	168	160	181	231
Dry day count		547	509	577	584	539	544
P_r	**Mean**	3.02	2.59	2.41	2.25	2.69	3.27
	SD	8.85	7.43	7.69	6.35	7.07	8.96
T_x	**Mean**	29.9	29.2	27.9	27.6	29.0	29.9
	SD	3.47	3.57	3.37	4.31	4.14	3.41
T_n	**Mean**	16.1	15.3	13.3	11.3	13.6	15.5
	SD	2.21	2.34	2.82	3.84	3.03	2.64
I_s	**Mean**	24.6	22.9	20.5	23.3	25.3	25.5
	SD	3.89	4.10	3.57	3.85	3.74	3.76
GENERATED		**Jan**	**Feb**	**March**	**Oct**	**Nov**	**Dec**
Wet day count		177	195	157	159	173	218
Dry day count		567	477	587	585	547	532
P_r	**Mean**	2.79	2.81	2.21	2.02	2.65	3.32
	SD	7.79	6.93	6.95	5.57	6.86	8.43
T_x	**Mean**	29.5	29.2	28.0	27.8	28.9	29.4
	SD	3.20	3.67	3.53	4.40	3.88	3.28
T_n	**Mean**	15.6	15.6	13.4	11.0	13.7	15.5
	SD	2.18	2.37	2.94	4.11	3.15	2.66
I_s	**Mean**	24.8	22.5	20.5	23.5	25.1	25.2
	SD	3.79	4.41	3.66	3.85	3.61	3.73

Table 7.7 Seasonal statistical analysis for the entire record length of Bronkhorstspruit

		OBSERVED					
		Jan	**Feb**	**March**	**Oct**	**Nov**	**Dec**
Wet day count		226	184	162	165	211	214
Dry day count		518	494	582	579	509	499
P_r	**Mean**	3.76	3.81	3.39	2.36	3.58	3.75
	SD	8.87	9.54	10.18	7.20	8.67	8.80
T_x	**Mean**	27.2	27.1	26.2	26.4	26.4	27.1
	SD	3.04	3.05	3.11	4.10	3.87	3.09
T_n	**Mean**	15.2	14.5	12.7	11.2	13.3	14.5
	SD	2.14	2.17	2.68	2.98	2.54	2.29
I_s	**Mean**	22.5	21.5	19.6	22.3	22.9	23.4
	SD	3.92	4.04	3.71	3.90	4.03	3.67
		GENERATED					
		Jan	**Feb**	**March**	**Oct**	**Nov**	**Dec**
Wet day count		234	197	166	154	189	207
Dry day count		510	481	578	590	531	506
P_r	**Mean**	3.93	3.85	3.06	2.29	3.05	3.45
	SD	8.48	9.87	8.98	6.50	7.33	8.04
T_x	**Mean**	26.9	27.3	26.2	26.4	26.8	27.1
	SD	3.10	3.13	3.09	4.22	3.76	3.21
T_n	**Mean**	15.1	14.5	12.8	11.0	13.3	14.4
	SD	2.09	2.22	2.81	3.16	2.58	2.34
I_s	**Mean**	22.4	21.6	19.3	22.4	23.1	23.6
	SD	3.93	4.10	3.86	3.96	4.10	3.60

Table 7.8 Seasonal statistical analysis for the entire record length of Lichtenburg

		OBSERVED					
		Jan	**Feb**	**March**	**Oct**	**Nov**	**Dec**
Wet day count		212	156	143	116	152	206
Dry day count		500	494	570	597	508	476
P_r	**Mean**	3.46	2.86	2.57	1.61	2.25	3.23
	SD	8.85	8.21	7.72	5.08	5.97	7.60
T_x	**Mean**	28.7	28.0	26.9	27.2	28.3	28.7
	SD	3.35	3.49	3.19	3.92	3.80	3.28
T_n	**Mean**	15.7	15.1	13.1	11.3	13.6	15.0
	SD	2.03	2.08	2.64	3.55	2.74	2.36
I_s	**Mean**	25.0	21.9	20.0	22.9	24.4	25.6
	SD	16.3	3.8	6.6	3.8	3.5	15.0
		GENERATED					
		Jan	**Feb**	**March**	**Oct**	**Nov**	**Dec**
Wet day count		232	187	138	139	193	207
Dry day count		482	480	575	597	551	512
P_r	**Mean**	3.87	3.16	2.21	1.74	2.39	3.19
	SD	9.04	9.80	6.55	5.11	5.91	7.47
T_x	**Mean**	28.6	28.1	26.7	27.2	27.7	28.4
	SD	3.28	3.43	3.18	4.14	3.75	3.22
T_n	**Mean**	15.9	15.3	12.9	12.1	13.6	14.4
	SD	2.58	2.34	3.10	4.45	3.84	3.66
I_s	**Mean**	21.6	20.8	18.3	21.2	22.4	23.1
	SD	7.03	4.54	5.87	5.02	4.71	4.47

Table 7.9 Seasonal statistical analysis for the entire record length of Marble Hall

		OBSERVED					
		Jan	**Feb**	**March**	**Oct**	**Nov**	**Dec**
Wet day count		294	204	201	207	300	309
Dry day count		636	643	729	723	600	590
P_r	**Mean**	2.84	2.26	2.13	1.83	3.15	3.56
	SD	7.09	7.11	8.07	5.71	7.24	8.03
T_x	**Mean**	31.3	31.7	30.3	29.7	30.0	30.7
	SD	3.26	3.12	3.07	4.24	4.09	3.22
T_n	**Mean**	18.7	18.5	17.0	15.0	17.0	18.0
	SD	2.20	2.01	2.33	3.14	2.58	2.75
I_s	**Mean**	23.9	22.9	20.3	22.7	23.5	24.2
	SD	3.42	3.63	3.21	3.79	4.07	3.64
		GENERATED					
		Jan	**Feb**	**March**	**Oct**	**Nov**	**Dec**
Wet day count		643	205	182	210	303	308
Dry day count		287	642	748	720	597	591
P_r	**Mean**	2.99	2.26	2.01	1.95	3.18	3.32
	SD	7.30	6.38	7.57	5.69	7.17	7.43
T_x	**Mean**	31.2	31.6	30.2	30.1	30.1	30.6
	SD	3.55	3.27	3.16	5.03	4.07	4.42
T_n	**Mean**	18.9	18.5	16.5	15.2	16.9	18.1
	SD	2.32	2.03	2.55	3.14	2.41	3.06
I_s	**Mean**	23.5	22.7	20.3	22.8	23.6	23.1
	SD	3.55	3.73	3.38	3.65	3.91	5.37

Table 7.10 Seasonal statistical analysis for the entire record length of Cedara

		OBSERVED					
		Jan	**Feb**	**March**	**Oct**	**Nov**	**Dec**
Wet day count		813	663	636	730	773	854
Dry day count		459	498	639	541	457	417
P_r	**Mean**	4.45	3.85	3.36	2.82	3.64	4.13
	SD	9.54	8.45	8.59	6.63	8.88	8.81
T_x	**Mean**	25.3	25.5	24.8	22.5	23.6	24.9
	SD	4.60	4.39	4.19	6.15	5.44	4.73
T_n	**Mean**	15.3	15.3	14.0	10.9	12.7	14.2
	SD	2.14	2.10	2.39	2.88	2.63	2.32
I_s	**Mean**	19.7	19.4	17.4	17.1	18.9	19.9
	SD	7.16	6.60	5.87	6.94	7.27	7.20
		GENERATED					
		Jan	**Feb**	**March**	**Oct**	**Nov**	**Dec**
Wet day count		778	559	567	659	670	746
Dry day count		494	602	708	612	560	525
P_r	**Mean**	4.03	3.40	3.12	2.84	3.33	3.91
	SD	9.15	6.76	7.49	5.46	5.89	7.50
T_x	**Mean**	29.5	25.7	24.7	22.5	22.6	24.4
	SD	5.13	4.20	4.23	6.58	5.99	5.87
T_n	**Mean**	17.1	15.3	14.0	11.0	12.1	13.9
	SD	2.68	2.05	2.54	3.36	3.34	3.11
I_s	**Mean**	23.6	19.5	16.8	16.4	18.2	19.1
	SD	5.14	5.96	5.65	7.01	7.07	7.28

7.3 Appendix C

Table 7.11 Soil physical and chemical properties used as input in the CropSyst model for the different selected areas

Layer	Thickness (m)	Texture (%)			Chemical properties	
		Sand	Clay	Silt	CEC	pH
BOTHAVILLE						
1	0.25	94.0	4.0	2.0	22.0	5.5
2	0.65	93.0	6.0	1.0	25.0	5.7
3	0.90	73.0	24.0	3.0	63.0	5.7
4	1.40	79.0	18.0	3.0	63.0	5.8
BRONKHORSTSPRUIT						
1	0.4	34.0	53.0	13.0	117	5.4
2	0.7	28.0	61.0	11.0	114	5.4
3	1.0	29.0	56.0	15.0	109	5.5
4	1.2	25.0	58.0	17.0	103	5.6
LICHTENBURG						
1	0.30	86.0	11.0	3.0	50.0	5.2
2	0.80	81.0	16.0	3.0	33.0	5.6
3	1.10	78.0	17.0	5.0	31.0	5.4
4	1.30	83.0	11.0	6.0	31.0	5.4
MARBLE HALL						
1	0.4	34.0	53.0	13.0	60	5.1
2	0.7	28.0	61.0	11.0	44	4.2
3	1.0	29.0	56.0	15.0	51	48
4	1.2	25.0	58.0	17.0	-	-
CEDARA						
1	0.10	29.7	38.0	32.4	25.1	4.5
2	0.20	29.9	44.0	26.1	15.5	4.5
3	0.30	29.2	44.0	26.8	15.1	4.5
4	0.50	30.0	43.0	27.1	13.0	4.5
5	0.70	32.9	43.0	24.2	14.1	4.8
6	0.90	30.0	36.0	34.0	0.00	0.0
7	1.00	30.5	38.0	31.5	16.3	4.7

Table 7.12 Soil hydraulic properties for selected locations used as input in the CropSyst model

Layer	Thickness (m)	PWP (m^3 m^{-3})	FC (m^3 m^{-3})	Bulk density	*WC at -1500 (m^3 m^{-3})	*WC at -33 (m^3 m^{-3})
			BOTHAVILLE			
1	0.25	0.02	0.02	1.75	0.02	0.02
2	0.65	0.02	0.04	1.69	0.02	0.04
3	0.90	0.08	0.13	1.44	0.08	0.13
4	1.40	0.06	0.11	1.50	0.06	0.11
			BRONKHORSTSPRUIT			
1	0.35	0.17	0.25	1.25	0.17	0.25
2	0.66	0.19	0.27	1.22	0.19	0.27
3	0.98	0.20	0.29	1.24	0.20	0.29
4	1.20	0.22	0.31	1.22	0.22	0.31
			LICHTENBURG			
1	0.30	0.09	0.17	1.58	0.09	0.17
2	0.80	0.12	0.19	1.52	0.12	0.19
3	1.10	0.12	0.20	1.50	0.12	0.20
4	1.30	0.09	0.17	1.58	0.09	0.17
			MARBLE HALL			
1	0.4	0.17	0.25	1.25	0.17	0.25
2	0.7	0.19	0.27	1.22	0.19	0.27
3	1.0	0.20	0.29	1.24	0.20	0.29
4	1.2	0.22	0.31	1.22	0.22	0.31
			CEDARA			
1	0.1	0.21	0.35	1.29	0.21	0.35
2	0.2	0.24	0.38	1.30	0.24	0.38
3	0.3	0.24	0.37	1.39	0.24	0.37
4	0.5	0.23	0.37	1.37	0.23	0.37
5	0.7	0.24	0.36	1.32	0.24	0.36
6	0.9	0.20	0.34	1.29	0.20	0.34
7	1.0	0.21	0.36	1.21	0.21	0.36

* volumetric water content

7.4 Appendix D

Table 7.13 Maize crop default values used as input variables for the CropSyst model

CROP PARAMETERS	
Growth parameters	**Default value**
Biomass-transpiration coefficient (kPa kg m^{-3})	10.0
Photosynthetically Active Radiation (PAR) (g MJ^{-1})	4.0
Mean daily temperature that limits early growth (^{o}C)	12.0
Maximum water uptake (mm day^{-1})	14.0
Leaf water potential at onset of stomatal closure	-1200
Wilting leaf water potential	-1800
Crop morphology	
Maximum rooting depth (m)	1.5
Initial green leaf area index (m^2 m^{-2})	0.0
Maximum expected leaf area index (LAI) (m^2 m^{-2})	5.0
Fraction of maximum LAI at physiological maturity	0.9
Specific leaf area (m^2 kg^{-1})	22.0
Initial canopy cover	0.0
Maximum canopy cover	0.9
Green canopy cover at maturity	0.1
Total canopy cover at maturity (green and senesced)	0.1
Begin senescence (degree-days)	1080
Stem/leaf partition coefficient	2.8
Evapotranspiration crop coefficient at full canopy	1.1
Leaf duration (degree-days)	850
Extinction coefficient for solar radiation	0.5
Leaf duration sensitivity to water stress	1.0
Above ground biomass transpiration coefficient	10.0
Crop phenology	
Growing degree days (GDD) emergence (^{o}C days)	150.0
GDD flowering (^{o}C days)	1040
GDD grain filling (^{o}C days) (^{o}C days)	1124
GDD physiological maturity (^{o}C days)	1300
Base temperature (^{o}C)	8.0
Cutoff temperature (^{o}C)	30.0
Phenologic sensitivity to water stress	1.0
Harvest	

Unstressed harvest index	0.5
Sensitivity to water stress during flowering	0.1
Sensitivity to water stress during grain filling	0.1

7.5 Appendix E

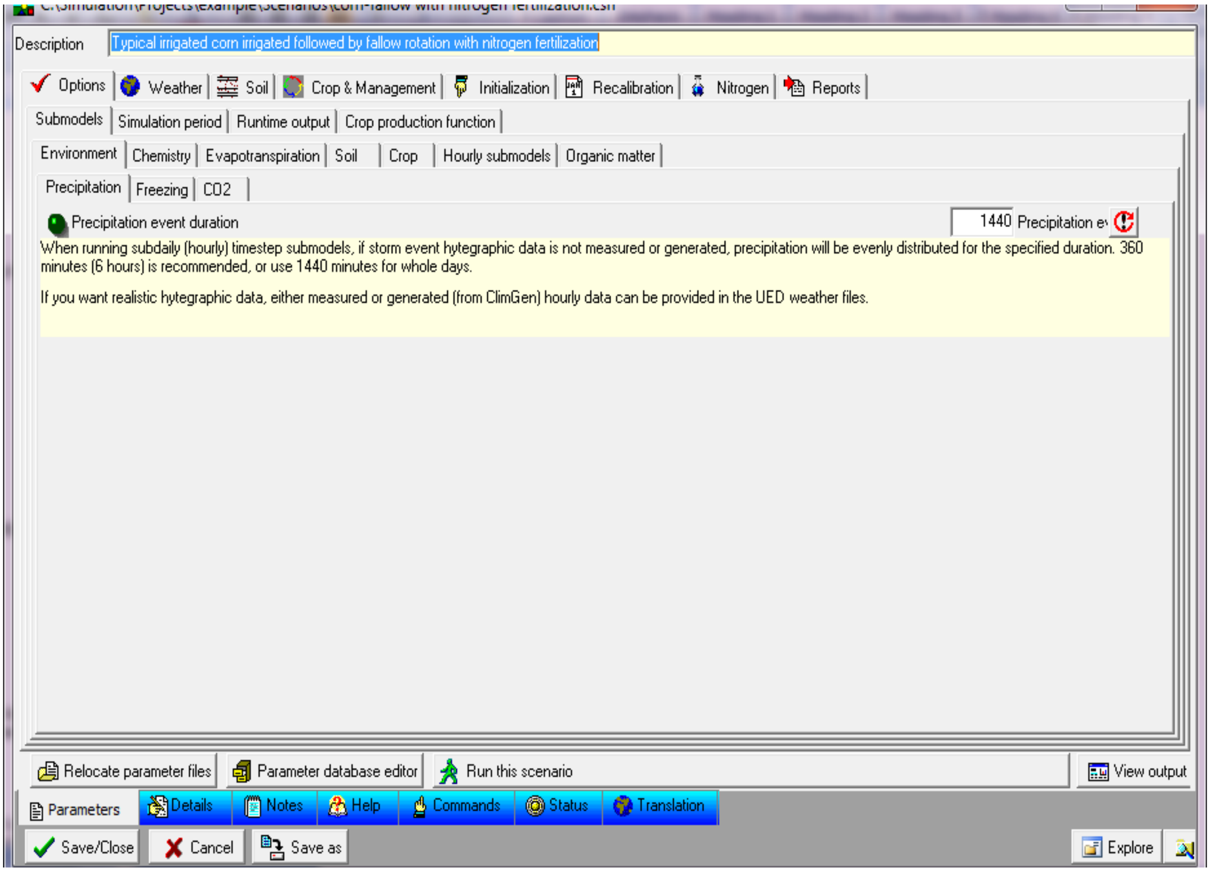

Figure 7.1 Simulation control file for the CropSyst model

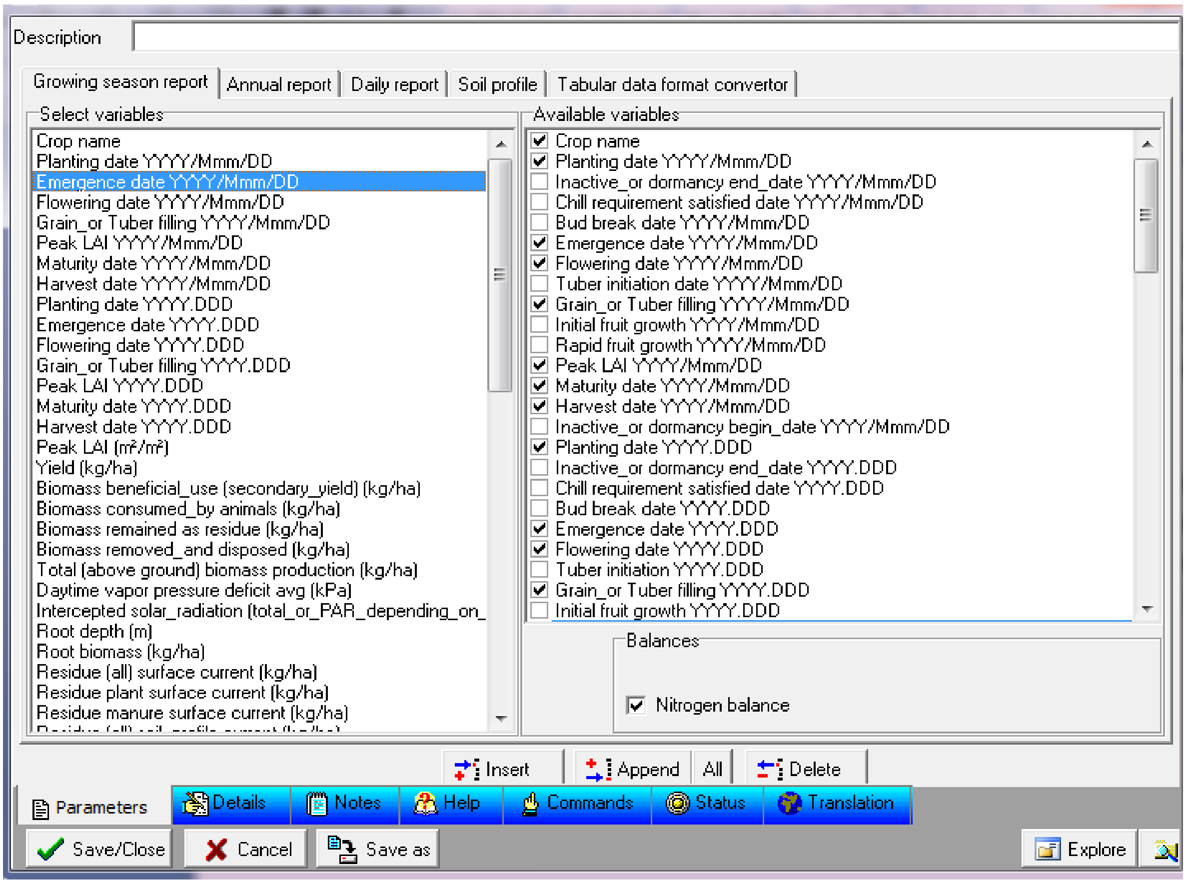

Figure 7.2 Output report format editor for the CropSyst model

Harvest Year	Planting	Restart Dormancy ends	Emergence	Maturity	Event date	Above ground biomass (before harvest or clipping)	Yield Grain, tuber, leaf, fruit or root	Removed and designated for beneficial use (clipped fodder, silage, etc.)	Consumed by animals	Removed from the field and disposed (unused)	Remained in the field laying as surface residue (straw, chaff, etc.)	Remained in the field as dead standing stubble/residue	Remained live biomass (after harvest or clipping)	Soil water drainage	ET act.	
Year	DOY	DOY	DOY	DOY	DOY	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	mm	mm	Description
1982	301	0	311	17	22	14543.656	6253.772	0.000	0.000	0.000	7460.896	828.988	0.000	71.2	260.3	Maize (Zea mays)
1983	301	0	311	17	22	13723.131	5900.947	0.000	0.000	0.000	7039.966	782.218	0.000	186.3	232.4	Maize (Zea mays)
1984	301	0	310	14	19	13359.925	5744.768	0.000	0.000	0.000	6853.641	761.516	0.000	146.3	232.3	Maize (Zea mays)
1985	301	0	311	16	21	16064.784	6907.857	0.000	0.000	0.000	8241.234	915.693	0.000	306.1	247.6	Maize (Zea mays)
1986	301	0	311	20	25	14966.678	6435.672	0.000	0.000	0.000	7677.906	853.101	0.000	117.6	250.0	Maize (Zea mays)
1987	301	0	313	18	23	14344.269	6168.036	0.000	0.000	0.000	7358.610	817.623	0.000	164.2	219.9	Maize (Zea mays)
1988	301	0	311	18	23	15556.096	6689.121	0.000	0.000	0.000	7980.277	886.697	0.000	142.9	254.3	Maize (Zea mays)
1989	301	0	310	19	24	17087.285	7347.533	0.000	0.000	0.000	8765.777	973.975	0.000	231.2	268.1	Maize (Zea mays)
1990	301	0	312	20	25	17295.545	7437.085	0.000	0.000	0.000	8872.615	985.846	0.000	183.9	280.9	Maize (Zea mays)

Done   Computer | Protected Mode: Off   85%

Figure 7.3 Output harvest report from the CropSyst model

Table 7.14 All the dates with missing climate data which needed patching

Location	Date Patched		Comment
	from	**to**	
Bothaville	1981/11/21	1981/12/06	Rainfall and Relative Humidity
	1989/08/01	1989/09/01	Rainfall and Relative Humidity
	1997/11/30	1997/12/15	Rainfall and Relative Humidity
	2001/05/06	2001/05/27	Rainfall and Relative Humidity
	1981/10/01	2002/12/16	Wind speed
	2004/05/10	2004/05/31	Wind speed
	2004/12/05	2004/12/14	Wind speed
Lichtenberg	1980/05/20	1980/05/26	Rainfall
	1981/04/14	1981/04/19	Rainfall
	1996/03/28	1996/04/12	Rainfall
	2000/11/05	2000/11/30	Rainfall
	2000/11/30	2010/12/31	Rainfall
	1981/03/24	1981/04/06	Relative Humidity
	1987/11/17	1987/12/01	Relative Humidity
	1989/03/06	1989/04/26	Relative Humidity
	1991/01/01	1991/01/12	Relative Humidity
	1996/04/24	1996/06/27	Relative Humidity
	1996/12/24	1997/01/02	Relative Humidity
	1997/12/07	1998/01/21	Relative Humidity
	1998/05/05	1998/09/02	Relative Humidity
	2000/06/06	2000/06/06	Relative Humidity
	1978	2004	Windspeed
Marble Hall	1999/11/30	1999/12/27	Rainfall and Relative Humidity
	2000/04/30	2000/05/31	Rainfall and Relative Humidity
	2001/10/01	2001/10/31	Rainfall and Relative Humidity
	2002/03/18	2002/03/25	Rainfall and Relative Humidity
	2002/06/30	2002/07/31	Rainfall and Relative Humidity
	2002/07/31	2011	Rainfall and Relative Humidity
	1981	2011	Windspeed